

Question 3: Long Answer

10 points

A For the correct diagram:

Point 01

B (i) For a correct explanation:

Point 02

Because gas particles are more dispersed (have more microstates) than solids, the entropy decreases as the reactants (which include a gas) convert to the solid product.

(ii) For the correct answer and a valid justification:

Point 03

Yes. Given that $\Delta G_{rxn}^{\circ} = \Delta H_{rxn}^{\circ} - T\Delta S_{rxn}^{\circ}$, the reaction must have $\Delta G_{rxn}^{\circ} < 0$ to be favorable. Because the reaction is exothermic, $\Delta H_{rxn}^{\circ} < 0$ and enthalpy contributes to favorability. $\Delta S_{rxn}^{\circ} < 0$, so entropy does not contribute to favorability.

C (i) For the correct calculated value reported with the correct number of significant figures:

Point 04

$$q = mc\Delta T = (100.1 \text{ g})(4.18 \text{ J/(g}\cdot^{\circ}\text{C)})(22.38^{\circ}\text{C} - 22.00^{\circ}\text{C})$$

$$q = 160 \text{ J} = 0.16 \text{ kJ}$$

(ii) For the correct calculated value, consistent with part C (i):

Point 05

$$q_{rxn} = -q_{surr} = -0.16 \text{ kJ}$$

$$\Delta H_{rxn}^{\circ} = \frac{-0.16 \text{ kJ}}{0.100 \text{ g P}_4\text{O}_{10}} \times \frac{283.9 \text{ g P}_4\text{O}_{10}}{1 \text{ mol P}_4\text{O}_{10}} \times \frac{1 \text{ mol P}_4\text{O}_{10}}{1 \text{ mol}_{rxn}} = -450 \text{ kJ/mol}_{rxn}$$

For the correct sign:

Point 06

$$-450 \text{ kJ/mol}_{rxn}$$

D For the correct answer and a valid justification:

Point 07

Less than. If less P_4O_{10} is present, less thermal energy will be transferred to the water during the reaction, causing the temperature increase to be less than it was with 0.100 g of P_4O_{10} .

E For the correct calculated value:**Point 08***Using Hess's law:*

$$\Delta H_{f, \text{PCl}_5(g)}^\circ = \frac{1}{4} \Delta H_1^\circ + \Delta H_2^\circ$$

$$\Delta H_{f, \text{PCl}_5(g)}^\circ = \frac{1}{4}(-1148) + (-88) = -375 \text{ kJ/mol}$$

F (i) For the correct calculated value:**Point 09**

$$K_p = \frac{P_{\text{PCl}_5}}{(P_{\text{PCl}_3})(P_{\text{Cl}_2})} = \frac{4.00}{(2.00)(6.00)} = \frac{1}{3} = 0.333$$

(ii) For the correct answer and a valid justification:**Point 10**

Decrease. The negative value of ΔH_2° indicates that the reaction is exothermic. Because exothermic reactions favor reactant formation at higher temperature, the value of K_p decreases.

Question 2: Long Answer

10 points

- (a) For the correct calculated value reported with the correct number of significant figures: 1 point

$$1.25 \text{ mol AlCl}_3 \times \frac{3 \text{ mol Cl}}{1 \text{ mol AlCl}_3} \times \frac{35.45 \text{ g Cl}}{1 \text{ mol Cl}} = 133 \text{ g Cl}$$

- (b) For the correct algebraic manipulation of either ΔH_2° or ΔH_4° (may be implicit): 1 point

Accept one of the following:

- Reversing reaction 2:



- Multiplying reaction 4 by $\frac{3}{2}$:



For the correct calculated value: 1 point

$$\Delta H_1^\circ = -\Delta H_2^\circ + \Delta H_3^\circ + 1.5(\Delta H_4^\circ) = -(-583) + 326 + 1.5(243) = 1274 \text{ kJ/mol}_{\text{rxn}}$$

