Lessons Learned from the 2018 AP Chemistry Exam
September 6, 2018

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Exam and Scoring Guidelines: https://apcentral.collegeboard.org/courses/ap-chemistry/exam
Roadmap

• How the AP Chemistry Exam gets written
• Exam logistics and scoring
• Pathway to becoming an AP Exam Reader
• Score profile on the 2018 Exam
• Common errors and misconceptions on each question
• “Big picture” advice from exam readers and leadership
Writing the AP Chemistry Exam
2017-18 Development Committee

Committee Co-Chairs
Renée Cole  
Kristen Cacciatore

University of Iowa, Iowa City, Iowa
East Boston High School, Boston, Massachusetts

Committee Members
Brenda Brockland
Thomas Bussey
Kevin (Kip) Hendren
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Alice Putti

Prairie Ridge High School, Crystal Lake, Illinois
University of California, San Diego
New Trier High School, Winnetka, Illinois
Cornell University, Ithaca, New York
Jenison High School, Jenison, Michigan

Chief Reader
Paul Bonvallet

College of Wooster, Wooster, Ohio
How the Exam Gets Written

AP Chemistry Curricular Framework

- Big Ideas (6)
  - Enduring Understandings (25)
    - Learning Objectives (117)
      - Essential Knowledge

SCIENCE PRACTICES (7) overlaid

Structure and vocabulary aligned with *Understanding by Design* Jay McTighe and Grant Wiggins

Each question (MC and FRQ) targets a specific Learning Objective and uses at least one Science Practice

https://apcentral.collegeboard.org/courses/ap-chemistry/exam
Goals for Each Question

• Targets knowledge **within the curriculum** – addresses a **Learning Objective** and uses **Science Practices**

• Probes **conceptual understanding**
  (vs. memorization or algorithmic problem-solving)

• Involves **real chemistry**

• Offers a **clear, concise answer / scoring rubric**
  (accuracy, fairness, and consistency in scoring)

• Uses **different challenge levels**
  (make every part accessible while differentiating ability)
We Score the Exams with...

ACCURACY
Applying the rubric correctly
FAIRNESS

Rewarding students who show a knowledge of chemistry
We Score the Exams with...

CONSISTENCY

Every reader applying the same criteria, every time
QUALITY CONTROL

Readers’ scores are checked by leaders
We Score the Exams with...

2018 SCORING GUIDELINES — Version 1.0

Question 1

Na$_2$S$_2$O$_3$(aq) + 4 NaOCl(aq) + 2 NaOH(aq) $\rightarrow$ 2 Na$_2$SO$_4$(aq) + 4 NaCl(aq) + H$_2$O(l)

A student performs an experiment to determine the value of the enthalpy change, $\Delta H^o_{\text{rxn}}$, for the oxidation-reduction reaction represented by the balanced equation above.

(a) Determine the oxidation number of Cl in NaOCl.

| +1 | 1 point is earned for the correct answer. |

(b) Calculate the number of grams of Na$_2$S$_2$O$_3$ needed to prepare 100.00 mL of 0.500 M Na$_2$S$_2$O$_3$(aq).

$$100.00 \text{ mL} \times \frac{0.500 \text{ mol Na}_2\text{S}_2\text{O}_3}{1000 \text{ mL}} \times \frac{158.10 \text{ g Na}_2\text{S}_2\text{O}_3}{1 \text{ mol Na}_2\text{S}_2\text{O}_3} = 7.90 \text{ g Na}_2\text{S}_2\text{O}_3$$

1 point is earned for correct calculation of mass of Na$_2$S$_2$O$_3$ consistent with the number of moles.
2018 SCORING GUIDELINES — Version 1.0

Question 1

\[ \text{Na}_2\text{S}_2\text{O}_3(aq) + 4 \text{NaOCl}(aq) + 2 \text{NaOH}(aq) \rightarrow 2 \text{Na}_2\text{SO}_4(aq) + 4 \text{NaCl}(aq) + \text{H}_2\text{O}(l) \]

A student performs an experiment to determine the value of the enthalpy change, \( \Delta H^\circ_{\text{rxn}} \), for the oxidation-reduction reaction represented by the balanced equation above.

(a) Determine the oxidation number of Cl in NaOCl.

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(b) Calculate the number of grams of Na\(_2\)S\(_2\)O\(_3\) needed to prepare 100.00 mL of 0.500 M Na\(_2\)S\(_2\)O\(_3\)(aq).

\[
100.00 \text{ mL} \times \frac{0.500 \text{ mol Na}_2\text{S}_2\text{O}_3}{1000 \text{ mL}} \times \frac{158.10 \text{ g Na}_2\text{S}_2\text{O}_3}{1 \text{ mol Na}_2\text{S}_2\text{O}_3} = 7.90 \text{ g Na}_2\text{S}_2\text{O}_3
\]

1 point is earned for correct number of moles of Na\(_2\)S\(_2\)O\(_3\) (may be implicit).

1 point is earned for the correct calculation of mass of Na\(_2\)S\(_2\)O\(_3\) consistent with the number of moles.
2018 SCORING GUIDELINES — Version 1.0

Question 1

\[ \text{Na}_2\text{S}_2\text{O}_3(aq) + 4 \text{NaOCl}(aq) + 2 \text{NaOH}(aq) \rightarrow 2 \text{Na}_2\text{SO}_4(aq) + 4 \text{NaCl}(aq) + \text{H}_2\text{O}(l) \]

A student performs an experiment to determine the value of the enthalpy change, \( \Delta H^\circ_{\text{rxn}} \), for the oxidation-reduction reaction represented by the balanced equation above.

(a) Determine the oxidation number of Cl in \( \text{NaOCl} \).

| +1 | 1 point is earned for the correct answer. |

(b) Calculate the number of grams of \( \text{Na}_2\text{S}_2\text{O}_3 \) needed to prepare 100.00 mL of 0.500 M \( \text{Na}_2\text{S}_2\text{O}_3(aq) \).

\[
100.00 \text{ mL} \times \frac{0.500 \text{ mol Na}_2\text{S}_2\text{O}_3}{1000 \text{ mL}} \times \frac{158.10 \text{ g Na}_2\text{S}_2\text{O}_3}{1 \text{ mol Na}_2\text{S}_2\text{O}_3} = 7.90 \text{ g Na}_2\text{S}_2\text{O}_3
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1 point is earned for correct number of moles of \( \text{Na}_2\text{S}_2\text{O}_3 \) (may be implicit).

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2018 SCORING GUIDELINES — Version 1.0

Question 1

$$\text{Na}_2\text{S}_2\text{O}_3(aq) + 4 \text{NaOCl}(aq) + 2 \text{NaOH}(aq) \rightarrow 2 \text{Na}_2\text{SO}_4(aq) + 4 \text{NaCl}(aq) + \text{H}_2\text{O}(l)$$

A student performs an experiment to determine the value of the enthalpy change, $\Delta H^\circ_{\text{rxn}}$, for the oxidation-reduction reaction represented by the balanced equation above.

(a) Determine the oxidation number of Cl in NaOCl.

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(b) Calculate the number of grams of $\text{Na}_2\text{S}_2\text{O}_3$ needed to prepare 100.00 mL of 0.500 $M\text{ Na}_2\text{S}_2\text{O}_3(aq)$.  

$$100.00 \text{ mL} \times \frac{0.500 \text{ mol } \text{Na}_2\text{S}_2\text{O}_3}{1000 \text{ mL}} \times \frac{158.10 \text{ g } \text{Na}_2\text{S}_2\text{O}_3}{1 \text{ mol } \text{Na}_2\text{S}_2\text{O}_3} = 7.90 \text{ g } \text{Na}_2\text{S}_2\text{O}_3$$

1 point is earned for correct number of moles of $\text{Na}_2\text{S}_2\text{O}_3$ (may be implicit).  

1 point is earned for the correct calculation of mass of $\text{Na}_2\text{S}_2\text{O}_3$ consistent with the number of moles.
How to Become an AP Reader
Applying to Become a Reader

Experienced high school teacher (3+ yrs teaching AP)
   a) http://apcentral.collegeboard.com
   b) Click on “Professional Development”
   c) “College Board Professional Opportunities”
   d) “Become an AP Reader”

College faculty
   a) http://aphighered.collegeboard.org
   b) Click on “Get Involved”
   c) Choose “Become an AP Reader”
Score Setting on the AP Chemistry Exam
Score Setting

• Meeting between ETS statisticians, Chief Reader, and College Board representatives

• Raw scores from both exam sections put onto a common scale, using equater questions to benchmark the AP (1-5) scores.

