



Chief Reader Report on Student Responses: 2024 AP[®] Chemistry Free-Response Questions

• Number of Students Scored	151,121		
• Number of Readers	505		
• Score Distribution	Exam Score	N	%At
	5	26,986	17.9
	4	41,462	27.4
	3	45,808	30.3
	2	25,490	16.9
	1	11,375	7.5
• Global Mean	3.31		

The following comments on the 2024 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: Lactic Acid and Sodium Hydroxide Titration/Calorimetry

Topic: Molecular Structure of Acids, Acid-Base Titrations, pH and pK_a , Solutions, Calorimetry, Enthalpy of Reaction

Max Score: 10

Mean Score: 4.43

What were the responses to this question expected to demonstrate?

Question 1 presents students with a series of questions concerning multiple experiments involving lactic acid and sodium hydroxide.

Part (a) requires students to circle the hydrogen atom in the provided structural formula of lactic acid that most readily participates in the chemical reaction with sodium hydroxide. The intent was for students to identify and circle the hydrogen atom on the carboxyl group (Learning Objective SAP-9.F/8.6.A, Skill 1.A from the *AP Chemistry Course and Exam Description*).

Part (b) requires students to calculate the molarity of a sodium hydroxide solution given the mass of NaOH and volume of the solution (SPQ-3.A/3.7.A, 5.F).

Part (c) requires students to approximate the pK_a of lactic acid based on the information from a weak acid-strong base titration curve. The intent of the question was for students to identify the half-equivalence point from the titration curve and recognize that the pH is equal to the pK_a at this point (SAP-9.E/8.5.A, 5.D).

Part (d)(i) requires students to draw an X on the area of the titration curve represented by a given particle diagram. The intent of the question was for students to recognize that there were more lactic acid particles compared to lactate ions (conjugate base) in the particle diagram and recognize that the diagram represents an area of the curve prior to the half-equivalence point (SAP-9.E/8.5.A, 3.A).

Part (d)(ii) requires students to justify the location of the X drawn on the titration curve. The intent of the question was for the students to explain the position of their X on the titration curve based on the particle diagram containing more lactic acid particles than lactate ions (conjugate base), which indicates that the pH is less than the pK_a , a condition that is only true before the half-equivalence point (SAP-10.A/8.7.A, 6.F).

Part (d)(iii) requires students to draw a weak acid-strong base titration curve for a second experiment on top of the titration curve from the first experiment. Experiment 2 uses a sodium hydroxide solution with twice the concentration, which would reach the equivalence point with half the volume of NaOH(aq) required in experiment 1. The question's intent was for students to adjust the expected titration curve based on changing one variable of the experiment (SAP-9.E/8.5.A, 3.A).

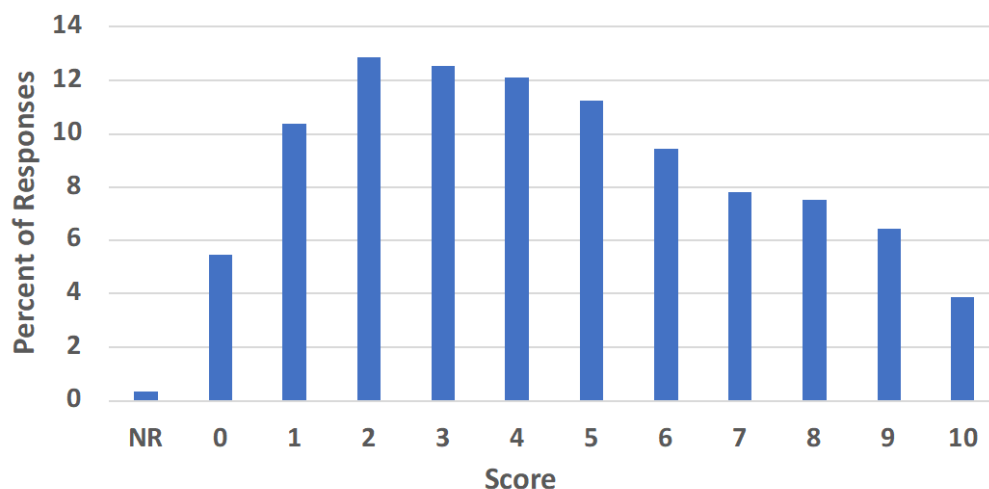
Part (e)(i) requires students to calculate the quantity of heat produced when solutions of lactic acid and sodium hydroxide are combined. This may be quantified by the equation $q = mc\Delta T$ (ENE-2.D/6.4.A, 5.F).

Part (e)(ii) requires students to calculate the molar enthalpy of the reaction based on the information and calculated response in part (e)(i), including the appropriate algebraic sign. The intent of the question was to relate the heat (q_{soln}) absorbed by the solution in part (e)(i) to the molar enthalpy of the reaction in kJ/mol_{rxn} (ENE-2.F/6.6.A, 5.F).

Part (e)(iii) requires students to agree or disagree with a student's claim that if heat is lost from the calorimeter to the surrounding air during the reaction, then the experimental value of the molar enthalpy would be smaller due to a smaller observed change in solution temperature. The intent of the question was to have students predict the effect heat loss would have on measurable observations (ENE-2.D/6.4.A, 6.G).

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 4.43 out of a possible 10 points, with a standard deviation of 2.77 points. The distribution of scores on this question is shown below.



Part (a) was very accessible for most students, where they successfully circled the H atom on the carboxyl group.

Part (b) was the most accessible point for students. Successful responses converted grams of NaOH to moles and divided by the converted volume in liters to calculate the correct molarity of the NaOH solution.

Part (c) was moderately accessible for students. Successful responses approximated the pK_a of lactic acid to be 3.9 based on the information in the graph. Typical errors involved reading the equivalence point pH as the acid pK_a , rather than the half-equivalence point pH.

Part (d)(i) was moderately accessible for most students. Successful responses placed an X on the titration curve past 3 mL and before the half-equivalence point; students were not required to quantitatively determine the specific volume of NaOH added corresponding to the particle diagram in part (d). Students had difficulty distinguishing between the half-equivalence point and the equivalence point, which challenged them to locate the position to place the X.

Part (d)(ii) was moderately accessible for most students. Student responses successfully identified more lactic acid particles than lactate ions (conjugate base) and recognized that therefore the region on the titration curve represented by the particle diagram must be before the half-equivalence point. Some student responses were able to earn the point based on a stoichiometric explanation of how far into the reaction (1/3 completion) the diagram represented, based on the number of acid and conjugate-base particles and comparing them to the equivalence point.

Part (d)(iii) was moderately accessible for many students. Successful responses started at a pH of 2, drew a similar weak acid-strong base titration curve with an inflection point at 8 mL ($1/2$ of the NaOH(aq) volume required in the first experiment), and finished the curve at a pH similar to the first experiment.

Part (e)(i) was an accessible point for most students. Successful responses calculated the mass of the solution from the given information (molarity, volume, and density). Incorrect responses often resulted from an incorrect determination of the solution mass from the information provided.

Part (e)(ii) was the least accessible point for students. Successful responses used the heat (q_{soln}) absorbed by the solution in part (e)(i) to calculate the molar enthalpy of the reaction, in kJ/mol_{rxn} . Many students did not use the correct number of moles of either lactic acid or NaOH to determine the moles of reaction involved. Many also had difficulty determining the correct algebraic sign for the answer, which was required.

Part (e)(iii) was somewhat less accessible for most students. Successful responses agreed with the student's claim that the loss of heat from the calorimeter would result in a smaller change in temperature, leading to a smaller q_{soln} and a smaller magnitude for the molar enthalpy of reaction. Students tended to repeat the prompt in the response without connecting the source of error to a smaller change in temperature, the only experimentally measurable parameter.

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

<i>Common Misconceptions/Knowledge Gaps</i>	<i>Responses that Demonstrate Understanding</i>
Part (a) <ul style="list-style-type: none"> Not following instructions: circling C atoms, O atoms, or covalent bonds. Circling the H on the hydroxyl group, or occasionally H atoms that are bonded to C atoms. 	Part (a) <ul style="list-style-type: none"> Circling the H atom attached to the carboxyl group.
Part (b) <ul style="list-style-type: none"> Incorrect conversions of mL to L (5 L, 0.05 L). Incorrect algebra: multiplying instead of dividing. 	Part (b) <ul style="list-style-type: none"> Correctly converting grams of NaOH to moles and dividing by the correctly converted liters of solution, with the correct number of significant figures. $M = \frac{10.22 \text{ g} \times \frac{1 \text{ mol}}{40.00 \text{ g}}}{0.500 \text{ L}} = 0.511 \text{ M}$
Part (c) <ul style="list-style-type: none"> The most common error was $\text{p}K_a = 8$, where students incorrectly used the pH at the equivalence point. Occasionally a K_a value was given instead of a $\text{p}K_a$ value. 	Part (c) <ul style="list-style-type: none"> Correctly approximating the $\text{p}K_a$ to be 3.9 or in the range of 3.7-4.0. A correctly calculated K_a value also earned the point because the student had to identify the $\text{p}K_a$ to calculate the K_a.
Part (d)(i) <ul style="list-style-type: none"> The most common error was students identifying that there are $\frac{1}{2}$ the number of $\text{C}_3\text{H}_5\text{O}_3^-$ particles compared to $\text{C}_3\text{H}_6\text{O}_3$ particles; therefore, the titration must be at the half-equivalence point. 	Part (d)(i) <ul style="list-style-type: none"> A correct placement of the X on the titration curve between 3 mL and before the half-equivalence point. The optimal position would be between 4-5 mL.