Total for part (b) 2 points

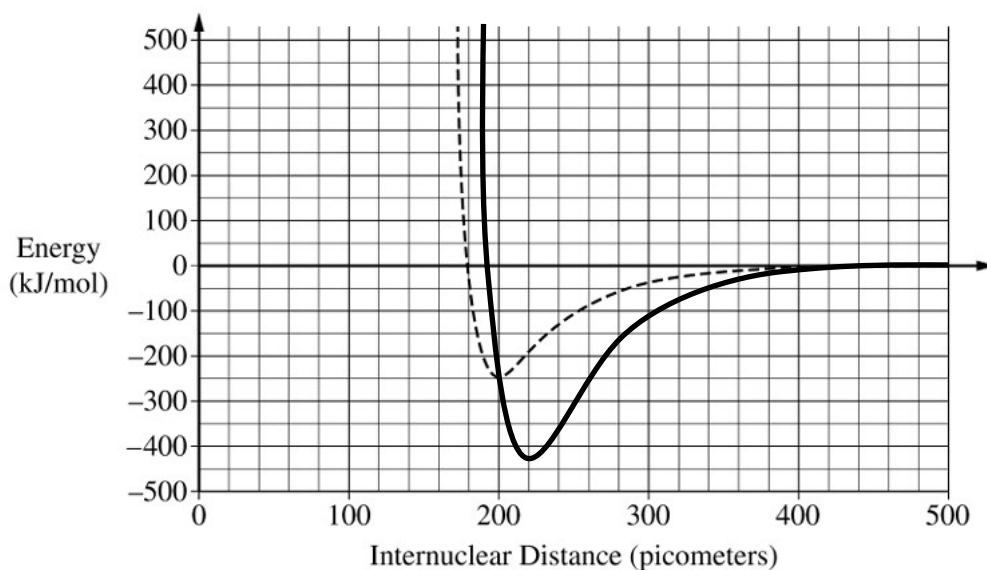
- (c) (i) For the correct answer: 1 point

200 picometers ($\pm 10 \text{ pm}$)

- (ii) For a curve with a minimum at an internuclear distance of $220 \pm 10 \text{ pm}$: 1 point

See sample curve below

For a curve with a minimum energy value of $-425 \pm 20 \text{ kJ/mol}$ that approaches zero as the internuclear distance approaches 500 pm : 1 point



Total for part (c) 3 points

(d)(i) For the correct answer and a valid justification: **1 point**

Diagram 2. Al has four electron domains in Diagram 2, which would be trigonal pyramidal, not trigonal planar.

(ii) For the correct answer and a valid justification: **1 point**

Diagram 1. All atoms in diagram 1 have a formal charge of zero, whereas atoms in diagrams 2 and 3 have nonzero formal charges.

Total for part (d) 2 points

(e) For the correct answer: **1 point**

$$K_p = \frac{P_{\text{Al}_2\text{Cl}_6}}{(P_{\text{AlCl}_3})^2}$$

(f) For the correct calculated value, consistent with part (e): **1 point**

$$K_p = \frac{\chi_{\text{Al}_2\text{Cl}_6}(P_{\text{total}})}{(\chi_{\text{AlCl}_3}(P_{\text{total}}))^2} = \frac{\frac{3}{10}(22.1)}{\left(\frac{7}{10}(22.1)\right)^2} = 0.0277$$

Total for question 2 10 points

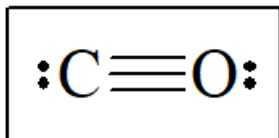
Question 2: Long Answer

10 points

- (a) For the correct answer and a valid justification: 1 point

The H atoms are reduced because they change from an oxidation number of +1 to 0.

- (b) For the correct answer: 1 point



- (c) (i) For the correct stoichiometry (may be implicit): 1 point

$$\Delta S^\circ_{rxn} = \Sigma \Delta S^\circ_{products} - \Sigma \Delta S^\circ_{reactants}$$

$$\Delta S^\circ_{rxn} = (\Delta S^\circ_{CO(g)} + 2(\Delta S^\circ_{H_2(g)})) - (\Delta S^\circ_{CH_3OH(g)})$$

- For the correct calculated value: 1 point

$$\Delta S^\circ_{rxn} = 198 + 2(131) - 240. = 220. \frac{J}{K \cdot mol_{rxn}}$$