• Equaters are a group of multiple-choice questions that were administered on a previous exam, allowing a valid year-to-year comparison of student performance
### Distribution of AP Scores

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>5</td>
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<td>12.5</td>
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<td>15.7</td>
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<td>+1.6</td>
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<td>28.1</td>
<td>27.5</td>
<td>26.1</td>
<td>25.0</td>
<td>−1.1</td>
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<tr>
<td>2</td>
<td>25.5</td>
<td>25.3</td>
<td>27.0</td>
<td>24.1</td>
<td>−2.9</td>
</tr>
<tr>
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<td>22.0</td>
<td>21.0</td>
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Students in 2018 generally performed better than those in 2017.

Average 2017 score: 2.67
Average 2018 score: 2.78

One of the largest increases among any subject!!!
### Distribution of AP Scores

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Students in 2018 generally performed better than those in 2017

- Improved learning?
- Improved teaching?
- Improved understanding of objectives and exam?
Common Errors and Misconceptions
Online Resources for Teachers

AP CHEMISTRY

The Exam

Home | The Course | Course Audit | Classroom Resources | The Exam | Professional Development

AP Central / AP Courses & Exams / AP Chemistry / The Exam

Important Updates

2017 Chief Reader Report Module
The Chief Reader for the 2017 AP Chemistry exam provides a brief walkthrough of the highlights of their Chief Reader Report. In this presentation, Paul Bonvallet of the College of Wooster gives bite-sized overviews of each free-response question—how students performed, teaching tips for areas where students struggled, and a deeper understanding of the questions and results.

Quantitative Skills in the AP Sciences (2018)
This reference guide is for students to use as they develop quantitative skills throughout the course.

Secure Exam for Classroom Use
A secure 2017 AP Chemistry Exam is available on the AP Course Audit website. To access, sign in to your AP Course Audit account, and click on the Secure Documents link in the Resources section of your Course Status page.

Narrated PowerPoint walkthrough

https://apcentral.collegeboard.org/courses/ap-chemistry/exam
For A Complete Walkthrough...

https://apcentral.collegeboard.org/courses/ap-chemistry/exam
Question 1

\[ \text{Na}_2\text{S}_2\text{O}_3(aq) + 4 \text{NaOCl}(aq) + 2 \text{NaOH}(aq) \rightarrow 2 \text{Na}_2\text{SO}_4(aq) + 4 \text{NaCl}(aq) + \text{H}_2\text{O}(l) \]

Q1: Mean 4.47 ± 2.27
\[
\text{Na}_2\text{S}_2\text{O}_3(aq) + 4 \text{NaOCl}(aq) + 2 \text{NaOH}(aq) \rightarrow 2 \text{Na}_2\text{SO}_4(aq) + 4 \text{NaCl}(aq) + \text{H}_2\text{O}(l)
\]

1. A student performs an experiment to determine the value of the enthalpy change, \( \Delta H_{rxn}^\circ \), for the oxidation-reduction reaction represented by the balanced equation above.

(a) Determine the oxidation number of Cl in NaOCl.

+1

1 point is earned for the correct answer.

Common errors/misconceptions:

1. \(-1\) (misidentified as chloride ion)
2. +4 (stoichiometric coefficient of NaOCl \( \times \) oxidation number = \( 4 \times 1 \))
3. +7 (the number of valence electrons in Cl)
Na₂S₂O₃(aq) + 4 NaOCl(aq) + 2 NaOH(aq) → 2 Na₂SO₄(aq) + 4 NaCl(aq) + H₂O(l)

1. A student performs an experiment to determine the value of the enthalpy change, $\Delta H^{\circ}_{rxn}$, for the oxidation-reduction reaction represented by the balanced equation above.

(b) Calculate the number of grams of Na₂S₂O₃ needed to prepare 100.00 mL of 0.500 M Na₂S₂O₃(aq).

\[
\begin{array}{c|c}
100.00 \text{ mL} \times \frac{0.500 \text{ mol Na}_2\text{S}_2\text{O}_3}{1000 \text{ mL}} \times \frac{158.10 \text{ g Na}_2\text{S}_2\text{O}_3}{1 \text{ mol Na}_2\text{S}_2\text{O}_3} \\
= 7.90 \text{ g Na}_2\text{S}_2\text{O}_3
\end{array}
\]

1 point is earned for the correct number of moles of Na₂S₂O₃ (may be implicit).

1 point is earned for the correct calculation of mass of Na₂S₂O₃ consistent with the number of moles.

Common errors/misconceptions:
1. Incorrect molar mass of Na₂S₂O₃
2. Expressing molarity in units of g/L
3. Confusing molarity of Na₂S₂O₃ solution with number of moles of Na₂S₂O₃ present
\[ \text{Na}_2\text{S}_2\text{O}_3(aq) + 4 \text{NaOCl}(aq) + 2 \text{NaOH}(aq) \rightarrow 2 \text{Na}_2\text{SO}_4(aq) + 4 \text{NaCl}(aq) + \text{H}_2\text{O}(l) \]

1. In the experiment, the student uses the solutions shown in the table below.

<table>
<thead>
<tr>
<th>Solution</th>
<th>Concentration (M)</th>
<th>Volume (mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{Na}_2\text{S}_2\text{O}_3(aq))</td>
<td>0.500</td>
<td>5.00</td>
</tr>
<tr>
<td>(\text{NaOCl}(aq))</td>
<td>0.500</td>
<td>5.00</td>
</tr>
<tr>
<td>(\text{NaOH}(aq))</td>
<td>0.500</td>
<td>5.00</td>
</tr>
</tbody>
</table>

(c) Using the balanced equation for the oxidation-reduction reaction and the information in the table above, determine which reactant is the limiting reactant. Justify your answer.
\[
\text{Na}_2\text{S}_2\text{O}_3(aq) + 4 \text{NaOCl}(aq) + 2 \text{NaOH}(aq) \rightarrow 2 \text{Na}_2\text{SO}_4(aq) + 4 \text{NaCl}(aq) + \text{H}_2\text{O}(l)
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</tr>
<tr>
<td>\text{NaOH}(aq)</td>
<td>0.500</td>
<td>5.00</td>
</tr>
</tbody>
</table>

Common errors/misconceptions:

1. No limiting reactant, because equimolar amount of all reactants (ignoring stoichiometry)
2. Equimolar amounts of reactants because all solutions have the same volume, or because all solutions have the same concentration (failure to consider volume and concentration)

(c) Using the balanced equation for the oxidation-reduction reaction and the information in the table above, determine which reactant is the limiting reactant. Justify your answer.

NaOCl is the limiting reactant.

Given that equal numbers of moles of each reactant were present initially, it follows from the coefficients of the reactants in the balanced equation that NaOCl will be depleted first.

1 point is earned for identifying the limiting reactant and providing a valid justification.
\[ \text{Na}_2\text{S}_2\text{O}_3(aq) + 4 \text{NaOCl}(aq) + 2 \text{NaOH}(aq) \rightarrow 2 \text{Na}_2\text{SO}_4(aq) + 4 \text{NaCl}(aq) + \text{H}_2\text{O}(l) \]

1. In the experiment, the student uses the solutions shown in the table below.

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</tr>
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<td>0.500</td>
<td>5.00</td>
</tr>
<tr>
<td>$\text{NaOH}(aq)$</td>
<td>0.500</td>
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</tr>
</tbody>
</table>

Common errors/misconceptions:

3. NaOCl, since it has the largest stoichiometric coefficient (without reference to solution volume, concentration, or the number of moles available)

4. NaOCl, since it has the lowest molar mass

(c) Using the balanced equation for the oxidation-reduction reaction and the information in the table above, determine which reactant is the limiting reactant. Justify your answer.

NaOCl is the limiting reactant.

Given that equal numbers of moles of each reactant were present initially, it follows from the coefficients of the reactants in the balanced equation that NaOCl will be depleted first.