<p>Part (d)(ii)</p> <ul style="list-style-type: none"> The most common error was students identifying that there are half the number of $\text{C}_3\text{H}_5\text{O}_3^-$ particles compared to $\text{C}_3\text{H}_6\text{O}_3$ particles; therefore, the titration must be at the half-equivalence point. Confusing the half-equivalence point with the equivalence point. Not using specific language to identify what is a base versus a conjugate base (i.e., does the “base” refer to NaOH or $\text{C}_3\text{H}_5\text{O}_3^-$). 	<p>Part (d)(ii)</p> <ul style="list-style-type: none"> Correctly identifying that there are more $\text{C}_3\text{H}_6\text{O}_3$ particles than $\text{C}_3\text{H}_5\text{O}_3^-$ ions present, therefore the titration is before the half-equivalence point, where the pH is less than the $\text{p}K_a$. $\text{pH} = \text{p}K_a + \log \frac{[\text{A}^-]}{[\text{HA}]} = 3.9 + \log \frac{1}{2} = 3.6$, since the ratio of $\text{C}_3\text{H}_5\text{O}_3^-$ to $\text{C}_3\text{H}_6\text{O}_3$ is 1:2 in the diagram.
<p>Part (d)(iii)</p> <ul style="list-style-type: none"> The most common error was not starting the new titration curve at a pH of 2. Many responses just traced over the given titration curve from experiment 1. Many responses had an abnormally high $\text{p}K_a$ value in the sketched titration curve. 	<p>Part (d)(iii)</p> <ul style="list-style-type: none"> A sketch correctly starting the titration curve at a pH of 2, with a sharp rise to an inflection point at 8 mL, and then leveling off to a pH slightly above that in experiment 1, preferably also with the correct $\text{p}K_a$ of 3.9 at 4 mL.
<p>Part (e)(i)</p> <ul style="list-style-type: none"> The most common error was using the molarity and volume of each solution to solve for moles of solute, converting each solute amount to grams, and adding the masses of the reactants together. This would result in 6.5 grams of “solution” and a heat of solution of $q = (6.5 \text{ g})(4.2 \frac{\text{J}}{\text{g}\cdot^\circ\text{C}})(3.2^\circ\text{C}) = 87 \text{ J}$. Some algebraic errors were common. Using the final temperature (23.2°C) as the change in temperature. 	<p>Part (e)(i)</p> <ul style="list-style-type: none"> Correctly using the equation $q = mc\Delta T$ to calculate the quantity of heat produced in the reaction, in J. $100.0 \text{ mL } \text{C}_3\text{H}_6\text{O}_3 + 100.0 \text{ mL NaOH} = 200.0 \text{ mL solution}$ $200.0 \text{ mL} \times \frac{1.00 \text{ g}}{1 \text{ mL}} = 200.0 \text{ g solution}$ $(200.0 \text{ g})(4.2 \frac{\text{J}}{\text{g}\cdot^\circ\text{C}})(23.2^\circ\text{C} - 20.0^\circ\text{C}) = 2700 \text{ J}$
<p>Part (e)(ii)</p> <ul style="list-style-type: none"> Failing to report the molar enthalpy as a negative value, corresponding to an exothermic reaction. Calculating the moles of each reactant using molarity and volume, then incorrectly adding the moles of reactants together to represent the moles of reaction. ($0.050 \text{ mol NaOH} + 0.050 \text{ mol } \text{C}_3\text{H}_6\text{O}_3 = 0.10 \text{ mol}_{\text{rxn}}$) The mol_{rxn} is implicit in the moles of either reactant, as equimolar amounts have been provided, and the stoichiometric coefficients are both 1. 	<p>Part (e)(ii)</p> <ul style="list-style-type: none"> Correctly using the q_{soln} calculated in part (e)(i), switching the sign to convert to q_{rxn}, converting J to kJ and dividing by the correct mol_{rxn}. $q_{\text{rxn}} = -q_{\text{soln}} = -2700 \text{ J}$ $-2700 \text{ J} \times \frac{1 \text{ kJ}}{1000 \text{ J}} = -2.7 \text{ kJ}$ $0.100 \text{ L} \times 0.500 \text{ mol/L} = 0.0500 \text{ mol}_{\text{rxn}}$ $\Delta H^\circ = \frac{-2.7 \text{ kJ}}{0.0500 \text{ mol}_{\text{rxn}}} = -54 \text{ kJ/mol}_{\text{rxn}}$

<p>Part (e)(iii)</p> <ul style="list-style-type: none"> The most common mistake was simply repeating the prompt that if heat is lost from the calorimeter, then the molar enthalpy of reaction is lower. The only experimentally measurable quantity is the temperature, and the response must refer to a change in the expected temperature measurement to earn the point. 	<p>Part (e)(iii)</p> <ul style="list-style-type: none"> Correctly indicating that a loss of heat from the calorimeter results in a smaller final temperature. This results in a smaller ΔT, q_{soln}, and ΔH_{rxn}.
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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?

- Students perform better on experiment-based questions when they have experienced the lab in class. Students should perform calorimetry and acid-base titration experiments in class.
- Students need practice predicting the outcome of an experiment when one variable of the lab is changed. This can be accomplished in the classroom by assigning lab groups to perform the same experiment with variations for comparison, and by asking post-lab questions that require students to propose how specific changes to an experimental procedure would affect (or not affect) the results of the experiment.
- Students should have experience interpreting a particulate diagram.
- Students should have experience describing 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

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

- Teachers can use AP Classroom to direct students to the AP Daily videos for Topics 3.7, 6.4, 6.6, 8.5, 8.6, and 8.7.
- Teachers can use AP Classroom to direct students to the 2022 AP Exam On-Demand Review [Session 1: Graphical Analysis Review](#) and the 2021 [Session 5: Experimental Methods & Analysis of Free-Response Questions](#).
- Teachers can give students practice with matching particulate diagrams to various points on a titration curve and follow up by having students draw their own particulate representations (see worksheets attached to [this post](#) to the Online Teacher Community and [this accompanying instructional video](#)).
- Teachers can assign topic questions and/or progress checks in AP Classroom to monitor student progress and identify areas that may need additional instruction or content and skill development.
- Teachers can also create custom quizzes from previously administered AP exam items from the Question Bank to help students practice and refine their understanding of key topics.

Question 2

Task: Maleic Acid and Sodium Bicarbonate

Topic: Moles and Molar Mass, Ideal Gas Law, Stoichiometry, Reaction Rates, Entropy, Gibbs Free Energy and Thermodynamic Favorability, Weak Acid Base Equilibria, Henderson-Hasselbalch

Max Score: 10

Mean Score: 5.84

What were the responses to this question expected to demonstrate?

Question 2 presents students with a series of questions concerning a reaction involving solid sodium bicarbonate and maleic acid.

Part (a)(i) requires students to calculate the mass of $\text{CO}_2(g)$ from the moles of $\text{CO}_2(g)$ produced in the reaction (Learning Objective SPQ-1.A/1.1A, Skill 5.F from the *AP Chemistry Course and Exam Description*).

Part (a)(ii) requires students to calculate the volume of $\text{CO}_2(g)$ produced in the reaction using the moles of $\text{CO}_2(g)$, the temperature, and the pressure, assuming ideal behavior (SAP-7.A/3.4.A, 5.F).

Part (b)(i) requires students to identify what happens to the surface area of chunks of $\text{H}_2\text{C}_4\text{H}_2\text{O}_4(s)$ and $\text{NaHCO}_3(s)$ when these are ground into powders. The intent was for students to identify that a ground up solid will have a larger surface area than solid chunks (TRA-3.A/5.1.A, 6.A).

Part (b)(ii) requires students to compare the dissolving time of the powdered and chunk solids. Students were required to make a claim about which dissolved faster and justify the claim. The intent of the question was for students to explain how the surface area of a solid affects the rate of dissolving in terms of the collisions of the particles (TRA-3.A/5.1.A, 6.E).

Part (b)(iii) requires students to make and justify a claim regarding what will happen to the volume of $\text{CO}_2(g)$ formed when the solids are ground into a powder. The intent was for students to explain that since the amount of reactants didn't change, the volume of $\text{CO}_2(g)$ wouldn't either (SPQ-4.A/4.5.A, 2.F).

Part (c) requires students to analyze a data table containing the initial masses of $\text{H}_2\text{C}_4\text{H}_2\text{O}_4(s)$ and $\text{NaHCO}_3(s)$ and the moles of $\text{CO}_2(g)$ produced and determine the limiting reagent and justify their choice. Students could justify the choice mathematically with stoichiometry or by stating that if the mass of $\text{H}_2\text{C}_4\text{H}_2\text{O}_4(s)$ is held constant, increasing the mass of $\text{NaHCO}_3(s)$ also increases the moles of $\text{CO}_2(g)$ produced (SPQ-4.A/4.5.A, 6.D).

Part (d) requires students to explain why the reaction between $\text{H}_2\text{C}_4\text{H}_2\text{O}_4(aq)$ and $\text{NaHCO}_3(aq)$ has a ΔS° value greater than 0. The intent was for students to give a particulate level explanation that entropy increases because a gas, CO_2 , is produced, and gases are more dispersed or occupy many more microstates (ENE-4.A/9.1.A, 4.C).

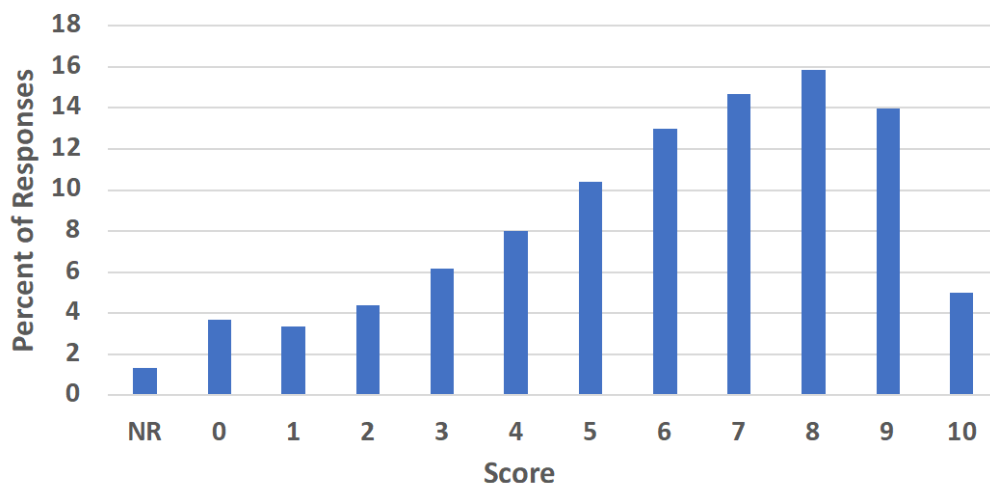
Part (e) requires students to assess a claim that an endothermic reaction is thermodynamically favorable at all temperatures. The intent was for students to state that an endothermic reaction (positive ΔH°) with a positive ΔS° is only thermodynamically favorable at high temperatures (ENE-4.4.A/9.3.A, 6.D).

Part (f) requires students to calculate the $\text{p}K_{a2}$ of $\text{HC}_4\text{H}_2\text{O}_4^-(aq)$. To do this, students first had to choose the correct K_a from the successive ionizations of diprotic maleic acid (SAP-9.C/8.3.A, 5.F).

Part (g) requires students to calculate the ratio of $[\text{C}_4\text{H}_2\text{O}_4^{2-}]$ to $[\text{HC}_4\text{H}_2\text{O}_4^-]$ in a pH 7.00 solution. The intent was for students to use the $\text{p}K_{a2}$ from part (f) and the Henderson-Hasselbalch equation to find the quantitative value of the ratio (SAP-10.C/8.9.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 2 was 5.84 out of a possible 10 points, with a standard deviation of 2.73 points. The distribution of scores is shown below.



Part (a)(i) was a very accessible point for students. Correct responses successfully provided the correct mass of $\text{CO}_2(g)$ for the moles of $\text{CO}_2(g)$.

Part (a)(ii) was a very accessible point for students, where correct responses successfully calculated the volume of $\text{CO}_2(g)$ using the ideal gas law.

Part (b)(i) was a very accessible point for students. Correct responses successfully stated that the surface area of a ground powder is greater than a solid chunk.

Part (b)(ii) was a very accessible point for students. Correct responses successfully explained that particles with larger surface area have more frequent collisions with water molecules and have a faster dissolving rate.