- (ii) For the correct calculated value: 1 point

$$\Delta G^\circ = \Delta H^\circ - T \Delta S^\circ$$

$$\Delta G^\circ = 90.0 \frac{kJ}{mol_{rxn}} - (375 K)(0.220 \frac{kJ}{K \cdot mol_{rxn}}) = +7.5 kJ/mol_{rxn}$$

Total for part (c) 3 points

- (d) For the correct calculated value: 1 point

$$P_{CO} = \frac{3}{10} (12.0 \text{ atm}) = 3.6 \text{ atm}$$

- (e) For the correct expression: 1 point

$$K_p = \frac{(P_{CO})(P_{H_2})^2}{(P_{CH_3OH})}$$

- (f) For the correct calculated value: 1 point

$$K_p = \frac{(P_{CO})(P_{H_2})^2}{(P_{CH_3OH})} = \frac{(4.2)(8.4)^2}{(2.7)} = 110$$

(g) For a correct comparison of Q and K : 1 point

Accept one of the following:

- *The change in volume causes the partial pressure of each species to decrease by a factor of two. Because there are more moles of gaseous products than reactants, the decrease of the numerator in Q will be larger than that in the denominator, making $Q_p < K_p$.*

- $$Q_p = \frac{\left(\frac{P_{\text{CO}}}{2}\right)\left(\frac{P_{\text{H}_2}}{2}\right)^2}{\left(\frac{P_{\text{CH}_3\text{OH}}}{2}\right)} = \frac{K_p}{4} \approx 27 < K_p$$

For the correct answer and a valid justification: 1 point

Decrease. Given that $Q_p < K_p$, the partial pressures (moles) of the products will increase as equilibrium re-establishes, decreasing the number of moles of CH_3OH .

Total for part (g) 2 points

Total for question 2 10 points

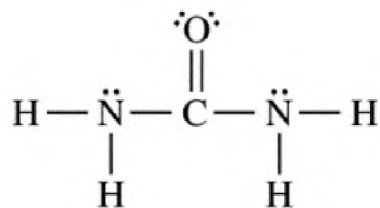
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Scoring Guidelines

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Question 1

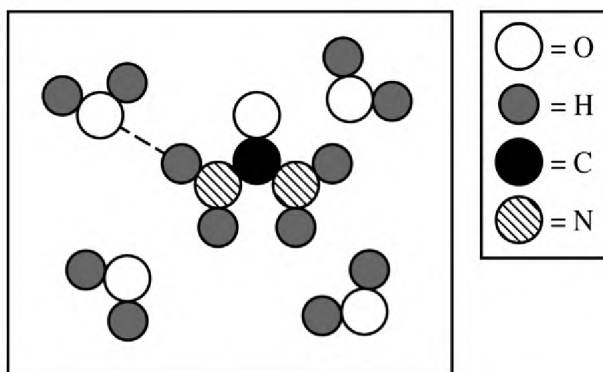


The compound urea, H_2NCONH_2 , is widely used in chemical fertilizers. The complete Lewis electron-dot diagram for the urea molecule is shown above.

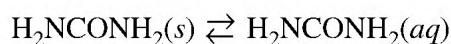
- (a) Identify the hybridization of the valence orbitals of the carbon atom in the urea molecule.

sp^2	1 point is earned for the correct answer.
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- (b) Urea has a high solubility in water, due in part to its ability to form hydrogen bonds. A urea molecule and four water molecules are represented in the box below. Draw ONE dashed line (----) to indicate a possible location of a hydrogen bond between a water molecule and the urea molecule.



A dashed line should connect a hydrogen atom in water to a nitrogen or oxygen atom in urea or an oxygen atom in water to a hydrogen atom in urea. One possible correct response is shown above.	1 point is earned for a correct answer.
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The dissolution of urea is represented by the equation above. A student determines that 5.39 grams of H_2NCONH_2 (molar mass 60.06 g/mol) can dissolve in water to make 5.00 mL of a saturated solution at 20.°C.

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Question 1 (continued)

- (c) Calculate the concentration of urea, in mol/L, in the saturated solution at 20.°C.