1 point is earned for identifying the limiting reactant and providing a valid justification.
\[ \text{Na}_2\text{S}_2\text{O}_3(aq) + 4 \text{NaOCl}(aq) + 2 \text{NaOH}(aq) \rightarrow 2 \text{Na}_2\text{SO}_4(aq) + 4 \text{NaCl}(aq) + \text{H}_2\text{O}(l) \]

1. The solutions, all originally at 20.0°C, are combined in an insulated calorimeter. The temperature of the reaction mixture is monitored, as shown in the graph below.

(d) According to the graph, what is the temperature change of the reaction mixture?
From the graph, the final temperature is 32.5°C. 
\[ \Delta T = T_f - T_i = 32.5°C - 20.0°C = 12.5°C \]

Common errors/misconceptions:
1. Reading tick marks incorrectly, resulting in incorrect \( T_{\text{final}} \) or \( T_{\text{initial}} \)
2. Rounding to the nearest ± 1°C rather than ± 0.1°C
3. Reporting \( \Delta T \) as −12.5°C
4. Reporting \( \Delta T \) as 285.5 K (12.5 + 273)

1 point is earned for the correct value of \( \Delta T \).

(d) According to the graph, what is the temperature change of the reaction mixture?
\[
Na_2S_2O_3(aq) + 4 NaOCl(aq) + 2 NaOH(aq) \rightarrow 2 Na_2SO_4(aq) + 4 NaCl(aq) + H_2O(l)
\]

1. (e) The mass of the reaction mixture inside the calorimeter is 15.21 g.

(i) Calculate the magnitude of the heat energy, in joules, that is released during the reaction. Assume that the specific heat of the reaction mixture is 3.94 J/(g·°C) and that the heat absorbed by the calorimeter is negligible.
\[
\text{Na}_2\text{S}_2\text{O}_3(\text{aq}) + 4 \text{NaOCl(} \text{aq}) + 2 \text{NaOH(} \text{aq}) \rightarrow 2 \text{Na}_2\text{SO}_4(\text{aq}) + 4 \text{NaCl(} \text{aq}) + \text{H}_2\text{O(}l) \]

1. (e) The mass of the reaction mixture inside the calorimeter is 15.21 g.

   (i) Calculate the magnitude of the heat energy, in joules, that is released during the reaction. Assume that the specific heat of the reaction mixture is 3.94 J/(g·°C) and that the heat absorbed by the calorimeter is negligible.

\[
q = mc\Delta T \\
= (15.21 \text{ g})(3.94 \text{ J/(g·°C)})(12.5\text{°C}) = 749 \text{ J}
\]

1 point is earned for the correct calculation of \(q\) consistent with the \(\Delta T\) value from part (d).

Common errors/misconceptions:
1. Expressing \(\Delta T\) in Kelvins, which doesn’t match units of °C in the solution specific heat
2. Assuming \(\Delta T = 20.0\text{°C}\) (the initial temperature) rather than the 12.5° C found previously
3. Errors in algebraic manipulation
\[ \text{Na}_2\text{S}_2\text{O}_3(aq) + 4 \text{NaOCl}(aq) + 2 \text{NaOH}(aq) \rightarrow 2 \text{Na}_2\text{SO}_4(aq) + 4 \text{NaCl}(aq) + \text{H}_2\text{O}(l) \]

1. (e) The mass of the reaction mixture inside the calorimeter is 15.21 g.

(ii) Using the balanced equation for the oxidation-reduction reaction and your answer to part (c), calculate the value of the enthalpy change of the reaction, $\Delta H_{rxn}^\circ$, in kJ/mol\(_{rxn}\). Include the appropriate algebraic sign with your answer.
\[ \text{Na}_2\text{S}_2\text{O}_3(aq) + 4 \text{NaOCl}(aq) + 2 \text{NaOH}(aq) \rightarrow 2 \text{Na}_2\text{SO}_4(aq) + 4 \text{NaCl}(aq) + \text{H}_2\text{O}(l) \]

(ii) Using the balanced equation for the oxidation-reduction reaction and your answer to part (c), calculate the value of the enthalpy change of the reaction, \( \Delta H^\circ_{\text{rxn}} \), in kJ/mol\( _{\text{rxn}} \). Include the appropriate algebraic sign with your answer.

\[
\begin{align*}
n_{\text{NaOCl}} & = 5.00 \text{ mL} \times \frac{0.500 \text{ mol NaOCl}}{1000 \text{ mL NaOCl}} = 0.00250 \text{ mol NaOCl} \\
n_{\text{rxn}} & = 0.00250 \text{ mol NaOCl} \times \frac{1 \text{ mol}_{\text{rxn}}}{4 \text{ mol NaOCl}} = 0.000625 \text{ mol}_{\text{rxn}} \\
\Delta H^\circ_{\text{rxn}} & = \frac{-0.749 \text{ kJ}}{0.000625 \text{ mol}_{\text{rxn}}} = -1.20 \times 10^3 \text{ kJ/mol}_{\text{rxn}}
\end{align*}
\]

1 point is earned for correctly calculating the value of mol\( _{\text{rxn}} \) consistent with the limiting reactant in part (c).

1 point is earned for a negative \( \Delta H^\circ_{\text{rxn}} \) obtained by dividing the calculated value of \( q \) by the calculated value of mol\( _{\text{rxn}} \).

Common errors/misconceptions:

1. Leaving \( \Delta H \) as a positive number
2. Incorrect conversion between J and kJ
3. Failing to adjust for reaction stoichiometry (not dividing by 4)
4. Dividing by 7 (interpreting mol\( _{\text{rxn}} \) as “sum of the stoichiometric coefficients of all reactants”)
Explanation of “mol_{rxn}”

Units in Thermochemical Calculations

Most introductory chemistry texts include an example of a calculation for the Gibbs energy change of a chemical reaction not unlike the following:

For the reaction \[ 2\text{CO(g)} + \text{O}_2(g) \rightarrow 2\text{CO}_2(g) \], calculate \( \Delta G^\circ \) at 298 K from the tabulated standard Gibbs energies of formation.

\[
\Delta G^\circ \text{(kJ/mol)}
\]

\[
\begin{align*}
\text{CO(g)} & : -137 \\
\text{O}_2(g) & : 0 \\
\text{CO}_2(g) & : -394
\end{align*}
\]

James N. Spencer, Franklin & Marshall College

https://apcentral.collegeboard.org/courses/ap-chemistry/classroom-resources/units-in-thermochemical-calculations
1. The student repeats the experiment, but this time doubling the volume of each of the reactants, as shown in the table below.

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</table>

(f) The magnitude of the enthalpy change, $\Delta H^\circ_{rxn}$, in kJ/mol$_{rxn}$, calculated from the results of the second experiment is the same as the result calculated in part (e)(ii). Explain this result.
1. The student repeats the experiment, but this time doubling the volume of each of the reactants, as shown in the table below.

<table>
<thead>
<tr>
<th>Solution</th>
<th>Concentration $(M)$</th>
<th>Volume (mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na$_2$S$_2$O$_3$(aq)</td>
<td>0.500</td>
<td>10.0</td>
</tr>
<tr>
<td>NaOCl(aq)</td>
<td>0.500</td>
<td>10.0</td>
</tr>
<tr>
<td>NaOH(aq)</td>
<td>0.500</td>
<td>10.0</td>
</tr>
</tbody>
</table>

Common errors/misconceptions:
1. Failing to indicate that both the number of moles and the heat evolved will double in the new experiment
2. Explanations that start along the right path, but end too early (e.g. “$\Delta H^\circ$ is intensive” as the entire answer)

(f) The magnitude of the enthalpy change, $\Delta H^\circ_{rxn}$, in kJ/mol$_{rxn}$, calculated from the results of the second experiment is the same as the result calculated in part (e)(ii). Explain this result.

By doubling the volumes, the number of moles of the reactants are doubled, which doubles the amount of energy produced. Therefore the amount of heat per mole will remain the same.

OR

In the second experiment, $\Delta H^\circ_{rxn} = \frac{2mc\Delta T}{2n} = \frac{mc\Delta T}{n} = \Delta H^\circ_{rxn}$.

Thus the magnitude is the same as calculated in the first experiment.