Part (b)(iii) was an accessible point for students. Correct responses successfully explained that the volume of $\text{CO}_2(g)$ would be equal in both trials because the starting mass of $\text{H}_2\text{C}_4\text{H}_2\text{O}_4(s)$ and $\text{NaHCO}_3(s)$ didn't change or because changing the surface area of the solids only changes the reaction rate, not the amount of $\text{CO}_2(g)$ produced.

Part (c) was an accessible point for students. Correct responses successfully identify NaHCO_3 as the limiting reactant and using the data table state that when the mass of $\text{H}_2\text{C}_4\text{H}_2\text{O}_4(s)$ is constant, if the mass of $\text{NaHCO}_3(s)$ increases, the amount of $\text{CO}_2(g)$ produced also increases. Alternatively, students could also use stoichiometry to calculate the moles (or mass) of CO_2 from the starting masses of $\text{H}_2\text{C}_4\text{H}_2\text{O}_4(s)$ and $\text{NaHCO}_3(s)$. A solid minority of the students chose this route.

Part (d) was a challenging point for students. Students who earned the point explained that the reaction entropy increases because 2 moles of gas were produced, and the gas particles are more dispersed (have more microstates) than the reactants.

Part (e) was an accessible point for students. Students who earned the point explained that the claim was false because an endothermic reaction (positive ΔH°) with a positive ΔS° is only thermodynamically favorable at high temperatures. The reverse argument, that a reaction thermodynamically favorable at all temperatures must be exothermic (negative ΔH°) and have a positive ΔS° , was also accepted.

Part (f) was a very accessible point for students. Correct responses first chose the correct K_a from two acid ionization reactions, then use this K_a to determine the $\text{p}K_a$.

Part (g) was another challenging point for students. Students who earned the point used the Henderson-Hasselbalch equation to determine the ratio of $[\text{C}_4\text{H}_2\text{O}_4^{2-}]$ to $[\text{HC}_4\text{H}_2\text{O}_4^-]$ in a pH 7 solution.

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

<i>Common Misconceptions/Knowledge Gaps</i>	<i>Responses that Demonstrate Understanding</i>
<p>Part (a)(i)</p> <ul style="list-style-type: none"> The most common error was using the wrong molar mass of CO_2. Common wrong molar masses were 12.01 g/mol, 28.01 g/mol or using the incorrect conversion of 2 moles = 44.01 g. 	<p>Part (a)(i)</p> <ul style="list-style-type: none"> $0.0114 \text{ mol} \times \frac{44.01 \text{ g}}{1 \text{ mol}} = 0.502 \text{ g}$
<p>Part (a)(ii)</p> <ul style="list-style-type: none"> Using an R with inconsistent units: $8.314 \frac{\text{J}}{\text{mol}\cdot\text{K}}$ instead of $0.08206 \frac{\text{L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}$. Forgetting to convert or incorrectly converting the temperature to kelvins. Using the volume of an ideal gas at STP, 22.4 L, to calculate the volume of $\text{CO}_2(\text{g})$. 	<p>Part (a)(ii)</p> <ul style="list-style-type: none"> $V = \frac{(0.0114 \text{ mol})(0.08206 \frac{\text{L}\cdot\text{atm}}{\text{mol}\cdot\text{K}})(293 \text{ K})}{1.25 \text{ atm}} = 0.219 \text{ L}$
<p>Part (b)(i)</p> <ul style="list-style-type: none"> Stating that the surface area decreases as a result of confusing the surface area of one particle with the total surface area of the reactants. 	<p>Part (b)(i)</p> <ul style="list-style-type: none"> The surface area of solid reactant increases when it is ground into a powder.
<p>Part (b)(ii)</p> <ul style="list-style-type: none"> The most common error was omitting a discussion of particle collisions in the response. 	<p>Part (b)(ii)</p> <ul style="list-style-type: none"> The reaction time is shorter. Since powdered solids have a larger surface area, there are more collisions between the water and solid particles, leading to a shorter reaction time.
<p>Part (b)(iii)</p> <ul style="list-style-type: none"> Stating that experiment 2 will have produced more $\text{CO}_2(\text{g})$ because the particles have a larger surface area. Providing an incorrect justification with a correct claim, such as stating that the volume of $\text{CO}_2(\text{g})$ will be equal because the temperature, pressure, and moles are the same (ideal gas law). 	<p>Part (b)(iii)</p> <ul style="list-style-type: none"> Equal because only the initial conditions of both reactions are the same or both reactions start with the same moles (amounts/concentrations) of reactants. Equal because changing the particle size/reaction rate does not affect the amount of product produced. The response does not need to include a discussion about the amounts of reactants.

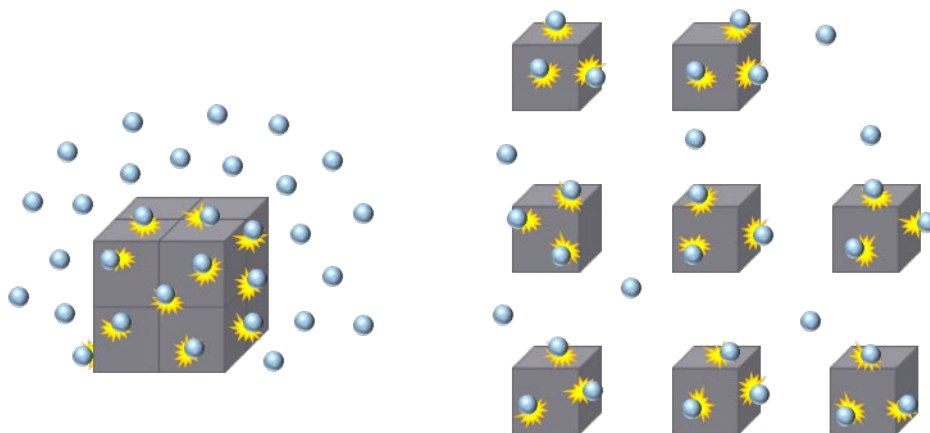
<p>Part (c)</p> <ul style="list-style-type: none"> Incorrect responses that state NaHCO_3 is the limiting reactant typically used one of the following justifications: <ul style="list-style-type: none"> in the data table, the initial mass of NaHCO_3 is smaller than $\text{H}_2\text{C}_4\text{H}_2\text{O}_4$. the molar mass of NaHCO_3 is smaller than $\text{H}_2\text{C}_4\text{H}_2\text{O}_4$. in the balanced equation, there are 2 NaHCO_3 for every 1 $\text{H}_2\text{C}_4\text{H}_2\text{O}_4$. Often an incorrect calculation only compared the calculated moles of NaHCO_3 to the moles of $\text{H}_2\text{C}_4\text{H}_2\text{O}_4$ without referencing the stoichiometric ratio between the reactants. 	<p>Part (c)</p> <ul style="list-style-type: none"> NaHCO_3. When the mass of $\text{H}_2\text{C}_4\text{H}_2\text{O}_4(s)$ is constant, if the mass of NaHCO_3 increases, the amount of $\text{CO}_2(g)$ produced also increases. $1.543 \text{ g H}_2\text{C}_4\text{H}_2\text{O}_4 \times \frac{1 \text{ mol H}_2\text{C}_4\text{H}_2\text{O}_4}{116.07 \text{ g}} \times \frac{2 \text{ mol CO}_2}{1 \text{ mol H}_2\text{C}_4\text{H}_2\text{O}_4} = 0.02659 \text{ mol CO}_2$ $1.251 \text{ g NaHCO}_3 \times \frac{1 \text{ mol NaHCO}_3}{84.01 \text{ g}} \times \frac{2 \text{ mol CO}_2}{2 \text{ mol NaHCO}_3} = 0.01489 \text{ mol CO}_2$
<p>Part (d)</p> <ul style="list-style-type: none"> Stating that ΔS° is positive because <ul style="list-style-type: none"> an implication that the gas was formed due to a physical phase change. gases are formed but without providing a particle level explanation. the products have more entropy due to the formation of liquid, gaseous, and aqueous substances rather than attributing the increase in entropy solely to the formation of a new gas from condensed phases. there are more total moles of product so the entropy increases. gases are “more random/chaotic/disordered.” 	<p>Part (d)</p> <ul style="list-style-type: none"> The entropy of the reaction increases because two moles of gas are produced from non-gaseous reactants. The gas particles have more microstates (are more dispersed) than the reactants, so there is greater entropy.
<p>Part (e)</p> <ul style="list-style-type: none"> Disagreeing with the claim because the reaction is not thermodynamically favorable at all temperatures [without further justification or explanation]. Disagreeing with the claim but citing only ΔS° or only ΔH° as the reason. Agreeing with the claim by incorrectly stating that $\Delta H^\circ < 0$ for an endothermic reaction. Referring to a negative absolute temperature. 	<p>Part (e)</p> <ul style="list-style-type: none"> Disagree. If a reaction has a positive ΔS° and is endothermic ($+\Delta H^\circ$), it will only be thermodynamically favorable ($-\Delta G^\circ$) at high temperatures. Disagree. For a reaction to be thermodynamically favorable at all temperatures, the reaction must be exothermic ($-\Delta H^\circ$) and have a positive ΔS°.

<p>Part (f)</p> <ul style="list-style-type: none"> Common errors include choosing the wrong K_a value from the acid ionization constants given and substituting that value into $pK_a = -\log K_a$: <ul style="list-style-type: none"> Choosing K_{a_1} instead of K_{a_2}. Multiplying $K_{a_1} \times K_{a_2} = K$, and using the result. 	<p>Part (f)</p> <ul style="list-style-type: none"> $pK_{a_2} = -\log(8.5 \times 10^{-7}) = 6.07$
<p>Part (g)</p> <ul style="list-style-type: none"> Stating the ratio $\frac{[C_4H_2O_4^{2-}]}{[HC_4H_2O_4^-]} = \frac{1}{1}$ because $pH = 7$. Subtracting incorrectly after substituting the values into the Henderson-Hasselbalch equation: $7.00 = 6.07 + \log \frac{[C_4H_2O_4^{2-}]}{[HC_4H_2O_4^-]}$ $\frac{[C_4H_2O_4^{2-}]}{[HC_4H_2O_4^-]} = 10^{-0.93} = 0.117$ Reversing the acid and base in the Henderson-Hasselbalch equation would also yield 0.117: $7.00 = 6.07 + \log \frac{[HC_4H_2O_4^-]}{[C_4H_2O_4^{2-}]}$ $\frac{[HC_4H_2O_4^-]}{[C_4H_2O_4^{2-}]} = 10^{0.93} = 8.5$ $\frac{[C_4H_2O_4^{2-}]}{[HC_4H_2O_4^-]} = \frac{1}{8.5} = 0.117$ Using base e instead of base 10: $e^{(7.00-6.07)} = 2.5$ 	<p>Part (g)</p> <ul style="list-style-type: none"> $7.00 = 6.07 + \log \frac{[C_4H_2O_4^{2-}]}{[HC_4H_2O_4^-]}$ $\frac{[C_4H_2O_4^{2-}]}{[HC_4H_2O_4^-]} = 10^{(7.00-6.07)} = 10^{0.93} = 8.5$ Some students successfully calculated the ratio of 8.5 using the value of K_{a_2} and an ICE table.