$5.39 \text{ g H}_2\text{NCONH}_2 \times \frac{1 \text{ mol}}{60.06 \text{ g}} = 0.0897 \text{ mol}$ $\frac{0.0897 \text{ mol}}{0.00500 \text{ L}} = 17.9 \text{ M}$	1 point is earned for the correct number of moles of urea (may be implicit). 1 point is earned for the correct molarity.
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- (d) The student also determines that the concentration of urea in a saturated solution at 25°C is 19.8 M. Based on this information, is the dissolution of urea endothermic or exothermic? Justify your answer in terms of Le Chatelier's principle.

The increased solubility at the higher temperature implies that the dissolution of urea is endothermic. If a saturated solution of urea is heated, then the equilibrium system is stressed. The stress is counteracted by the endothermic dissolution of more urea.	1 point is earned for the correct answer with an appropriate justification.
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Polystyrene Cup



Thermometer



Stirring Rod



Bottle of Urea



Balance



Distilled Water

- (e) The equipment shown above is provided so that the student can determine the value of the molar heat of solution for urea. Knowing that the specific heat of the solution is 4.18 J/(g·°C), list the specific measurements that are required to be made during the experiment.

mass of urea, mass of water, initial temperature of water, final temperature of solution	1 point is earned for the masses. 1 point is earned for the temperatures.
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Question 1 (continued)

	S° (J/(mol·K))
$\text{H}_2\text{NCONH}_2(s)$	104.6
$\text{H}_2\text{NCONH}_2(aq)$	?

- (f) The entropy change for the dissolution of urea, $\Delta S^\circ_{\text{soln}}$, is 70.1 J/(mol·K) at 25°C. Using the information in the table above, calculate the absolute molar entropy, S° , of aqueous urea.

$\Delta S^\circ_{\text{soln}} = S^\circ(\text{H}_2\text{NCONH}_2(aq)) - S^\circ(\text{H}_2\text{NCONH}_2(s))$ $70.1 \text{ J/(mol·K)} = S^\circ(\text{H}_2\text{NCONH}_2(aq)) - 104.6 \text{ J/(mol·K)}$ $S^\circ(\text{H}_2\text{NCONH}_2(aq)) = 174.7 \text{ J/(mol·K)}$	1 point is earned for the correct answer.
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- (g) Using particle-level reasoning, explain why $\Delta S^\circ_{\text{soln}}$ is positive for the dissolution of urea in water.

Urea molecules in solution have a greater number of possible arrangements than in solid urea. This increased number of arrangements corresponds to a positive $\Delta S^\circ_{\text{soln}}$.	1 point is earned for a correct explanation.
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- (h) The student claims that ΔS° for the process contributes to the thermodynamic favorability of the dissolution of urea at 25°C. Use the thermodynamic information above to support the student's claim.

Thermodynamic favorability for a process at standard conditions is determined by the sign of ΔG° , with $\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$. Since ΔS° is positive, the $T\Delta S^\circ$ term makes the value of ΔG° smaller and thus makes the dissolution more thermodynamically favorable.	1 point is earned for the correct answer.
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Question 2

Answer the following questions relating to the chemistry of the halogens.

- (a) The molecular formulas of diatomic bromine, chlorine, fluorine, and iodine are written below. Circle the formula of the molecule that has the longest bond length. Justify your choice in terms of atomic structure.



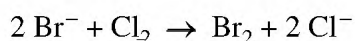
I_2 has the longest bond length because the radius of the I atom is greater than the radii of the other halogen atoms. Thus, the distance between the nuclei of atoms in I_2 is greater than it is in smaller halogens.

1 point is earned for circling I_2 and providing a valid explanation.

A chemistry teacher wants to prepare Br_2 . The teacher has access to the following three reagents: $\text{NaBr}(aq)$, $\text{Cl}_2(g)$, and $\text{I}_2(s)$.

Half-Reaction	E° at 25°C (V)
$\text{Br}_2 + 2 e^- \rightarrow 2 \text{Br}^-$	1.07
$\text{Cl}_2 + 2 e^- \rightarrow 2 \text{Cl}^-$	1.36
$\text{I}_2 + 2 e^- \rightarrow 2 \text{I}^-$	0.53

- (b) Using the data in the table above, write the balanced equation for the thermodynamically favorable reaction that will produce Br_2 when the teacher combines two of the reagents. Justify that the reaction is thermodynamically favorable by calculating the value of E° for the reaction.



$$E^\circ \equiv E^\circ(\text{reduced species}) - E^\circ(\text{oxidized species}) \\ = 1.36 \text{ V} - 1.07 \text{ V} = +0.29 \text{ V}.$$

Because E° for the reaction has a positive value, the reaction is thermodynamically favorable.