1 point is earned for a valid explanation.
\[ \text{Na}_2\text{S}_2\text{O}_3(aq) + 4 \text{NaOCl}(aq) + 2 \text{NaOH}(aq) \rightarrow 2 \text{Na}_2\text{SO}_4(aq) + 4 \text{NaCl}(aq) + \text{H}_2\text{O}(l) \]

1. (g) Write the balanced net ionic equation for the given reaction.
Na₂S₂O₃(\textit{aq}) + 4 \textit{NaOCl}(\textit{aq}) + 2 \textit{NaOH}(\textit{aq}) \rightarrow 2 \textit{Na}_2\text{SO}_4(\textit{aq}) + 4 \textit{NaCl}(\textit{aq}) + \textit{H}_2\text{O}(\textit{l})

1. (g) Write the balanced net ionic equation for the given reaction.

<table>
<thead>
<tr>
<th>( \text{S}_2\text{O}_3^{2-}(\textit{aq}) + 4 \textit{OCl}^-(\textit{aq}) + 2 \textit{OH}^-(\textit{aq}) \rightarrow 2 \textit{SO}_4^{2-}(\textit{aq}) + 4 \textit{Cl}^-(\textit{aq}) + \textit{H}_2\text{O}(\textit{l}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 point is earned for the correct net ionic equation.</td>
</tr>
</tbody>
</table>

Common errors/misconceptions:
1. Imbalance with respect to mass and/or charge
2. Including spectator ions
3. Using incorrect ionic charges, often sulfate or thiosulfate ions with \(-1\) charge
4. Breaking down polyatomic ions into elemental ions, e.g. sulfate as \( \text{S}^{2-} + 4 \text{O}^{2-} \)
1. Have students perform calculations with data read from a graph or table.

2. Emphasize the similarities and differences between $q$ (amount of thermal energy absorbed or released in a given situation) versus $\Delta H_{\text{rxn}}^\circ$ (standard enthalpy change for a reaction). Pay attention to sign conventions in these two values.

3. Reinforce the concept of “per mole reaction” and its application in thermochemistry problems.

4. Practice writing net-ionic equations for chemical reactions, helping students to recognize the ionic charge of common polyatomic ions.
Question 2

Oxides of nitrogen: NO, NO\textsubscript{2}, N\textsubscript{2}O\textsubscript{3}, HONO

Q2: Mean 4.07 ± 2.58
2. A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of NO(g) and NO₂(g), which the student produces by using the reaction represented above.

(a) The particle-level representation of the equimolar mixture of NO(g) and NO₂(g) in the flask at the completion of the reaction between NO(g) and O₂(g) is shown below in the box on the right. In the box below on the left, draw the particle-level representation of the reactant mixture of NO(g) and O₂(g) that would yield the product mixture shown in the box on the right. In your drawing, represent oxygen atoms and nitrogen atoms as indicated below.

Oxygen atom = ○  Nitrogen atom = ●
1 point is earned for correctly representing molecules of NO and O₂.

1 point is earned for correctly representing atom conservation.

\[ 2 \text{NO}(g) + \text{O}_2(g) \rightarrow 2 \text{NO}_2(g) \]

Oxygen atom = ⭕️  Nitrogen atom = ⭕️️

Reactant Mixture  →  Product Mixture
Common errors/misconceptions:
1. Drawing species not part of chemical reaction (N$_2$, O)
2. Improper scale (incorrect number of reactant molecules)
3. Failure to account for excess of NO

2 NO(g) + O$_2$(g) $\rightarrow$ 2 NO$_2$(g)
2 The student reads in a reference text that NO(g) and NO₂(g) will react as represented by the equation below. Thermodynamic data for the reaction are given in the table below the equation.

\[
\text{NO}(g) + \text{NO}_2(g) \rightleftharpoons \text{N}_2\text{O}_3(g)
\]

<table>
<thead>
<tr>
<th>$\Delta H^\circ_{298}$</th>
<th>$\Delta S^\circ_{298}$</th>
<th>$\Delta G^\circ_{298}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-40.4 \text{ kJ/mol}_{\text{rxn}}$</td>
<td>$-138.5 \text{ J/(K \cdot mol}_{\text{rxn}}$</td>
<td>$0.87 \text{ kJ/mol}_{\text{rxn}}$</td>
</tr>
</tbody>
</table>

(b) The student begins with an equimolar mixture of NO(g) and NO₂(g) in a rigid reaction vessel and the mixture reaches equilibrium at 298 K.

(i) Calculate the value of the equilibrium constant, $K$, for the reaction at 298 K.
NO(g) + NO₂(g) ⇌ N₂O₃(g)

2. (b) The student begins with an equimolar mixture of NO(g) and NO₂(g) in a rigid reaction vessel and the mixture reaches equilibrium at 298 K.

   (i) Calculate the value of the equilibrium constant, \( K \), for the reaction at 298 K.

\[
\Delta G^° = -RT \ln K
\]
\[
K = e^{-\Delta G^° / RT}
\]
\[
K = e^{\frac{-870 \text{ J/mol}}{(8.314 \text{ J mol}^{-1} \text{ K}^{-1})(298 \text{ K})}}
\]
\[
K = 0.70
\]

1 point is earned for a correct calculation of \( K \).
NO(g) + NO₂(g) ⇌ N₂O₃(g)

2. (b) The student begins with an equimolar mixture of NO(g) and NO₂(g) in a rigid reaction vessel and the mixture reaches equilibrium at 298 K.

   (i) Calculate the value of the equilibrium constant, K, for the reaction at 298 K.

\[
\Delta G^\circ = -RT \ln K
\]

\[
K = e^{-\Delta G^\circ/RT}
\]

\[
K = e^{-\frac{870 \text{ J/mol}}{(8.314 \text{ J mol}^{-1} \text{ K}^{-1})(298 \text{ K})}}
\]

\[
K = 0.70
\]

1 point is earned for a correct calculation of K.

Common errors/misconceptions:
1. Trying to solve for K using concentrations or partial pressures
2. Different version of gas constant R, such as 0.08206 L atm mol⁻¹ K⁻¹
2. The student reads in a reference text that NO\((g)\) and NO\(_2\)(\(g\)) will react as represented by the equation below. Thermodynamic data for the reaction are given in the table below the equation.

\[
\text{NO}(g) + \text{NO}_2(g) \rightleftharpoons \text{N}_2\text{O}_3(g)
\]

<table>
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<tr>
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</tr>
</tbody>
</table>

(b) The student begins with an equimolar mixture of NO\((g)\) and NO\(_2\)(\(g\)) in a rigid reaction vessel and the mixture reaches equilibrium at 298 K.

(ii) If both \(P_{\text{NO}}\) and \(P_{\text{NO}_2}\) in the vessel are initially 1.0 atm, will \(P_{\text{N}_2\text{O}_3}\) at equilibrium be equal to 1.0 atm? Justify your answer.
NO(g) + NO₂(g) ⇌ N₂O₃(g)

2. (b) The student begins with an equimolar mixture of NO(g) and NO₂(g) in a rigid reaction vessel and the mixture reaches equilibrium at 298 K.

(ii) If both $P_{\text{NO}}$ and $P_{\text{NO₂}}$ in the vessel are initially 1.0 atm, will $P_{\text{N₂O₃}}$ at equilibrium be equal to 1.0 atm? Justify your answer.

No, the pressure will not equal 1 atm.

$P_{\text{N₂O₃}}$ would only equal 1 atm if the reaction goes to completion.

OR

The value of $K$ indicates that a substantial amount of reactants will be present at equilibrium.

1 point is earned for a correct choice and valid justification based on the value of $K$. 
\[
\text{NO(g) + NO}_2(g) \rightleftharpoons \text{N}_2\text{O}_3(g)
\]

2. (b) The student begins with an equimolar mixture of NO(g) and NO\(_2\)(g) in a rigid reaction vessel and the mixture reaches equilibrium at 298 K.

(ii) If both \(P_{\text{NO}}\) and \(P_{\text{NO}_2}\) in the vessel are initially 1.0 atm, will \(P_{\text{N}_2\text{O}_3}\) at equilibrium be equal to 1.0 atm? Justify your answer.

No, the pressure will not equal 1 atm.