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?

- Remind students to show work for all calculations, including relevant units on their setups.
- Have students practice answering explanation and justification questions on homework assignments, quizzes, and tests, using precise scientific language.
- Frequently review molar mass and stoichiometry calculations.
- Have students practice calculations using applications of the universal gas constant, R , with varying units ($0.08206 \frac{\text{L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}$ vs. $8.314 \frac{\text{J}}{\text{mol}\cdot\text{K}}$).

- Students seem to be confused by the term “surface area” and the difference between the surface area of one particle versus the total surface area of the reactant when it is divided into smaller pieces. It may help students to draw and discuss particle drawings like the one below.



- Review collision theory and factors that influence the probability of effective collisions. Have students answer questions on collision theory in small groups and evaluate/elaborate/improve each other’s responses.
- Review the conditions of thermodynamic favorability in terms of the signs of ΔH° and ΔS° . Practice writing about conditions affecting ΔG° , don’t just practice calculations or memorize the signs of ΔH° and ΔS° .
- Review the Henderson-Hasselbalch equation and calculations using ICE tables and K_a/K_b values. Ideally, students would recognize that the former is the logarithmic application of the latter.

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

- Teachers can use AP Classroom to direct students to the AP Daily videos for Topics 3.4, 4.5, 5.1, 8.3, 8.9, 9.1, and 9.3.
- Teachers can use AP Classroom to direct students to the 2024 AP Exam On-Demand Review [Session 6: FRQ \(Long\)](#), 2022 [Session 2: Kinetics Multiple-Choice and Free-Response](#), and 2021 [Session 8: Free-Response Medley & Exam Strategies](#).
- Teachers can review the concept of entropy with respect to dispersal and/or microstates.
 - This [entropy video](#) can be shared with students.
 - This [video](#) is for teacher reference.
 - Teachers can have students complete this PhET [activity](#) on entropy and microstates.
- Teachers can assign topic questions and/or progress checks in AP Classroom to monitor student progress and identify areas that may need additional instruction or content and skill development.

Question 3

Task: Sterling Silver

Topics: Structure of Metals and Alloy, Periodic Trends, Stoichiometry, Oxidation/ Reduction Reactions, Cell Potential, Electrolysis and Faraday's Law

Max Score: 10

Mean Score: 4.42

What were the responses to this question expected to demonstrate?

Question 3 presents students with a sequence of items regarding the structure, composition, and electroplating of sterling silver.

Part (a) requires students to assign oxidation numbers to silver as elemental $\text{Ag}(s)$ and in the binary compound $\text{Ag}_2\text{S}(s)$. The intent was for respondents to apply the generally accepted rules for determining oxidation numbers to the silver atoms in these substances (Learning Objective TRA-2.A/4.7.A, Skill 1.A from the *AP Chemistry Course and Exam Description*).

Part (b)(i) requires students to use the provided atomic radii of the primary constituents of sterling silver to justify the classification of this alloy as substitutional rather than interstitial. The intent was for respondents to recognize that for atoms with radii as similar as those for Ag and Cu, a substitutional alloy is the appropriate category (SAP-3.D/2.4.A, 4.C).

Part (b)(ii) requires students to use principles of atomic structure and Coulomb's law to explain why silver has a larger atomic radius than copper. The intent was for respondents to recognize that atomic size is largely a function of the occupied principal energy level, n , and that one additional value of occupied levels ($5s$, $4d$) for Ag than for Cu ($4s$, $3d$) means that electrons in the larger shells experience weaker Coulombic attractions due to their increased distance from the nucleus. This, combined with the increased Coulombic interelectron repulsions in Ag, results in silver having the larger atomic radius (SAP-2.A/1.7.A, 4.A).

Part (c) requires students to calculate the number of moles of Ag atoms in a layer of Ag_2S tarnish given masses of a sample of sterling silver before and after the sulfide was removed. The intent was for respondents to first recognize that the difference of these masses was the mass of Ag_2S tarnish, and then perform a stoichiometric conversion from the mass of Ag_2S to moles Ag present in the compound (SPQ-1.A/1.1.A, SPQ-4.A/4.5.A, 5.F).

Part (d)(i) requires students to write a balanced net ionic equation for plating $\text{Rh}(s)$ from acidified $\text{Rh}_2(\text{SO}_4)_3(aq)$ given two applicable half-reactions. The intent was for respondents to correctly identify which reduction half-reaction to reverse and then appropriately combine it with the remaining reduction half-reaction to create a balanced net ionic equation (TRA-2.C/4.9.A, 5.E).

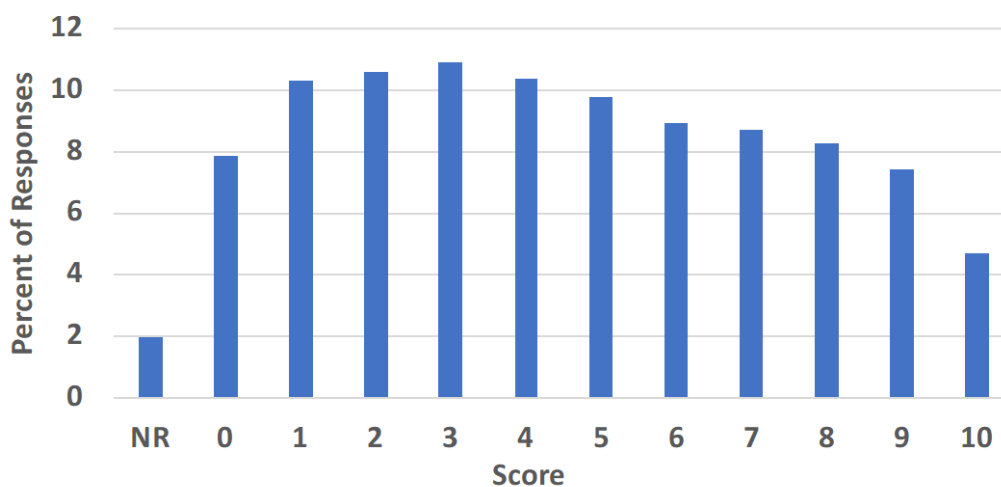
Part (d)(ii) requires students to calculate the value of E_{cell}° for the reaction in part (d)(i). The intent was for respondents to correctly manipulate E° values from the provided half-reactions to obtain the value of E_{cell}° that is consistent with the equation written in part (d)(i) (ENE-6.B/9.9.A, 5.F).

Part (d)(iii) requires students to explain the need for an external power source for this electroplating process based on the E_{cell}° derived in part (d)(ii). The intent was that respondents recognize that the negative E_{cell}° value indicates that the electrolytic process is thermodynamically unfavorable and therefore a power source would be required for the reaction to occur (ENE-6.B/9.9.A, 6.D).

Part (e) requires students to use a given current and mass of plated $\text{Rh}(s)$ to calculate the time required for the plating to occur. The intent was for respondents to correctly use the number of moles of electrons consistent with the process detailed in part (d)(i) to calculate the time required for the reaction to occur. The correct number of significant figures was required in this part (ENE-6.D/9.11.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 3 was 4.42 out of a possible 10 points, with a standard deviation of 2.99 points. The distribution of scores is shown below.



Part (a) was the most accessible point for most students. Correct student responses assigned oxidation numbers of 0 and +1 to silver in $\text{Ag}(s)$ and $\text{Ag}_2\text{S}(s)$, respectively.

Part (b)(i) was a moderately accessible point for students, with most correctly identifying the similar radii of Ag and Cu atoms as the reason that sterling silver is a substitutional alloy rather than an interstitial alloy. Many included the detail that Cu atoms are too large to fit into the spaces of an Ag lattice.

Part (b)(ii) was a very accessible point, with most students accounting for the radius difference by observing that Ag has more occupied electron shells than Cu. The terms for electron shell were varied (shell, level, ring, layer), which still earned the point. Responses that then continued forward to relate Coulombic attraction to the occupied shell of the valence electrons were rarer.

Part (c) had two points, the more accessible point being for the subtraction, either explicitly or implicitly, to obtain 10.27 g of $\text{Ag}_2\text{S}(s)$ lost. To obtain the requested moles of Ag, most students also correctly completed the stoichiometric conversion to moles of Ag for the second point. A somewhat common alternative solution employed the percent composition of Ag in Ag_2S to determine the moles of Ag.

Part (d)(i) was a very accessible point, with most responses containing a correct balanced net ionic equation for the described process.

Part (d)(ii) was a moderately accessible point, which was earned for the correct determination of $E_{\text{cell}}^{\circ} = -0.43 \text{ V}$ with an obvious close correlation between this point and a correct equation in part (d)(i).

Part (d)(iii) was also a somewhat accessible point for students. Correct responses recognized that the negative E_{cell}° value in part (d)(ii) indicates a thermodynamically unfavorable process which would therefore require an external power source.

Part (e) was another reasonably accessible computation point for either explicitly or implicitly converting the given mass of Rh into moles of electrons transferred in the cell, consistent with part (d)(i). The second point was earned by using this intermediate result and the current to calculate the time required for the stated process to occur to the proper number of significant figures.

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

Common Misconceptions/Knowledge Gaps	Responses that Demonstrate Understanding
<p>Part (a)</p> <ul style="list-style-type: none"> The most common error was an incomplete or incorrect understanding of generally accepted rules for assigning oxidation numbers; for example, assigning Ag(s) a +1 oxidation number. 	<p>Part (a)</p> <ul style="list-style-type: none"> Correctly assigning oxidation numbers of 0 to Ag(s) and +1 to Ag in Ag₂S(s).
<p>Part (b)(i)</p> <ul style="list-style-type: none"> Stating that categorizing sterling silver as a substitutional alloy is due to the mass differences between Ag and Cu. 	<p>Part (b)(i)</p> <ul style="list-style-type: none"> The alloy is substitutional because the radii of Ag and Cu are similar. Sterling silver can't be interstitial because Cu atoms are too large to fit in the spaces between the Ag atoms.
<p>Part (b)(ii)</p> <ul style="list-style-type: none"> Not recognizing that relative atomic radius is largely a function of the principal quantum number, <i>n</i>, of occupied electron shells. Using vague terms to describe occupied electron shells (e.g., "Ag has more orbitals/subshells/electrons than Cu" without identifying differences in principal energy levels). 	<p>Part (b)(ii)</p> <ul style="list-style-type: none"> Silver's valence electrons have weaker Coulombic attractions to the nucleus (or stronger Coulombic repulsions between other electrons) because they occupy one additional energy level compared to copper. Ag has a larger atomic radius because it has one additional level of electrons. Ag is larger than Cu due to one extra principal energy level of electrons. Ag has 5s electrons and Cu only has 4s.
<p>Part (c)</p> <ul style="list-style-type: none"> Failing to apply stoichiometric ratio of elements in a formula (i.e., 2 mol Ag/1 mol Ag₂S). Failing to recognize that the mass of a mixture (sterling silver) cannot be converted directly to moles of a substance (Ag₂S). 	<p>Part (c)</p> <ul style="list-style-type: none"> $10.27 \text{ g} \times \frac{1 \text{ mol Ag}_2\text{S}}{247.80 \text{ g Ag}_2\text{S}} \times \frac{2 \text{ mol Ag}}{1 \text{ mol Ag}_2\text{S}} = 0.08289 \text{ mol Ag}$ $10.27 \text{ g} \times \frac{1 \text{ mol Ag}_2\text{S}}{247.80 \text{ g Ag}_2\text{S}} = 0.041 \text{ mol Ag}_2\text{S}$ <p>(earned one of two points due to calculating moles of Ag₂S instead of moles of Ag)</p> $10.27 \text{ g} \times \frac{1 \text{ mol Ag}_2\text{S}}{247.80 \text{ g Ag}_2\text{S}} = 0.041 \text{ mol Ag}$ <p>(earned one of two points due to the omission of the mole ratio between Ag and Ag₂S)</p>