1 point is earned for the correct balanced equation.

1 point is earned for the correct calculation of E° .

Br_2 and Cl_2 can react to form the compound BrCl .

- (c) The boiling point of Br_2 is 332 K, whereas the boiling point of BrCl is 278 K. Explain this difference in boiling point in terms of all the intermolecular forces present between molecules of each substance.

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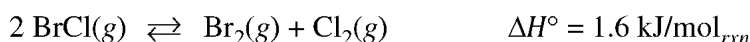
Question 2 (continued)

The only intermolecular attractions in $\text{Br}_2(l)$ are London forces, while those in $\text{BrCl}(l)$ include both London forces and dipole-dipole forces. However, due to the greater polarizability of the electron cloud of Br_2 compared to that of BrCl , the London forces in $\text{Br}_2(l)$ are stronger than the combined intermolecular forces in $\text{BrCl}(l)$. Thus, the boiling point of $\text{Br}_2(l)$ is greater than that of $\text{BrCl}(l)$.

1 point is earned for identifying the intermolecular forces in each substance.

1 point is earned for a valid explanation.

The compound BrCl can decompose into Br_2 and Cl_2 , as represented by the balanced chemical equation below.



A 0.100 mole sample of pure $\text{BrCl}(g)$ is placed in a previously evacuated, rigid 2.00 L container at 298 K. Eventually the system reaches equilibrium according to the equation above.

(d) Calculate the pressure in the container before equilibrium is established.

$$P = \frac{nRT}{V} = \frac{(0.100 \text{ mol})(0.08206 \text{ L atm mol}^{-1} \text{ K}^{-1})(298 \text{ K})}{2.00 \text{ L}} = 1.22 \text{ atm}$$

1 point is earned for a correct pressure with consistent units.

(e) Write the expression for the equilibrium constant, K_{eq} , for the decomposition of BrCl .

$$K_{eq} = \frac{[\text{Br}_2][\text{Cl}_2]}{[\text{BrCl}]^2} \quad \text{or} \quad K_{eq} = \frac{P_{\text{Br}_2} P_{\text{Cl}_2}}{(P_{\text{BrCl}})^2}$$

1 point is earned for a correct equilibrium expression.

After the system has reached equilibrium, 42 percent of the original BrCl sample has decomposed.

(f) Determine the value of K_{eq} for the decomposition reaction of BrCl at 298 K.



I	1.22	0	0
C	$-2x$	$+x$	$+x$
E	0.71	0.26	0.26

$$P_{\text{BrCl decomposed}} = (0.42)(1.22 \text{ atm}) = 0.51 \text{ atm}$$

$$2x = 0.51 \text{ atm} \Rightarrow x = 0.26 \text{ atm}$$

$$K_{eq} = \frac{(0.26)(0.26)}{(0.71)^2} = 0.13$$

Note: The solution is in terms of pressures. Solutions in terms of molar concentrations also earn full credit.

1 point is earned for correct stoichiometric values at equilibrium.

1 point is earned for a consistent value of K_{eq} .

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Question 2 (continued)

Calculate the bond energy of the Br-Cl bond, in kJ/mol, using ΔH° for the reaction (1.6 kJ/mol information in the following table).

Bond	Bond Energy (kJ/mol)
Br – Br	193
Cl – Cl	243
Br – Cl	?

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

$$-136 \text{ kJ/mol} = 2(\text{Br-Cl bond energy}) - (193 \text{ kJ/mol} + 243 \text{ kJ/mol})$$

$$-136 + 1.6 \text{ kJ/mol} = 2(\text{Br-Cl bond energy})$$

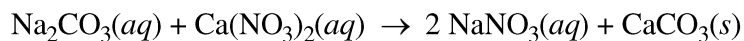
$$\text{Br-Cl bond energy} = 219 \text{ kJ/mol}$$

1 point is earned for a correct calculation of the Br-Cl bond energy.