\(P_{\text{N}_2\text{O}_3}\) would only equal 1 atm if the reaction goes to completion.

OR

The value of \(K\) indicates that a substantial amount of reactants will be present at equilibrium.

Common errors/misconceptions:

1. Failure to realize (or articulate) the relationship between \(K\) and extent of reaction

2. Extensive (albeit correct) mathematical calculation of \(K\) to show \(K \neq 1\)
\[ \text{NO}(g) + \text{NO}_2(g) \rightleftharpoons \text{N}_2\text{O}_3(g) \]

2 (c) The student hypothesizes that increasing the temperature will increase the amount of \( \text{N}_2\text{O}_3(g) \) in the equilibrium mixture. Indicate whether you agree or disagree with the hypothesis. Justify your answer.
NO(g) + NO₂(g) ⇌ N₂O₃(g)

2  (c) The student hypothesizes that increasing the temperature will increase the amount of N₂O₃(g) in the equilibrium mixture. Indicate whether you agree or disagree with the hypothesis. Justify your answer.

Disagree.

Because the reaction is exothermic, increasing the temperature of the reaction will favor the formation of the reactants (according to Le Chatelier’s principle).

1 point is earned for the correct choice and a correct justification.
\[ \text{NO}(g) + \text{NO}_2(g) \rightleftharpoons \text{N}_2\text{O}_3(g) \]

2. (c) The student hypothesizes that increasing the temperature will increase the amount of \( \text{N}_2\text{O}_3(g) \) in the equilibrium mixture. Indicate whether you agree or disagree with the hypothesis. Justify your answer.

<table>
<thead>
<tr>
<th>Disagree.</th>
<th>1 point is earned for the correct choice and a correct justification.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disagree.</td>
<td></td>
</tr>
<tr>
<td>Because the reaction is exothermic, increasing the temperature of the reaction will favor the formation of the reactants (according to Le Chatelier’s principle).</td>
<td></td>
</tr>
</tbody>
</table>

Common errors/misconceptions:

1. Focusing on \( \Delta G^\circ \) or \( \Delta S^\circ \) instead of \( \Delta H^\circ \)
2. Arguments about the influence of temperature on the *kinetics* of the reaction
3. Failure to recognize (or effectively articulate) effect of temperature on an exothermic reaction
N\textsubscript{2}O\textsubscript{3}(g) reacts with water to form nitrous acid, HNO\textsubscript{2}(aq), a compound involved in the production of acid rain. The reaction is represented below.

\[ \text{N}_2\text{O}_3(g) + \text{H}_2\text{O}(l) \rightarrow 2 \text{HNO}_2(aq) \]

(d) The skeletal structure of the HNO\textsubscript{2} molecule is shown in the box below.

(i) Complete the Lewis electron-dot diagram of the HNO\textsubscript{2} molecule in the box below, including any lone pairs of electrons.
2. $\text{N}_2\text{O}_3(g)$ reacts with water to form nitrous acid, $\text{HNO}_2(aq)$, a compound involved in the production of acid rain. The reaction is represented below.

$$\text{N}_2\text{O}_3(g) + \text{H}_2\text{O}(l) \rightarrow 2 \text{HNO}_2(aq)$$

(d) The skeletal structure of the $\text{HNO}_2$ molecule is shown in the box below.

(i) Complete the Lewis electron-dot diagram of the $\text{HNO}_2$ molecule in the box below, including any lone pairs of electrons.

1 point is earned for a valid diagram.
2. $\text{N}_2\text{O}_3(g)$ reacts with water to form nitrous acid, $\text{HNO}_2(aq)$, a compound involved in the production of acid rain. The reaction is represented below.

$$\text{N}_2\text{O}_3(g) + \text{H}_2\text{O}(l) \rightarrow 2 \text{HNO}_2(aq)$$

(d) The skeletal structure of the HNO$_2$ molecule is shown in the box below.

(i) Complete the Lewis electron-dot diagram of the HNO$_2$ molecule in the box below, including any lone pairs of electrons.

![Lewis structure of HNO$_2$](image)

1 point is earned for a valid diagram.

Common errors/misconceptions:
1. Incorrect number of valence electrons
2. Octet rule violations, unpaired electrons
3. Rearranging skeletal framework
(ii) Based on your completed diagram above, identify the hybridization of the nitrogen atom in the HNO₂ molecule.

| $sp^2$ | 1 point is earned for the correct answer. |

Common errors/misconceptions:
1. Incorrect counting of electron domains
2. Reporting electron configuration of atoms or molecular geometry, rather than hybridization
To produce an aqueous solution of HNO₂, the student bubbles N₂O₃(g) into distilled water. Assume that the reaction goes to completion and that HNO₂ is the only species produced. To determine the concentration of HNO₂(aq) in the resulting solution, the student titrates a 100. mL sample of the solution with 0.100 M KOH(aq). The neutralization reaction is represented below.

\[
\text{HNO}_2(aq) + \text{OH}^-(aq) \rightarrow \text{NO}_2^-(aq) + \text{H}_2\text{O}(l)
\]

The following titration curve shows the change in pH of the solution during the titration.

2 (e) Use the titration curve and the information above to
(i) determine the initial concentration of the HNO₂(aq) solution
2 (e) Use the titration curve and the information above to
(i) determine the initial concentration of the HNO₂(aq) solution

Common error:
Assuming that nitrous acid is a strong acid, then substituting
the initial pH into the expression [HNO₂] = 10⁻ᵖᴴ

20. mL KOH × \( \frac{0.100 \text{ mol KOH}}{1000 \text{ mL KOH}} \) = 0.0020 mol KOH added
⇒ 0.0020 mol HNO₂ in 100. mL of solution because the stoichiometry
of the neutralization reaction is 1 to 1.
\( \frac{0.0020 \text{ mol HNO}_2}{0.100 \text{ L}} = 0.020 M \text{ HNO}_2 \)

1 point is earned for the correct calculation of the initial concentration.
(e) Use the titration curve and the information above to
   (ii) estimate the value of $pK_a$ for $\text{HNO}_2(aq)$

The value of $pK_a$ is about 3.4.

1 point is earned for an acceptable estimate for the value of $pK_a$. 
2 (e) Use the titration curve and the information above to
• (ii) estimate the value of p\(K_a\) for \(\text{HNO}_2(aq)\)

Common errors/misconceptions:
1. Estimating \(K_a\) from the pH at the equivalence point, rather than at the half-equivalence point
2. Mathematically intensive (albeit correct) estimation:

\[
K_a = \frac{(10^{-2.5})(10^{-2.5})}{(\sim 0.020)}
\]

\[
pK_a = -\log (0.00050) = 3.3
\]

The value of p\(K_a\) is about 3.4.

1 point is earned for an acceptable estimate for the value of p\(K_a\).
2 (f) During the titration, after a volume of 15 mL of 0.100 M KOH(aq) has been added, which species, HNO₂(aq) or NO₂⁻(aq), is present at a higher concentration in the solution? Justify your answer.

Common errors/misconceptions:

1. Claiming that the weak acid is the dominant species, since the solution pH at this point is less than 7

2. Mathematically intensive (albeit correct) calculation of [HNO₂] and [NO₂⁻] and then comparing them numerically

**NO₂⁻(aq)**

The titration is past the half-equivalence point, therefore there will be more conjugate base present than acid.

1 point is earned for the correct choice and a valid justification.
1. Give students opportunities to interpret particulate diagrams to enhance their conceptual understanding of stoichiometry and mass balance.

2. Encourage students to always include units with every numerical quantity that they use. This practice will help to avoid simple mistakes like using a version of the gas constant $R$ that has incompatible units.

3. Students should practice identifying electron domains and their relationship to hybridization. Many students seemed to misunderstand the term “hybridization” and the method for counting electron domains.

4. Ask students to articulate what happens to the analyte and titrant at each point in a titration experiment. Clarify the meaning of, and differences between, the equivalence point and half-equivalence point.
Question 3
Iron, its ions, and its oxides

Q3: Mean 3.09 ± 2.46
Question 3

Answer the following questions relating to Fe and its ions, Fe$^{2+}$ and Fe$^{3+}$.

(a) Write the ground-state electron configuration of the Fe$^{2+}$ ion.