<p>Part (d)(i)</p> <ul style="list-style-type: none"> Failing to recognize textual clues in the description of a reaction; in this prompt, Rh(s) and O₂(g) are clearly designated as products. Not including both an oxidation and a reduction half-reaction in an overall redox reaction. Providing a final balanced equation that represents a thermodynamically favorable process. 	<p>Part (d)(i)</p> <ul style="list-style-type: none"> $4 \text{Rh}^{3+}(\text{aq}) + 6 \text{H}_2\text{O}(\text{l}) \rightarrow 4 \text{Rh}(\text{s}) + 3 \text{O}_2(\text{g}) + 12 \text{H}^+(\text{aq})$ $4 \text{Rh}^{3+} + 6 \text{H}_2\text{O} \rightarrow 4 \text{Rh} + 3 \text{O}_2 + 12 \text{H}^+$
<p>Part (d)(ii)</p> <ul style="list-style-type: none"> Including coefficients from the balanced chemical equation in the calculation of E_{cell}° : $E_{\text{cell}}^{\circ} = (4)(0.80 \text{ V}) - (3)(1.23 \text{ V}) = -0.49 \text{ V}$ 	<p>Part (d)(ii)</p> <ul style="list-style-type: none"> $E_{\text{cell}}^{\circ} = +0.80 \text{ V} - 1.23 \text{ V} = -0.43 \text{ V}$ $E_{\text{cell}}^{\circ} = -1.23 \text{ V} - 0.80 \text{ V} = +0.43 \text{ V}$ (earns the point if the response includes the reversed reaction in part (d)(i))
<p>Part (d)(iii)</p> <ul style="list-style-type: none"> Incorrectly interpreting the relationship of the sign of E_{cell}° and the direction of thermodynamic favorability. Failing to recognize the distinction between a power source providing continuous energy to sustain a reaction in the unfavorable direction rather than to simply overcome the activation energy requirements. 	<p>Part (d)(iii)</p> <ul style="list-style-type: none"> $E_{\text{cell}}^{\circ} < 0$ gives $\Delta G^{\circ} > 0$, so the reaction is not favorable in this direction and an external energy supply must drive it. $E_{\text{cell}}^{\circ} < 0$ indicates a nonspontaneous reaction, therefore energy must be supplied to drive the reaction in that direction. Negative E_{cell}° indicates the cell is electrolytic, so energy must be supplied to the system to operate.
<p>Part (e)</p> <ul style="list-style-type: none"> Failure to correctly apply stoichiometric conversions based on the moles of electrons transferred, which in this part was $\frac{3 \text{ mol } e^{-}}{1 \text{ mol Rh}}$ 	<p>Part (e)</p> <ul style="list-style-type: none"> $2.8 \text{ g Rh} \times \frac{1 \text{ mol Rh}}{102.9 \text{ g Rh}} \times \frac{3 \text{ mol } e^{-}}{1 \text{ mol Rh}} = 0.082 \text{ mol } e^{-}$ $0.082 \text{ mol } e^{-} \times \frac{96,485 \text{ C}}{1 \text{ mol } e^{-}} \times \frac{1 \text{ s}}{2.0 \text{ C}} = 3900 \text{ s}$ $2.8 \text{ g Rh} \times \frac{1 \text{ mol Rh}}{102.9 \text{ g Rh}} \times \frac{3 \text{ mol } e^{-}}{1 \text{ mol Rh}} \times \frac{96,485 \text{ C}}{1 \text{ mol } e^{-}} \times \frac{1 \text{ s}}{2.0 \text{ C}} = 3900 \text{ s}$ $2.8 \text{ g Rh} \times \frac{1 \text{ mol Rh}}{102.9 \text{ g Rh}} \times \frac{96,485 \text{ C}}{1 \text{ mol } e^{-}} \times \frac{1 \text{ s}}{2.0 \text{ C}} = 1300 \text{ s}$ (earned one of two points due to the omission of the $\frac{3 \text{ mol } e^{-}}{1 \text{ mol Rh}}$ ratio but an otherwise correct calculation)

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?

- Many students found using precise scientific language a challenge when describing phenomena or trends. Additional practice and feedback using specific vocabulary (e.g., principal energy levels, thermodynamic favorability, etc.) will improve both student understanding and student performance when explaining concepts verbally or in writing.
- Students should practice writing equations using textual clues to identify the reactants and products in a reaction and ensure that such equations are balanced by atom and charge.
- Algebraic signs in thermodynamic applications (including electrochemistry) continue to be a difficult problem to tackle. Students should practice precision in determining algebraic signs and discussing what these signs mean when defining thermodynamic favorability.

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

- Teachers can use AP Classroom to direct students to the AP Daily videos for Topics 1.7, 2.4, 4.5, 4.7, 4.9, 9.9, and 9.11.
- Teachers can use AP Classroom to direct students to the 2023 AP Exam On-Demand Review [Session 6: FRQ \(Long\)](#) and [2021 Session 7: Everything You Need to Know about Electrochemistry](#).
- Teachers can use in-class experiments and online simulations as [described on the Chemistry Interactive Demonstrations and Educational Resources \(CIDER\) website](#) to help students understand what occurs at the particle level during an electrolysis experiment. The [online simulation](#) can also be used to make predictions and quickly test the outcome to identify misconceptions and open a discussion of relevant concepts.
- Teachers can assign topic questions and/or progress checks in AP Classroom to monitor student progress and identify areas that may need additional instruction or content and skill development.

Question 4

Task: Calorimetry and Specific Heat of Unknown Metal and Aluminum

Topic: Heat Capacity and Calorimetry, Kinetic Molecular Theory, Recording Measurements, Particle Representation

Max Score: 4

Mean Score: 2.60

What were the responses to this question expected to demonstrate?

Question 4 presents students with an array of questions related to recording measurements in the laboratory, calorimetry, specific heat calculation for an unknown metal, and the comparison of temperature changes for different metals given equal masses and quantities of heat energy transferred.

Part (a) requires students to collect data from a representation of an analog thermometer and record the final temperature of the water in a calorimeter to the nearest 0.1°C (Learning Objective ENE-2.D/6.4.A, Skill 2.D from the *AP Chemistry Course and Exam Description*).

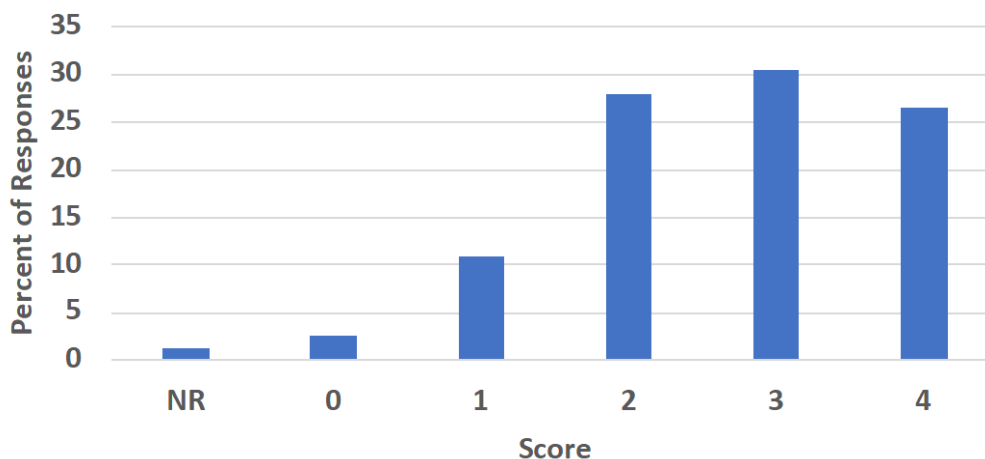
Part (b) requires students to explain the relationship between changes in temperature and the motion of water particles using a provided particle diagram. The left-side particle diagram provides students with a representation of three water molecules (represented with circles) in the calorimeter with arrows that represent the relative speed of the particles. The prompt asks students to draw arrows in the right-side diagram to represent the relative speed of the three water molecules at a higher temperature (SAP-7.B/3.5.A, 3.C).

Part (c) requires students to calculate the specific heat of the metal that is transferring a specified quantity of heat using calorimetry calculations and data from the table shown before part (a) (ENE-2.D/6.4.A, 5.F).

Part (d) requires students to explain the relationship between the magnitude of temperature change for two different metals with different specific heat values, given the same mass and quantity of heat transferred for each metal (ENE-2.D/6.4.A, 5.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 4 was 2.60 out of a possible 4 points, with a standard deviation of 1.12 points. The distribution of scores on this question is shown below.



Part (a) was a moderately accessible point for most students. Correct student responses successfully provided the final temperature to the nearest 0.1°C from the representation of the thermometer.

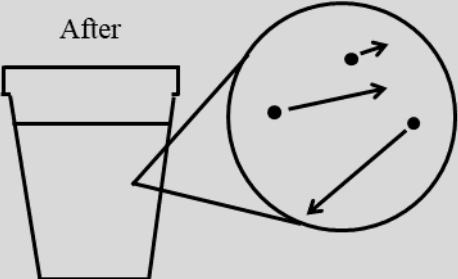
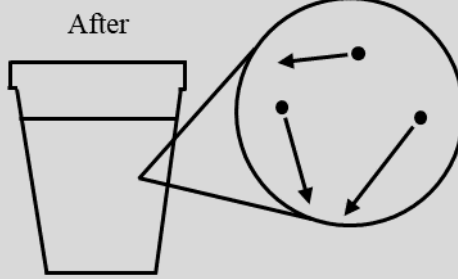
Part (b) was a somewhat less accessible point for most students. Correct student responses successfully indicated that the particles in the water would have increased speed (longer arrows) after the hot metal was added.

Part (c) was the most challenging point for students. Although many students were able to successfully apply the algorithm for specific heat using $q = mc\Delta T$, many were unable to choose the correct values from the data table and the information in part (a) to use for the mass, initial temperature, and final temperature of the metal.

Part (d) was moderately accessible for most students. Correct responses were successfully able to compare the magnitudes of the temperature changes for the two metals using one of the following explanations.

- Comparing the given specific heat of aluminum to the specific heat of the metal calculated in part (c) and understanding the inverse relationship between the magnitude of the temperature change and the specific heat capacity, given equivalent values of heat transfer and masses for each metal.
- Calculating the temperature change for aluminum using the same mass and quantity of heat transferred to the unknown metal in part (c), then comparing this value to the temperature change indicated in part (c).