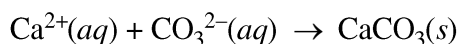
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Question 3

A student is given 50.0 mL of a solution of Na_2CO_3 of unknown concentration. To determine the concentration of the solution, the student mixes the solution with excess 1.0 M $\text{Ca}(\text{NO}_3)_2(aq)$, causing a precipitate to form. The balanced equation for the reaction is shown below.

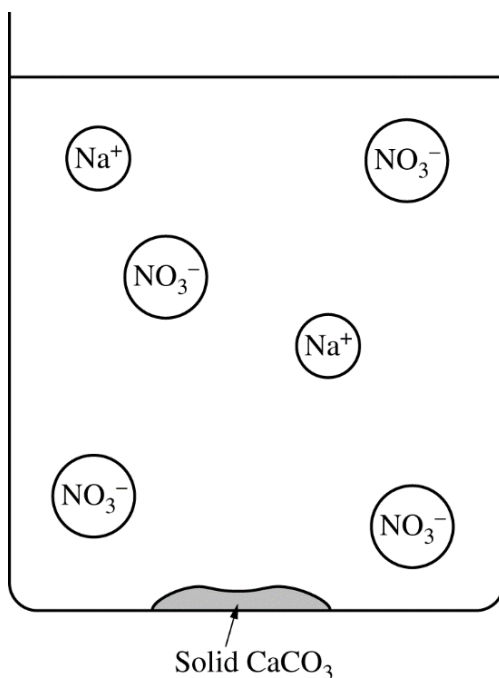


Write the net ionic equation for the reaction that occurs when the solutions of Na_2CO_3 and $\text{Ca}(\text{NO}_3)_2$ are mixed.



1 point is earned for the correct equation.

The diagram below is incomplete. Draw in the species needed to accurately represent the major ionic species remaining in the solution after the reaction has been completed.



The drawing shows one Ca^{2+} ion.

1 point is earned for drawing a Ca^{2+} ion.

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Question 3 (continued)

The student filters and dries the precipitate of CaCO_3 (molar mass 100.1 g/mol) and records the data in the table below.

Volume of Na_2CO_3 solution	50.0 mL
Volume of 1.0 M $\text{Ca}(\text{NO}_3)_2$ added	100.0 mL
Mass of CaCO_3 precipitate collected	0.93 g

Determine the number of moles of Na_2CO_3 in the original 50.0 mL of solution.

$0.93 \text{ g CaCO}_3 \times \frac{1 \text{ mol CaCO}_3}{100.1 \text{ g}} = 0.0093 \text{ mol CaCO}_3$ $0.0093 \text{ mol CaCO}_3 \times \frac{1 \text{ mol Na}_2\text{CO}_3}{1 \text{ mol CaCO}_3} = 0.0093 \text{ mol Na}_2\text{CO}_3$	1 point is earned for the correct answer.
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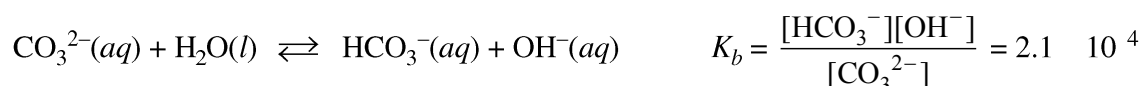
The student realizes that the precipitate was not completely dried and claims that as a result, the calculated Na_2CO_3 molarity is too low. Do you agree with the student's claim? Justify your answer.

Disagree. The presence of water in the solid will cause the measured mass of the precipitate to be greater than the actual mass of CaCO_3 . As a result, the calculated number of moles of CaCO_3 and moles of Na_2CO_3 will be greater than the actual moles present. Therefore the calculated concentration of $\text{Na}_2\text{CO}_3(aq)$ will be too high.	1 point is earned for the correct answer with valid justification.
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After the precipitate forms and is filtered, the liquid that passed through the filter is tested to see if it can conduct electricity. What would be observed? Justify your answer.

The liquid conducts electricity because ions ($\text{Na}^+(aq)$, aq), and $\text{NO}_3^-(aq)$) are present in the solution.	1 point is earned for the correct answer with valid justification.
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The student decides to determine the molarity of the same Na_2CO_3 solution using a second method. When is dissolved in water, $\text{CO}_3^{2-}(aq)$ hydrolyzes to form $\text{HCO}_3^-(aq)$, as shown by the following equation.