Neutral Fe: \[ 1s^2 \ 2s^2 \ 2p^6 \ 3s^2 \ 3p^6 \ 4s^2 \ 3d^6 \]

Common errors/misconceptions:

1. \[ 1s^2 \ 2s^2 \ 2p^6 \ 3s^2 \ 3p^6 \ 4s^2 \ 3d^4 \] removing two e$^-$ from 3d
2. \[ 1s^2 \ 2s^2 \ 2p^6 \ 3s^2 \ 3p^6 \ 4s^1 \ 3d^5 \] removing one e$^-$ from 4s and 3d
3. \[ 1s^2 \ 2s^2 \ 2p^6 \ 3s^2 \ 3p^6 \ 4s^2 \ 3d^6 \] not removing any e$^-$ at all
3 (b) The radii of the ions are given in the table above. Using principles of atomic structure, explain why the radius of the Fe$^{2+}$ ion is larger than the radius of the Fe$^{3+}$ ion.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Ionic Radius (pm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe$^{2+}$</td>
<td>92</td>
</tr>
<tr>
<td>Fe$^{3+}$</td>
<td>79</td>
</tr>
</tbody>
</table>

Common errors/misconceptions:

1. Stating that Fe$^{3+}$ has one additional proton compared to Fe$^{2+}$
2. Responses that start along the right path, but end too early:
   “Fe$^{2+}$ has more electrons” as the entire answer
   “Effective nuclear charge” as the entire answer
Common error:
In Coulomb’s law, mis-interpreting the denominator to mean “distance between the Fe$^{3+}$ nucleus and its outermost electrons”

<table>
<thead>
<tr>
<th>Ion</th>
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<tbody>
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</tr>
</tbody>
</table>

3 (c) Fe$^{3+}$ ions interact more strongly with water molecules in aqueous solution than Fe$^{2+}$ ions do. Give one reason for this stronger interaction, and justify your answer using Coulomb’s law.
3 A student obtains a solution that contains an unknown concentration of Fe$^{2+}$($aq$). To determine the concentration of Fe$^{2+}$($aq$) in the solution, the student titrates a sample of the solution with MnO$_4^-$($aq$), which converts Fe$^{2+}$($aq$) to Fe$^{3+}$($aq$), as represented by the following equation.

$$5 \text{Fe}^{2+}(aq) + \text{MnO}_4^-(aq) + 8 \text{H}^+(aq) \rightarrow 5 \text{Fe}^{3+}(aq) + \text{Mn}^{2+}(aq) + 4 \text{H}_2\text{O}(l)$$

(d) Write the balanced equation for the half-reaction for the oxidation of Fe$^{2+}$($aq$) to Fe$^{3+}$($aq$).

Common errors/misconceptions:

1. Subtracting electrons from reactants, rather than adding them to products
2. Neglecting to balance total charge, most commonly as:

$$\text{Fe}^{2+} + e^- \rightarrow \text{Fe}^{3+} \quad \text{or} \quad 5\text{Fe}^{2+} \rightarrow 5\text{Fe}^{3+} + e^-$$
5 Fe^{2+}(aq) + \text{MnO}_4^-(aq) + 8 \text{H}^+(aq) \rightarrow 5 \text{Fe}^{3+}(aq) + \text{Mn}^{2+}(aq) + 4 \text{H}_2\text{O}(l)

3 (e) The student titrates a 10.0 mL sample of the Fe^{2+}(aq) solution. Calculate the value of [Fe^{2+}] in the solution if it takes 17.48 mL of added 0.0350 M KMnO_4(aq) to reach the equivalence point of the titration.

Common error:
Using the equation \( M_1V_1 = M_2V_2 \) to find moles of Fe^{2+}, which neglects the stoichiometric ratio of Fe^{2+} to KMnO_4\(^-\).
3. To deliver the 10.0 mL sample of the Fe$^{2+}(aq)$ solution in part (e), the student has the choice of using one of the pieces of glassware listed below.

- 25 mL buret
- 25 mL graduated cylinder
- 25 mL beaker
- 25 mL volumetric flask

(f) Explain why the 25 mL volumetric flask would be a poor choice to use for delivering the required volume of the Fe$^{2+}(aq)$ solution.

Common errors/misconceptions:

1. Making irrelevant statements about the shape of the volumetric flask or the size of its opening
2. Some students seemed unfamiliar with the term “volumetric flask”
3 In a separate experiment, the student is given a sample of powdered Fe(s) that contains an inert impurity. The student uses a procedure to oxidize the Fe(s) in the sample to Fe₂O₃(s). The student collects the following data during the experiment.

<table>
<thead>
<tr>
<th>Mass of Fe(s) with inert impurity</th>
<th>6.724 g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of Fe₂O₃(s) produced</td>
<td>7.531 g</td>
</tr>
</tbody>
</table>

(g) Calculate the number of moles of Fe in the Fe₂O₃(s) produced.

Common error:

Neglecting the 2:1 stoichiometric ratio of Fe to Fe₂O₃
3 (h) Calculate the percent by mass of Fe in the original sample of powdered Fe(s) with the inert impurity.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
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<tbody>
<tr>
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<td>7.531 g</td>
</tr>
</tbody>
</table>

Common errors/misconceptions:

1. Calculating percent yield or percent error rather than mass percent.
2. Comparing the calculated mass of Fe to the mass of the oxidized sample, rather than to the mass of the original sample.
<table>
<thead>
<tr>
<th>Mass of Fe(s) with inert impurity</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Mass of Fe₂O₃(s) produced</td>
<td>7.531 g</td>
</tr>
</tbody>
</table>

(i) If the oxidation of the Fe(s) in the original sample was incomplete so that some of the 7.531 g of product was FeO(s) instead of Fe₂O₃(s), would the calculated mass percent of Fe(s) in the original sample be higher, lower, or the same as the actual mass percent of Fe(s)? Justify your answer.
Common errors/misconceptions:

1. Confusing the **actual** amount of \( \text{Fe}_2\text{O}_3 \) produced with the **calculated** amount of \( \text{Fe}_2\text{O}_3 \) produced, thereby arriving at the reverse of the correct answer

2. Using vague or ambiguous wording, making it impossible to tell whether the student was discussing the original sample, the fully-oxidized sample, or the partially-oxidized sample

(i) If the oxidation of the Fe(s) in the original sample was incomplete so that some of the 7.531 g of product was FeO(s) instead of \( \text{Fe}_2\text{O}_3(s) \), would the calculated mass percent of Fe(s) in the original sample be higher, lower, or the same as the actual mass percent of Fe(s)? Justify your answer.

<table>
<thead>
<tr>
<th>The calculated mass percent of Fe would be lower than the actual mass percent of Fe.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A sample that contains any FeO (rather than ( \text{Fe}_2\text{O}_3 )) will have a higher <strong>actual</strong> mass percent of Fe than a completely oxidized sample would have. Therefore, when the moles of Fe are calculated (assuming all the mass of the sample is ( \text{Fe}_2\text{O}_3 )) the <strong>calculated</strong> number of moles of Fe, and hence the <strong>calculated</strong> mass percent of Fe, will be lower.</td>
</tr>
</tbody>
</table>
1. When forming a transition metal ion, the $s$ valence electrons in the highest $n$ shell are removed before the $d$ electrons in the $n−1$ shell.

2. Give students opportunities to apply Coulomb’s law in situations beyond effective nuclear charge.

3. Discourage mnemonic shortcuts like $M_1V_1 = M_2V_2$ in stoichiometry problems, as they neglect the stoichiometric coefficients in a balanced chemical equation.

4. Practice error analysis questions, asking students to predict the specific quantitative outcome of the experiment and to clearly articulate their line of reasoning.
Question 4

Intermolecular forces and the ideal gas law in CS$_2$ and COS

Q4: Mean 1.87 ± 1.12
The table above gives the molecular structures and boiling points for the compounds $\text{CS}_2$ and $\text{COS}$.

(a) In terms of the types and relative strengths of all the intermolecular forces in each compound, explain why the boiling point of $\text{CS}_2(l)$ is higher than that of $\text{COS}(l)$. 