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

Common Misconceptions/Knowledge Gaps	Responses that Demonstrate Understanding
<p>Part (a)</p> <ul style="list-style-type: none"> Not recognizing that each mark on the thermometer between 30 and 40 degrees represents 1°C. Quite a few students thought these individual marks represented 0.1°C increments. 	<p>Part (a)</p> <ul style="list-style-type: none"> 38.5°C $38.5 \pm 0.1^{\circ}\text{C}$
<p>Part (b)</p> <ul style="list-style-type: none"> Not recognizing that temperature increase corresponds to an increase in average particle speed. Not connecting this question with the information given in part (a) and providing an illustration that was inconsistent with the fact that the temperature of the water increased. 	<p>Part (b)</p> <ul style="list-style-type: none">  

<p>Part (c)</p> <ul style="list-style-type: none"> Applying the algorithm for specific heat using the wrong values from the data in part (a) to calculate the temperature change ($T_{final} - T_{initial}$) for water instead of the metal, or using ($T_{initial,metal} - T_{initial,water}$) and/or using incorrect mass value (using either the mass of the water or the total mass of the water and the metal). Understanding that the metal lost heat and making the quantity of heat negative, but then failing to calculate the temperature change by ($T_{final} - T_{initial}$). Not understanding that, by definition, the value of specific heat cannot be negative. Making algebraic errors when solving for specific heat, most commonly dividing incorrectly ($c = \frac{m\Delta T}{q}$) or not dividing the quantity of heat by BOTH the mass and the temperature change ($c = \frac{q}{m} \Delta T$). 	<p>Part (c)</p> <ul style="list-style-type: none"> $-2940 \text{ J} = (98.1 \text{ g})(c)(38.5^\circ\text{C} - 100.0^\circ\text{C})$ $c = \frac{-2940 \text{ J}}{(98.1 \text{ g})(-61.5^\circ\text{C})} = 0.487 \frac{\text{J}}{\text{g}\cdot^\circ\text{C}}$ $100.0^\circ\text{C} - 38.5^\circ\text{C} = 61.5^\circ\text{C}$ $c = \frac{q}{m\Delta T} = \frac{2940 \text{ J}}{(98.1 \text{ g})(61.5^\circ\text{C})} = 0.487 \frac{\text{J}}{\text{g}\cdot^\circ\text{C}}$ If an incorrect temperature was recorded in part (a), e.g., 41.5°C, a point would be earned for the response: $c = \frac{-2940 \text{ J}}{(98.1 \text{ g})(41.5^\circ\text{C} - 100.0^\circ\text{C})} = 0.512 \frac{\text{J}}{\text{g}\cdot^\circ\text{C}}$
<p>Part (d)</p> <ul style="list-style-type: none"> Not understanding the inverse relationship between specific heat and temperature change (when mass and quantity of heat are constant). Incorrectly using the inequality sign (< versus >). Relating specific heat to the time it takes for temperature to increase or decrease and referring to one metal heating up “faster,” rather than relating specific heat to temperature change. Not understanding the term “magnitude” and comparing a negative temperature change with a positive temperature change rather than comparing the magnitudes of the changes. Failing to use appropriate vocabulary : <ul style="list-style-type: none"> Confusing “heat” and “temperature.” Referring to the temperature being larger or smaller instead of the <i>change</i> in temperature. Using “it” so the response is unclear whether the metal or the aluminum was referred to. Be specific in writing explanations/justifications. 	<p>Part (d)</p> <ul style="list-style-type: none"> Since aluminum has a higher specific heat than the metal in the experiment (nearly double), the temperature change is smaller (nearly half) compared to the metal in the first experiment. $2940 \text{ J} = (98.1 \text{ g})(0.897 \frac{\text{J}}{\text{g}\cdot^\circ\text{C}})(\Delta T_{\text{Al}})$ $\Delta T_{\text{Al}} = 33.4^\circ\text{C}$ $\Delta T_{\text{metal}} = 61.5^\circ\text{C}$ The temperature change of the aluminum is less than the temperature change of the unknown metal. For an incorrect specific heat value calculated in part (c), a point could be earned with a comparison and explanation consistent with the value calculated in part (c). For instance, if the response in part (c) determined $c = 2.22 \frac{\text{J}}{\text{g}\cdot^\circ\text{C}}$, the point in part (d) was earned for stating that the magnitude of the temperature change for aluminum would be <i>larger</i> than the magnitude of the temperature change for the unknown metal since the specific heat of aluminum ($0.897 \frac{\text{J}}{\text{g}\cdot^\circ\text{C}}$) is <i>smaller</i>.

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?

- Reinforce the inclusion of correct units in calculation setups and responses.
- Offer students adequate exposure to laboratory equipment and proper technique when recording laboratory measurements using analog instruments such as analog thermometers, rulers, volumetric glassware, etc. Ensure that students have practice with selecting appropriate data from tables of information.
- Calorimetry concepts and calculations are common on the AP exam, and teachers should include a calorimetry laboratory in their courses.
- Students require practice when applying the kinetic molecular theory to particle motion using diagrams. This can be done in small groups with time allotted for students to provide feedback and critiques to diagrams that others generate so that they can refine them further and make them clearer.
- Students need much more practice solving problems using mathematical equations for all different variables, as algebraic errors are very common.
- Students need practice writing chemistry and need to receive specific feedback on how to improve their writing: describing relationships between different properties, explaining steps of laboratory procedures and processes, and practicing using accurate vocabulary. Feedback can come from teachers and peers alike.

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

- Teachers can use AP Classroom to direct students to the AP Daily videos for Topics 3.5 and 6.4.
- Teachers can use AP Classroom to direct students to the 2024 AP Exam On-Demand Review [Session 6: FRQ \(Long\)](#) and 2021 [Session 3: Experiment-Based Free-Response: Calorimetry & Beer's Law](#).
- Teachers can have students use this [online simulation](#) to test the effects of different masses, metals with different specific heat capacities, and different liquids. Students can calculate a predicted outcome and test their predictions by running the simulation. When running the simulation, students can monitor both a graphical view and a microscopic/particle view and summarize what they observe at the particle level.
- Teachers can assign topic questions and/or progress checks in AP Classroom to monitor student progress and identify areas that may need additional instruction or content and skill development.

Question 5

Task: HI Equilibrium

Topic: Reaction Quotient & Equilibrium Constant, Representations of Equilibrium, Le Chatelier's Principle

Max Score: 4

Mean Score: 2.07

What were the responses to this question expected to demonstrate?

Question 5 presents students with a series of questions allowing them to demonstrate their understanding of dynamic equilibria and the effects related to disturbances in a gaseous system (Le Chatelier's principle).

Part (a) requires students to write a concentration-based equilibrium expression given a gaseous reaction involving the synthesis of hydrogen iodide from elemental hydrogen and iodine (Learning Objective TRA-7.A/7.3.A, Skill 5.B from the *AP Chemistry Course and Exam Description*).

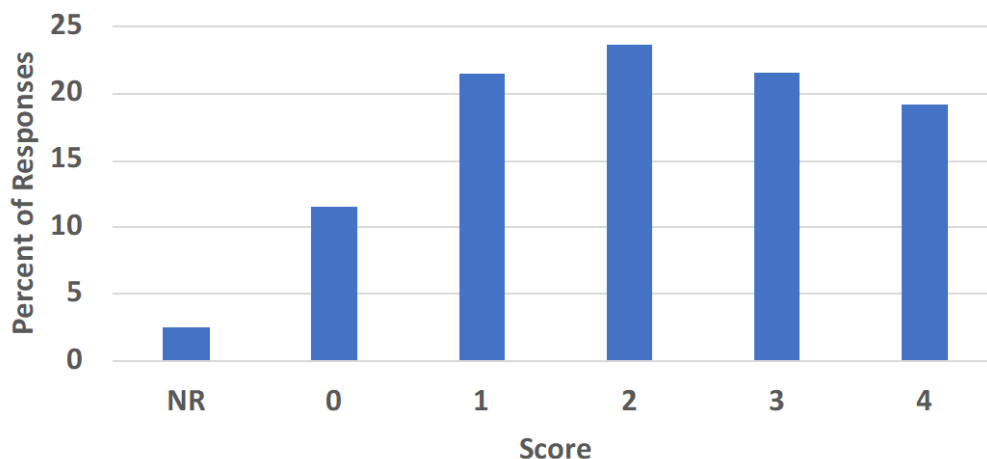
Part (b)(i) requires students to analyze an incomplete particle diagram representation of the system. Given the relative quantities of $\text{H}_2(\text{g})$ and $\text{I}_2(\text{g})$ in the particle diagram, students were to use the equilibrium expression from part (a) to determine the appropriate number of $\text{HI}(\text{g})$ molecules to draw in the diagram to accurately represent the system (TRA-7.F/7.8.A, 3.B).

Part (b)(ii) requires students to hypothesize an experimental change responsible for an equilibrium shift represented by a provided graph that shows how the moles of $\text{HI}(\text{g})$ change as a function of time. At time t , there is an increase in the moles of $\text{HI}(\text{g})$ produced (TRA-8.A/7.9.A, 2.B).

Part (b)(iii) requires students to further demonstrate their understanding of Le Chatelier's principle given a new disturbance caused by moving the reaction system from its original container to another rigid container of larger volume (TRA-8.A/7.9.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 5 was 2.07 out of a possible 4 points, with a standard deviation of 1.33 points. The distribution of scores on this question is shown below.



Most responses attempted all four parts, with the most accessible point earned in part (a). Most students correctly wrote the expression as a ratio of products to reactants with appropriate exponents and using brackets to indicate concentration in moles per liter.

For part (b)(i), most students understood the need to utilize the relative numbers of molecules displayed in the particle diagram and the equilibrium expression written in part (a) to determine the total number of HI molecules.

For part (b)(ii), most students understood that a disturbance was responsible for the sudden increase in the production of moles of HI, with many noting an increase in the concentration of reactants (H_2 , I_2 , or both H_2 and I_2). Similarly, many students were able to utilize the provided enthalpy value to determine that the reaction was exothermic, and therefore a decrease in temperature would also result in a rightward shift in equilibrium position and an increase in the number of moles of HI.

For part (b)(iii), most students properly determined that the new disturbance would result in the same number of moles of HI. Justifications and explanations varied, with the conceptual explanation of Le Chatelier's principle being the predominant explanation. Most students understood that an increase in volume would create a decrease in pressure, causing the equilibrium to shift to the side with more moles of gaseous molecules, but given that the reaction equation had equal moles of gaseous reactants and products, no equilibrium shift would result. Fewer students attempted to explain the lack of equilibrium position change by comparing the reaction quotient, Q , to the equilibrium constant, K , then demonstrating an understanding that the relative ratios of products to reactants would remain the same (i.e., $Q = K$).