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Question 3 (continued)

The student decides to first determine $[\text{OH}^-]$ in the solution, then use that result to calculate the initial concentration of $\text{CO}_3^{2-}(\text{aq})$.

- (i) Identify a laboratory method (not titration) that the student could use to collect data to determine $[\text{OH}^-]$ in the solution.

Determine the pH of the solution using a pH meter.

1 point is earned for identifying a valid method.

- (ii) Explain how the student could use the measured value in part (f)(i) to calculate the initial concentration of $\text{CO}_3^{2-}(\text{aq})$. (Do not do any numerical calculations.)

First determine $[\text{OH}^-]$ using $\text{pOH} = 14 - \text{pH}$, then $[\text{OH}^-] = 10^{-\text{pOH}}$.

use the K_b expression and an ICE table (see example below) to determine $[\text{CO}_3^{2-}]$ and $[\text{HCO}_3^-]$ at equilibrium. The initial concentration of CO_3^{2-} , c_i , is equal to the sum of the equilibrium concentrations of CO_3^{2-} and HCO_3^- .

	$\text{CO}_3^{2-}(\text{aq}) + \text{H}_2\text{O}(\text{l})$	$\rightleftharpoons$	$\text{HCO}_3^-(\text{aq}) + \text{OH}^-(\text{aq})$
	c_i	---	0
	$-x$	---	$+x$
	$c_i - x$	---	x

$$K_b = \frac{(x)(x)}{c_i - x} \Rightarrow c_i = \frac{(x)(x)}{K_b} + x$$

1 point is earned for a valid method of determining $[\text{OH}^-]$ from the measured value.

1 point is earned for a valid method of determining the initial concentration of CO_3^{2-} .

In the original Na_2CO_3 solution at equilibrium, is the concentration of $\text{HCO}_3^-(\text{aq})$ greater than, less than, or equal to the concentration of $\text{CO}_3^{2-}(\text{aq})$? Justify your answer.

Less than. The small value of K_b , 2.1×10^{-4} , indicates the reactants are favored.

1 point is earned for the correct answer with a valid justification.

The student needs to make a $\text{CO}_3^{2-}/\text{HCO}_3^-$ buffer. Is the Na_2CO_3 solution suitable for making a buffer with a pH of 6? Explain why or why not.

The Na_2CO_3 solution is not suitable. The $\text{p}K_a$ of HCO_3^- is 10.32. Buffers are effective when the required pH is approximately equal to the $\text{p}K_a$ of the weak acid. An acid with a $\text{p}K_a$ of 10.32 is not appropriate to prepare a buffer with a pH of 6.

1 point is earned for the correct answer with a valid explanation.

2019 SCORING GUIDELINES

Question 4

A student is doing experiments with $\text{CO}_2(\text{g})$. Originally, a sample of the gas is in a rigid container at 299 K and 0.70 atm. The student increases the temperature of the $\text{CO}_2(\text{g})$ in the container to 425 K.

Describe the effect of raising the temperature on the motion of the $\text{CO}_2(\text{g})$ molecules.

the average speed of the molecules increases as temperature increases.	1 point is earned for the correct answer.
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Calculate the pressure of the $\text{CO}_2(\text{g})$ in the container at 425 K.

Both the volume and the number of molecules are constant, therefore $\frac{P_1}{T_1} = \frac{P_2}{T_2} \quad \Rightarrow \quad \frac{0.70 \text{ atm}}{299 \text{ K}} = \frac{P_2}{425 \text{ K}} \quad \Rightarrow \quad P_2 = 0.99 \text{ atm}$	1 point is earned for the correct answer.
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In terms of kinetic molecular theory, briefly explain why the pressure of the $\text{CO}_2(\text{g})$ in the container changes as it is heated to 425 K.