<table>
<thead>
<tr>
<th>Compound</th>
<th>Molecular Structure</th>
<th>Boiling Point at 1 atm (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{CS}_2$</td>
<td><img src="image" alt="Molecular Structure of CS2" /></td>
<td>319</td>
</tr>
<tr>
<td>$\text{COS}$</td>
<td><img src="image" alt="Molecular Structure of COS" /></td>
<td>223</td>
</tr>
</tbody>
</table>
Common errors/misconceptions:

1. Stating that both \( \text{CS}_2 \) and \( \text{COS} \) have only London dispersion forces, or that both have dipole-dipole forces.
2. Implying or explicitly stating that boiling involves the breaking of covalent bonds.
3. Using molar mass as the sole justification of the boiling point trend.
4. Claiming that dipole-dipole interactions are always stronger than London dispersion forces.
5. Equating boiling point with vapor pressure.

(a) In terms of the types and relative strengths of all the intermolecular forces in each compound, explain why the boiling point of \( \text{CS}_2(l) \) is higher than that of \( \text{COS}(l) \).

\[
\begin{array}{|l|l|}
\hline
\text{CS}_2 & \text{has only London dispersion forces, while COS has London dispersion forces and dipole-dipole forces.} \\
\hline
\text{The London dispersion forces in CS}_2 & \text{are stronger than the combination of London dispersion forces and dipole-dipole forces in COS.} \\
\hline
\end{array}
\]

1 point is earned for correctly identifying all of the intermolecular forces in both molecules.

1 point is earned for a valid explanation.
Question 4

(b) A 10.0 g sample of CS$_2$(l) is put in an evacuated 5.0 L rigid container. The container is sealed and heated to 325 K, at which temperature all of the CS$_2$(l) has vaporized. What is the pressure in the container once all of the CS$_2$(l) has vaporized?

Common errors/misconceptions:

1. Incorrectly calculating number of moles of CS$_2$ (either dividing molar mass by mass of CS$_2$, or assuming an arbitrary amount of CS$_2$ like 1.0 g or 1.0 moles)
2. Using the incorrect temperature, e.g. 319°C
3. Various errors with the ideal gas constant:
   - Using $R = 0.0821$ and reporting pressure without any units
   - Reporting the pressure in atm after using $R = 8.314 \text{ J mol}^{-1} \text{ K}^{-1}$ or $R = 62.396 \text{ L torr mol}^{-1} \text{ K}^{-1}$
1. Address **common misconceptions**, such as: covalent bonds breaking during phase changes, or that the strength of a covalent bond influences boiling point, or that dipole-dipole forces are always stronger than London dispersion forces.

2. Help students to **use correct terminology** in their answers. Responses that mentioned “London dispersion bonds” were given the benefit of the doubt, but those that only mentioned “bonds” made it challenging to discern whether they were truly talking about intermolecular forces.

3. Encourage students to compare and contrast the ideas of polar bonds vs. polar molecules. **Molecular geometry can sometimes be critically important in predicting molecular polarity.**

4. Insist that students use **full and complete unit labels** in all calculations, even in intermediate work. Students often mis-matched their value of $R$ with their units in the final answer of pressure in part (b).
Question 5
Ionization and $K_a$ of HF

Q5: Mean 1.32 ± 1.15
Question 5

\[ \text{HF}(aq) + \text{H}_2\text{O}(l) \rightleftharpoons \text{F}^- (aq) + \text{H}_3\text{O}^+ (aq) \]

The ionization of HF\(_{aq}\) in water is represented by the equation above. In a 0.0350 \(M\) HF\(_{aq}\) solution, the percent ionization of HF is 13.0 percent.

(a) Two particulate representations of the ionization of HF molecules in the 0.0350 \(M\) HF\(_{aq}\) solution are shown below in Figure 1 and Figure 2. Water molecules are not shown. Explain why the representation of the ionization of HF molecules in water in Figure 1 is more accurate than the representation in Figure 2. (The key below identifies the particles in the representations.)

---

= \(\text{H}_3\text{O}^+\)  = HF  = \(\text{F}^-\)

---

Figure 1  Figure 2
(a) Two particulate representations of the ionization of HF molecules in the 0.0350 M HF(aq) solution are shown below in Figure 1 and Figure 2. Water molecules are not shown. Explain why the representation of the ionization of HF molecules in water in Figure 1 is more accurate than the representation in Figure 2. (The key below identifies the particles in the representations.)

![Diagram showing particles and their labels: \( \text{H}_3\text{O}^+ \), \( \text{HF} \), \( \text{F}^- \).]

Figure 1

Figure 2

HF is a weak acid and is only partially ionized. This fact is consistent with Figure 1, which shows that one out of eight (~13%) HF molecules is ionized (to form one \( \text{H}_3\text{O}^+ \) and one \( \text{F}^- \)).

OR

Figure 2 cannot represent HF because it represents 100% ionization of the acid.

1 point is earned for a valid explanation.
Common errors/misconceptions:

1. Equating the percent ionization with a $K_{sp}$ or percent dissolution
2. Describing the extent to which HF undergoes hydrogen bonding

HF is a weak acid and is only partially ionized. This fact is consistent with Figure 1, which shows that one out of eight (~13%) HF molecules is ionized (to form one $\text{H}_3\text{O}^+$ and one $\text{F}^-$).

OR

Figure 2 cannot represent HF because it represents 100% ionization of the acid.

1 point is earned for a valid explanation.
(b) Use the percent ionization data above to calculate the value of $K_a$ for HF.

Common errors/misconceptions:

1. Interpreting 13.0% ionization as meaning that $[\text{H}_3\text{O}^+]$ and/or $[\text{HF}] = 13.0$ M or 0.130 M

2. Neglecting to perform the subtraction to determine $[\text{HF}]$ (i.e., 0.0350 M – 0.00455 M). Students often assumed that $[\text{HF}]$ remained unchanged at 0.0350 M.

3. Assuming that $K_a = [\text{H}_3\text{O}]^+$
(c) If 50.0 mL of distilled water is added to 50.0 mL of 0.035 M HF(aq), will the percent ionization of HF(aq) in the solution increase, decrease, or remain the same? Justify your answer with an explanation or calculation.
(c) If 50.0 mL of distilled water is added to 50.0 mL of 0.035 \( M \) HF(aq), will the percent ionization of HF(aq) in the solution increase, decrease, or remain the same? Justify your answer with an explanation or calculation.

\[
\text{OR} \\
\text{New volume = twice original volume, thus new } [\text{HF}]_i = \frac{0.035}{2} = 0.0175 \, M \\
K_a = \frac{[\text{H}_3\text{O}^+][\text{F}^-]}{[\text{HF}]} = 6.81 \times 10^{-4} \text{ (value from part (b))} \\
\text{Let } [\text{H}_3\text{O}^+] = [\text{F}^-] = x \\
\text{Then } 6.81 \times 10^{-4} = \frac{(x)(x)}{(0.0175 - x)} \approx \frac{x^2}{(0.0175)} \Rightarrow x \approx 0.00345 \, M \\
\text{Percent ionization } = \frac{0.00345 \, M}{0.0175 \, M} \times 100 = 20.\% \\
20.\% > 13.0\%, \text{ therefore the percent ionization increases.}
\]
If 50.0 mL of distilled water is added to 50.0 mL of 0.035 M HF(aq), will the percent ionization of HF(aq) in the solution increase, decrease, or remain the same? Justify your answer with an explanation or calculation.

The percent ionization of HF in the solution would increase. Doubling the volume of the solution decreases the initial concentration of each species by one-half.

Therefore \[ Q = \frac{\left(\frac{1}{2}[H_3O^+]_i\right)\left(\frac{1}{2}[F^-]_i\right)}{\frac{1}{2}[HF]_i} = \frac{1}{2}K_a \Rightarrow Q < K_a, \]

consequently the equilibrium position will shift toward the products and increase the percent ionization.

Common errors/misconceptions:
1. Stating that percent ionization is a constant, dictated only by the identity of the weak acid
2. Equating percent ionization with \( K_a \), and thus stating that [HF] remains at a constant 13.0% ionization
3. Using Le Chatelier’s principle to claim that the dilution increases the concentration of water and thus shifts the equilibrium towards products
Question 5 Roundup: Advice from Readers
Average = 1.32

1. Provide students with multiple contexts (esp. particulate diagrams) to evaluate and predict the behavior of weak acids.