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

<i>Common Misconceptions/Knowledge Gaps</i>	<i>Responses that Demonstrate Understanding</i>
Part (a) <ul style="list-style-type: none"> The most common error was using parentheses rather than brackets when writing the K_c expression. Writing a K_p expression instead of the K_c expression that was asked for in the prompt. 	Part (a) <ul style="list-style-type: none"> K_c expressions written with brackets, species written with proper notations and exponents demonstrated the greatest understanding.
Part (b)(i) <ul style="list-style-type: none"> Calculating the number of molecules stoichiometrically by limiting reagent rather than using the equilibrium expression. 	Part (b)(i) <ul style="list-style-type: none"> Drawing two molecules of HI. While not required, many students wrote out calculations utilizing the relative numbers of H_2 and I_2 molecules in their equilibrium expression to determine the relative number of HI molecules to include in the diagram.

<p>Part (b)(ii)</p> <ul style="list-style-type: none"> Chemically inaccurate explanations revealing misconceptions related to equilibrium resulted in a loss of the point. Mistaking the reaction as endothermic rather than exothermic and then indicating that an increase in temperature occurred at time t. Including disturbances external to the system (e.g., use of a catalyst, introduction of an inert gas, etc.). 	<p>Part (b)(ii)</p> <ul style="list-style-type: none"> Common correct responses included a decrease in temperature (sometimes noting the exothermic nature of the reaction). Common correct responses included the addition of H_2, I_2, both H_2 and I_2, “the reactants,” or similar phrases. While not required, responses offered chemical explanations for the suggested disturbance, demonstrating an understanding of Le Chatelier’s principle.
<p>Part (b)(iii)</p> <ul style="list-style-type: none"> Many responses correctly indicated that the number of moles of HI remains the same, but justifications were chemically inaccurate, which failed to earn the point. Failing to note the change in container volume, leading to a discussion related to the ideal gas law or combined gas law. Associated with this misunderstanding was a false assumption that HI was the only gas in the container. Incorrectly implying that the equilibrium is static rather than dynamic, noting that since the reaction had reached equilibrium, therefore <i>no</i> disturbance of any kind could produce a further equilibrium change. Ignoring the disturbance caused by the change in volume and utilizing only the constant temperature in the justification, concluding that there was no shift in equilibrium. 	<p>Part (b)(iii)</p> <ul style="list-style-type: none"> Most of the time, students responded that the moles of HI would remain the same. Conceptual interpretations related to the increase in container volume causing a decrease in pressure would typically result in a shift in equilibrium to the side with “more moles of gas.” Associating the stoichiometric coefficients in the reaction with equal “moles of gas” in the equation and concluding that the decrease in pressure would cause no shift in the equilibrium position. Less often, responses would demonstrate a conceptual calculation of Q given the disturbance in volume and conclude that $Q = K$ and therefore no shift in the equilibrium occurs.

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?

- Emphasize that chemical equilibrium is dynamic, not static, to better understand the cause-and-effect nature of a disturbance applied to a system at equilibrium.
- Offer students multiple opportunities to articulate the relationship between system disturbances and changes in equilibrium position.
- Differences in Q and K can help identify when a change in experimental conditions introduces a disturbance to an equilibrium system and can help predict the reaction’s response to a disturbance. Practice predicting changes in Q or K based on experimental stimuli and using the change to predict the reaction behavior.
- Differentiate between K_c and K_p in terms of the quantities being used and the appropriate units of measurement represented by each one.
- Support students with multiple opportunities to address a question prompt explicitly and directly with the intention of the selected topic as noted by given information. In some cases, students say too much by bringing forward unsupported, unrelated topical information. In other cases, responses are far too short to convey a true understanding of chemistry.

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

- Teachers can use AP Classroom to direct students to the AP Daily videos for Topics 7.3, 7.8, 7.9, and 7.10.
- Teachers can use AP Classroom to direct students to the 2022 AP Exam On-Demand Review [Session 4: Equilibrium Multiple-Choice and Free-Response](#), and 2022 [Session 5: Challenging Free-Response Questions](#).
- Teachers can direct students to the “[Write This, Not That](#)” document in the Resources section of the [Online Teacher Community](#) to help students understand how to write about chemistry with greater precision and specificity.
- Teachers can assign topic questions and/or progress checks in AP Classroom to monitor student progress and identify areas that may need additional instruction or content and skill development.

Question 6

Task: Nitrogen Dioxide Decomposition

Topic: Reaction Order and Rate Laws, Lewis Diagrams, VSEPR Models

Max Score: 4

Mean Score: 2.26

What were the responses to this question expected to demonstrate?

Question 6 presented students with a variety of chemical situations involving nitrogen dioxide.

Part (a) requires students to explain how one of the two provided graphical representations of kinetic data indicates that the reaction is a second-order process. The intent of the question was for students to identify the rate law expression by interpreting graphical information showing how the concentration of a reaction species changes over time (Learning Objective TRA-3.C/5.3.A, Skill 5.D from the *AP Chemistry Course and Exam Description*).

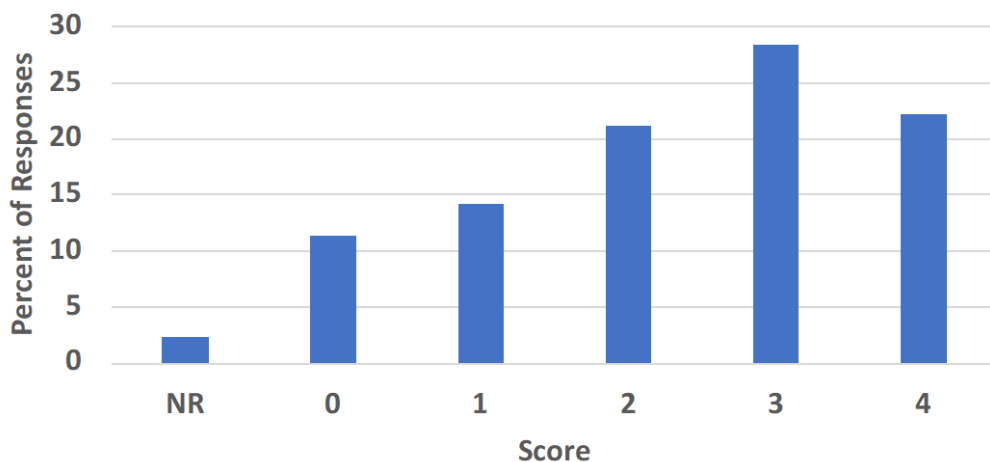
Part (b) requires students to calculate the relative rate of appearance of the O_2 product given the relative rate of disappearance of the NO_2 reactant. The question's intent was for students to use the experimental data and balanced chemical reaction equation to calculate a product's rate of appearance (TRA-3.B/5.2.A, 5.F).

Part (c)(i) requires students to draw the Lewis diagram for the NO_2^+ ion, given a Lewis diagram of the NO_2 molecule and information that the NO_2 can be oxidized to form NO_2^+ . The intent of the question was for students to demonstrate an understanding of ion formation and rules for drawing Lewis diagrams (SAP-4.A/2.5.A, 3.B).

Part (c)(ii) requires students to agree or disagree with a student claim that the bond angles of NO_2 and NO_2^+ would be different. The question's intent was for students to support a scientific argument by comparing the two Lewis diagrams (SAP-4.C/2.7.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 on Question 6 was 2.26 out of a possible 4 points, with a standard deviation of 1.35 points. The distribution of scores is shown below.



Part (a) was a somewhat accessible point for the students. Correct responses interpreted the two graphs and related the justification to the linear trend seen in the graph of $1/[NO_2]$ versus time. When the point was not earned, it was most often for not specifically describing a characteristic of a second-order reaction directly related to the graph provided.

Part (b) was a very accessible point for the students. Correct student responses considered the reaction stoichiometry and calculated the relative rate of appearance of O₂. Most students showed work or explained in words the reaction stoichiometry and its relation to the relative rates of appearance or disappearance. Because the units were provided in the prompt, units were not required in the answer, but if included they had to be correct. Very few instances of incorrect units were observed.

Part (c)(i) was a reasonably accessible point for students. Correct student responses removed the single electron and then included 2 N=O bonds to meet the octet rule. The most common error was adding an electron to form NO₂⁻ instead of removing one to form NO₂⁺.

Part (c)(ii) was a less accessible point for students. Correct student responses discussed the angle difference caused by having a different geometry (bent versus linear), different number of electron domains (3 versus 2), or the repulsive effect of the lone electron in NO₂ versus the lack of that repulsion in NO₂⁺.

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

<i>Common Misconceptions/Knowledge Gaps</i>	<i>Responses that Demonstrate Understanding</i>
Part (a) <ul style="list-style-type: none"> • Incomplete description of second-order rate characteristics (e.g., the graph on the right is linear). • Misinterpreting the graph (e.g., the slope equals 1, 1/k, or -k). 	Part (a) <ul style="list-style-type: none"> • The graph of 1 / [NO₂] versus time shows a linear relationship. • The 1 / [NO₂] graph has a line with a positive slope.
Part (b) <ul style="list-style-type: none"> • Stoichiometry errors <ul style="list-style-type: none"> ○ Ignoring stoichiometry by stating that the rate of disappearance = rate of appearance. ○ Reversing stoichiometry by multiplying instead of dividing by 2. • Using rate law instead of stoichiometry, or mistaking relative rates of appearance/disappearance for the general rate law (e.g., taking the square root or squaring the given [NO₂]) • Combining rate law and stoichiometry (e.g., dividing by 4, which is 2²). • Using the y-axis label 1 / [NO₂] with the given [NO₂] instead of the stoichiometric ratio of NO₂ and O₂. 	Part (b) <ul style="list-style-type: none"> • As 2 moles of NO₂ disappear, 1 mole of O₂ appears: $\frac{6.52 \times 10^{-7} M/s}{2} = 3.26 \times 10^{-7} M/s$ • $6.52 \times 10^{-7} M/s \times \frac{1 \text{ mol O}_2}{2 \text{ mol NO}_2} = 3.26 \times 10^{-7} M/s$

<p>Part (c)(i)</p> <ul style="list-style-type: none"> • Adding an electron instead of removing one. • Lacking an octet on the nitrogen atom. • Drawing a resonance form of the Lewis diagram of NO_2 and mistaking this for NO_2^+. 	<p>Part (c)(i)</p> <ul style="list-style-type: none"> • A structure showing nitrogen (with no lone pairs of electrons) double bonded to two oxygen atoms, each having two lone pairs of electrons. • As an accepted alternate, a structure showing nitrogen (with no lone pairs of electrons) triple bonded to one oxygen atom (with one lone pair of electrons) and single bonded to one oxygen atom (with three lone pairs of electrons). These responses often indicate the presence of accepted resonance structures.
<p>Part (c)(ii)</p> <ul style="list-style-type: none"> • Not acknowledging that the single electron has an effect on bond angle even though it is not an electron pair. • Not acknowledging that the repulsive effect of a single lone electron is different than the effect of a pair of electrons. • Claiming that a difference in polarity causes the difference in bond angle. (e.g., NO_2 is bent because it is polar/asymmetric while NO_2^+ is linear because it is nonpolar/symmetric) • Claiming that a difference in bonding pattern (1 single and 1 double versus 2 double bonds) causes a change in bond angle in this case. • Attributing the different bond angles to the formation of a cation versus a neutral molecule. • Providing contradictory bond angles with a stated geometry (e.g., linear geometry has 120° bond angles). 	<p>Part (c)(ii)</p> <ul style="list-style-type: none"> • “I agree because the bond angles in NO_2^+ are 180° and the bond angles in NO_2 are 120°.” • “I agree because NO_2^+ is linear structure while in NO_2 there is an unshared electron that pushes the bonding pairs closer to each other creating a bent shape.” • “I agree because NO_2 has 3 electron domains and NO_2^+ has 2 electron domains.” • “I agree because NO_2 is sp^2 hybridized and NO_2^+ is sp hybridized.” • For an answer where a structure for NO_2^- is mistakenly drawn in part (c)(i): “I agree because the extra electron on the N in the ion causes more repulsion than the single electron on N in NO_2.” (earns the point for a response consistent with the diagram in part (c)(i))

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?