2. Incorporate the concept of percent ionization into discussions of weak acid equilibria, showing its relationship to \([H^+], [A^-], \text{ and } [HA] \). 

3. Emphasize the importance of using equilibrium concentration, rather than initial concentration, in the calculation of \(K_a\) and other equilibrium constants.

4. Demonstrate how comparing \(Q \text{ vs. } K\) complements (and in some cases is more helpful than) Le Chatelier’s principle.
Question 6
Galvanic cells

Q6: Mean 1.49 ± 1.35
A student sets up a galvanic cell at 298 K that has an electrode of Ag(s) immersed in a 1.0 M solution of Ag⁺(aq) and an electrode of Cr(s) immersed in a 1.0 M solution of Cr³⁺(aq), as shown in the diagram above.

(a) The student measures the voltage of the cell shown above and discovers that it is zero. Identify the missing component of the cell, and explain its importance for obtaining a nonzero voltage.
Common errors/misconceptions:

1. Misidentification of the salt bridge
2. Indicating that electrons flow through the salt bridge
3. Responses that start along the right path, but end too early:
   “balances charge” as the entire answer
   “completes the circuit” as the entire answer
   “neutralizes charge” as the entire answer

The salt bridge is missing. The salt bridge allows for the migration of ions to maintain charge balance in each half-cell. 1 point is earned for the correct answer and a valid explanation.
Common errors/misconceptions:

1. Multiplying the Ag\(^+\) reduction potential by 3, the stoichiometric coefficient of silver(I) ion in the balanced chemical equation reaction

2. Misidentifying the reduction potentials at the anode and cathode

3. Calculating the oxidation potential of chromium (+0.74 V) without converting to a reduction potential.

---

<table>
<thead>
<tr>
<th>Half-Reaction</th>
<th>(E^\circ) (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{Ag}^+(aq) + e^- \rightarrow \text{Ag}(s))</td>
<td>+0.80</td>
</tr>
<tr>
<td>(\text{Cr}^{3+}(aq) + 3e^- \rightarrow \text{Cr}(s))</td>
<td>?</td>
</tr>
</tbody>
</table>

(b) The student adds the missing component to the cell and measures \(E^\circ_{\text{cell}}\) to be +1.54 V. As the cell operates, Ag\(^+\) ions are reduced. Use this information and the information in the table above to do the following.

(i) Calculate the value of \(E^\circ\) for the half-reaction \(\text{Cr}^{3+}(aq) + 3e^- \rightarrow \text{Cr}(s)\).
Common errors/misconceptions:

1. Reversing the order of the reactants and products, making the cell electrolytic rather than galvanic
2. Omitting the stoichiometric coefficient for silver
3. Combining two reductive half-reactions: \( \text{Ag}^+ + \text{Cr}^{3+} \rightarrow \text{Ag} + \text{Cr} \)
4. Writing a full equation that includes electrons as reactants or products, such as 
   \( 4e^- + \text{Ag}^+ + \text{Cr}^{3+} \rightarrow \text{Ag} + \text{Cr} \)

(b) The student adds the missing component to the cell and measures \( E^{\circ}_{\text{cell}} \) to be 1.54 V. As the cell operates, Ag\(^+\) ions are reduced. Use this information and the information in the table above to do the following.

(ii) Write the balanced net-ionic equation for the overall reaction that occurs as the cell operates.
Common errors/misconceptions:

1. Using a value other than \( n = 3 \) for the number of moles of electrons transferred. Typical values included \( n = 2 \) or \( n = 4 \), which came from adding or subtracting the number of electrons shown in the table of standard reduction potentials.

2. Substituting the silver or chromium half-cell potential in place of the overall cell potential of 1.54 V.

---

<table>
<thead>
<tr>
<th>Half-Reaction</th>
<th>( E^\circ ) (V)</th>
</tr>
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<tbody>
<tr>
<td>( \text{Ag}^+(aq) + e^- \rightarrow \text{Ag}(s) )</td>
<td>+ 0.80</td>
</tr>
<tr>
<td>( \text{Cr}^{3+}(aq) + 3 \ e^- \rightarrow \text{Cr}(s) )</td>
<td>?</td>
</tr>
</tbody>
</table>

(b) The student adds the missing component to the cell and measures \( E^\circ_{\text{cell}} \) to be +1.54 V. As the cell operates, \( \text{Ag}^+ \) ions are reduced. Use this information and the information in the table above to do the following.

(iii) Calculate the value of \( \Delta G^\circ \) for the overall cell reaction in J/mol\(_{\text{rxn}}\).
1. Encourage students to verbally describe the operating principles of a galvanic cell, focusing on an appropriate level of detail, proper terminology, and precision in language.

2. Encourage students to read the question fully. The question states that Ag$^+$ is reduced in the galvanic cell, yet many responses showed the oxidation of Ag.

3. Emphasize the importance of mastering terminology like anode vs. cathode and oxidation potential vs. reduction potential. Mnemonic devices (e.g., “LEO GER” or “OIL RIG”) can be helpful but must be applied consistently and correctly.

4. Review the structure and pace of your course so that electrochemistry is addressed before the date of the AP Chemistry Exam. A small but noticeable population of students stated in their response that they had never seen electrochemistry before.
Question 7

Photoelectron spectroscopy and half-life

Q7: Mean 2.02 ± 1.48
The complete photoelectron spectrum of an element is represented above.

(a) Identify the element.

Common errors/misconceptions:

Mis-interpretation of the y-axis

- Boron (1s\(^2\) 2s\(^2\) 2p\(^1\))
- Neon (1s\(^2\) 2s\(^2\) 2p\(^6\))
- Lithium (three peaks = 3 electrons total)
The complete photoelectron spectrum of an element is represented above.

(a) Identify the element.

The element is nitrogen, N.  
1 point is earned for correctly identifying the element.

Common errors/misconceptions:

Mis-interpretation of the x-axis  
- Zirconium (atomic number = 40)
- Calcium (atomic mass = 40 Da)

Discussion of mass-to-charge ratio
A radioactive isotope of the element decays with a half-life of 10 minutes.

(b) Calculate the value of the rate constant, \(k\), for the radioactive decay. Include units with your answer.

Common errors/misconceptions:
1. Algebraic errors
2. Including time units (e.g., min or s) instead of inverse time units
3. Adding extra quantities to the inverse time units (e.g., atoms/min, mol/min, decays/min)
A radioactive isotope of the element decays with a half-life of 10. minutes.

(c) If 64 atoms of the radioactive isotope are originally present in a sample, what is the expected amount of time that will pass until only one atom of the isotope remains? Show how you arrived at your answer.
(c) If 64 atoms of the radioactive isotope are originally present in a sample, what is the expected amount of time that will pass until only one atom of the isotope remains? Show how you arrived at your answer.

64 → 32 → 16 → 8 → 4 → 2 → 1
6 half-lives are required.
6 × 10. min = 60. min

OR

\[ \ln[A]_t - \ln[A]_0 = -kt \]

\[ t = \frac{\ln(1) - \ln(64)}{-0.069 \text{ min}^{-1}} = 60. \text{ min} \]

1 point is earned for the correct answer and a valid method.

Common errors/misconceptions:
1. Miscounting number of half-lives at the beginning or end of the decay sequence
2. Miscalculating time by starting with 64 atoms at \( t = 10. \text{ minutes} \) rather than 64 atoms at \( t = 0 \) minutes
3. Reducing the half-life by a factor of two for every successive half-life (\( t_{\frac{1}{2}} = 10 \text{ min} \), then 5 min, then 2.5 min…)
4. Using the second-order integrated rate law
1. Compare and contrast various types of graphical, instrumental data (PES vs. mass spectrometry vs. absorption spectroscopy) to clarify what kind of information each experiment provides.

2. Reinforce the importance of including units throughout a calculation. Avoid unnecessary unit conversions when a specific type of unit is not required.

3. Require students to show their work, even when mental math is possible.

4. Write units clearly, using standard abbreviations. Labels like m or M (which are reserved for other quantities) is a poor way to express units of minutes.
STOP

END OF EXAM
Acknowledgements

Lew Acampora, Exam Leader

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