- Understanding of concentration vs. time relationships for the integrated rate laws should be more than just memorization. Be able to relate the graphical behavior of an integrated rate law to its corresponding linear function. (e.g., the relationship between $1/[\text{A}]$ vs. t and the integrated rate law for a second order reaction)
- Emphasize that reaction order is different than reaction rate, and that integrated rate laws reflect the relationship between concentration and time and differential rate laws represent the relationship between concentration and reaction rate.
- Students should practice comparing relative rates of appearance/disappearance of products/reactant to reaction rates, rate laws, and the stoichiometry of the balanced chemical equation.
- Ensure students have exposure to odd-electron molecules, and ensure that they differentiate between lone pairs of electrons and a lone electron—many students used “lone pair” to refer to the lone electron on N.

- Help students to understand that when we use the term “bond angle,” it refers to an angle less than 180° . Responses like “the lone electron in NO_2 repels the O atoms creating a larger bond angle” imply that the response was referring to the angle above the lone electron and not the O-N-O angle (from the bottom).
- When drawing Lewis diagrams, always follow the octet rule first. Recognize which exceptions to the octet rule are possible with 2nd period elements, and that expanded octets can only occur with 3rd period elements and lower. If multiple structures are possible, formal charge can be a guide to evaluate the best structure.
- Students should properly associate removal of an electron with cation formation and addition of an electron with anion formation.
- Emphasizing that the number of bonding electrons, a lone pair of electrons, and a single electron (number of electron domains) exert different magnitudes of repulsion, which affects bond angle; however, they do not define the geometry, which is based on number of domains and not what is in those domains.
- Emphasize careful reading of material. We saw a fair number of instances where the student said “disagree” but then went on provide reasoning consistent with an “agreement” with the prompt.
- Encourage students to write legibly. Students who make a mistake and cannot fully erase it should cross it out and then re-write the answer in a box. Erasures are difficult to interpret on digitally scanned papers.
- Show the setup for calculations along with the final answer. Circling or boxing a final answer makes it easier for the Reader to know the intended answer.

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

- Teachers can use AP Classroom to direct students to the AP Daily videos for Topics 2.5, 2.7, 5.2, and 5.3.
- Teachers can use AP Classroom to direct students to the 2024 AP Exam On-Demand Review [Session 7: FRQ \(Long\)](#), 2023 [Session 2: FRQ \(Short\)](#), 2022 [Session 2: Kinetics Multiple-Choice and Free-Response](#), and 2022 [Session 7: Bonding and the Condensed State](#).
- Teachers can have students use online drawing tools like [PhET Molecule Shapes](#) and [Alchemie Lewis Structures](#) to explore how the number of electron domains influence the geometry of a molecule.
- Teachers can have students use spreadsheets to linearize their concentration versus time data from a kinetics experiment to determine if a reaction is zero, first, or second order based on the most linear plot.
- Teachers can assign topic questions and/or progress checks in AP Classroom to monitor student progress and identify areas that may need additional instruction or content and skill development.

Question 7

Task: NaCl Chromatography Solvent

Topic: Solutions and Mixtures, Separation of a Mixture by Chromatography

Max Score: 4

Mean Score: 2.03

What were the responses to this question expected to demonstrate?

Question 7 required students to describe how to prepare a sodium chloride solution then use this solution in a chromatography experiment. Students also are asked to predict the outcome of an experiment when a single variable is adjusted.

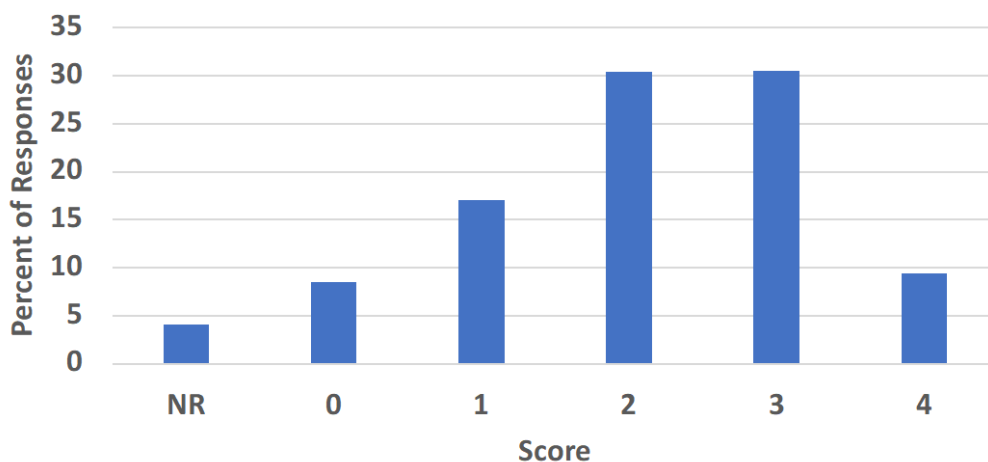
Part (a) asks students to calculate the mass of NaCl required to prepare a solution given the molarity and the volume. The intent of the question is to examine the ability to solve problems using mathematical relationships (Learning Objective SPQ-3.A/3.7.A, Skill 5.F from the *AP Chemistry Course and Examination Description*).

Part (b) provides students with a list of materials that they can choose from to accurately prepare a 100.0 mL NaCl solution. The intent is to demonstrate knowledge of proper laboratory technique when quantitatively preparing a standard solution (SPQ-3.A/3.7.A, 2.C).

Part (c) provides students with a diagram representing the results from a paper chromatography experiment lasting 30 minutes. Students are then to address how the separation between the spots (labeled X and Y) will change in a second experiment lasting 15 minutes (SPQ-3.C/3.9.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 7 was 2.03 out of a possible 4 points, with a standard deviation of 1.17 points. The distribution of scores on this question is shown below.



Part (a) was the most commonly earned point on this question. Most students showed mathematical work that correctly uses the molarity, volume, and molar mass to determine the mass of the required NaCl.

In part (b), most students earned the first point for adding the solid with some water to a volumetric flask. The second point was less frequently earned for indicating that the solution must be diluted with distilled water to the calibration mark on the volumetric flask.

Part (c) was also very accessible for students for correctly noting that the separation between spots X and Y would decrease for a chromatography experiment with a short run-time.

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

<i>Common Misconceptions/Knowledge Gaps</i>	<i>Responses that Demonstrate Understanding</i>
<p>Part (a)</p> <ul style="list-style-type: none"> The most common error was not using volume correctly to find moles. Students would convert mL to L and then divide molarity by volume, rather than multiplying. Other common mistakes were omitting the volume, multiplying 0.340 M by molar mass, or using volume incorrectly, to find grams. Many responses failed to earn the point due to omitting the setup from the calculated value. 	<p>Part (a)</p> <ul style="list-style-type: none"> $0.1000 \text{ L} \times \frac{0.340 \text{ mol}}{1 \text{ L}} \times \frac{58.44 \text{ g}}{1 \text{ mol}} = 1.99 \text{ g NaCl}$
<p>Part (b)</p> <ul style="list-style-type: none"> Incorrect descriptions in Step 2 typically include: <ul style="list-style-type: none"> Add NaCl to a beaker with 100 mL of water. Add NaCl to a graduated cylinder with 50 mL of water with no further explanation. Incorrect descriptions in Step 4 include: <ul style="list-style-type: none"> Add water to anything other than a volumetric flask. Transfer solution from (beaker/graduated cylinder) to volumetric flask and fill to the mark without rinsing the original container to ensure complete transfer of the solute. A minority of students thought Step 4 referred to the paper chromatography experiment instead of finishing the preparation of the NaCl solution. 	<p>Part (b)</p> <ul style="list-style-type: none"> Step 2. Add the solid to <ul style="list-style-type: none"> a volumetric flask and add some water (less than 100 mL). a beaker and some water (less than 100 mL). a graduated cylinder then 50 mL of water. Step 4. <ul style="list-style-type: none"> Fill the volumetric flask to the mark, or add the solution from the (beaker/graduated cylinder) to the volumetric flask, rinse with distilled water, then fill the volumetric flask to the mark.
<p>Part (c)</p> <ul style="list-style-type: none"> Some responses did not compare the distance difference between X and Y in Experiment 1 and Experiment 2. Most responses correctly stated that the distance would decrease, but with an incorrect justification or reasoning. Typically, this included an implication that one of the compounds did not move in Experiment 2. 	<p>Part (c)</p> <ul style="list-style-type: none"> The distance between X and Y would decrease because <ul style="list-style-type: none"> Neither compound would move as far Not enough time was given for X and Y to separate

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?

- When teaching molarity, show how the units cancel out when using molarity, volume, and/or molar mass to find the quantity of interest. This is a great way to reinforce why unit/dimensional analysis is so important. Require students to include units on each step of their setup and on their final answer.
- Have students practice making standard solutions more frequently using volumetric glassware. Ensure students know and are aware of the accuracy of the volumetric flask versus a beaker (100.0 mL vs. 100 mL, for example) and the importance of filling to the mark. Encourage students to discuss when high-precision measuring tools are needed.
- Precise language should be practiced when writing responses. Ensure students have practice with describing experimental procedures with specificity and clarity.

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

- Teachers can use AP Classroom to direct students to the AP Daily videos for Topics 2.5, 2.7, 5.2, and 5.3.
- Teachers can use AP Classroom to direct students to the 2023 AP Exam On-Demand Review [Session 1: MCQ \(Individual Questions\)](#), 2022 [Session 7: Bonding and the Condensed State](#), and 2021 [Session 3: Experiment-Based Free-Response: Calorimetry & Beer's Law](#).
- Teachers can have students complete the [Preparing Solutions Simulation](#) on the [American Association of Chemistry Teachers \(AACT\) website](#) as a prelab to preparing their own solutions as part of a laboratory procedure. This allows students to understand the sequence of steps and calculations before using laboratory equipment.
- Teachers can have students use [chromatography simulations](#) to explore how separation of components is affected by time and solvent polarity.
- Teachers can assign topic questions and/or progress checks in AP Classroom to monitor student progress and identify areas that may need additional instruction or content and skill development.