Faster-moving gas particles collide more frequently with the walls of the container, thus increasing the pressure. Faster-moving gas particles collide more forcefully with the walls of the container, thus increasing the pressure.	1 point is earned for a correct explanation.
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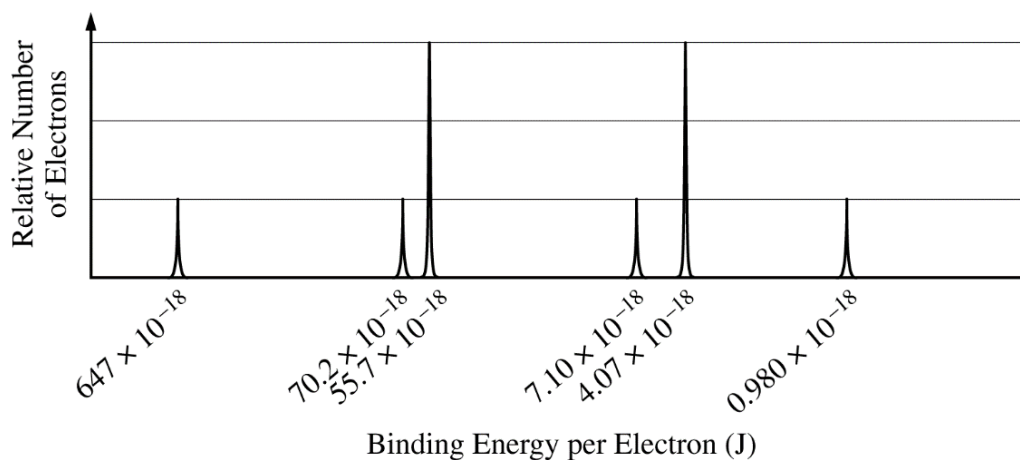
The student measures the actual pressure of the $\text{CO}_2(\text{g})$ in the container at 425 K and observes that it is less than the pressure predicted by the ideal gas law. Explain this observation.

The attractive forces between CO_2 molecules result in a pressure that is lower than that predicted by the ideal gas law.	1 point is earned for a correct explanation.
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2019 SCORING GUIDELINES

Question 5

The complete photoelectron spectrum of an element in its ground state is represented below.



Based on the spectrum,

(i) write the ground-state electron configuration of the element, and

$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2$ or $[\text{Ar}] 4s^2$	1 point is earned for the correct answer.
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(ii) identify the element.

Ca	1 point is earned for the correct answer.
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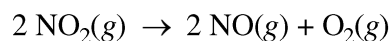
Calculate the wavelength, in meters, of electromagnetic radiation needed to remove an electron from the valence shell of an atom of the element.

Energy (E) required = $0.980 \times 10^{-18} \text{ J}$ $E = h\nu = \frac{hc}{\lambda} \Rightarrow \lambda = \frac{hc}{E}$ $\lambda = \frac{(6.626 \times 10^{-34} \text{ Js})(2.998 \times 10^8 \text{ ms}^{-1})}{0.980 \times 10^{-18} \text{ J}}$ $\lambda = 2.03 \times 10^{-7} \text{ m}$	1 point is earned for the correct identification of the energy required to remove an electron from the valence shell (may be implicit). 1 point is earned for calculating the correct wavelength.
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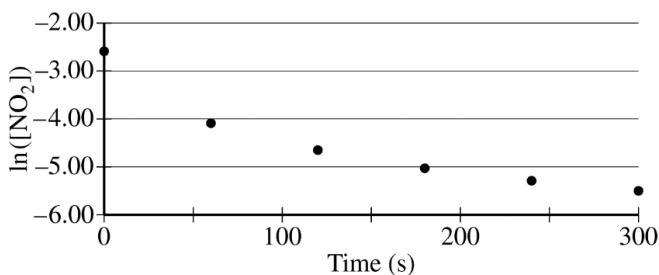
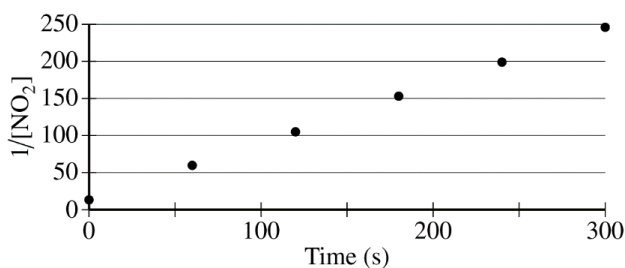
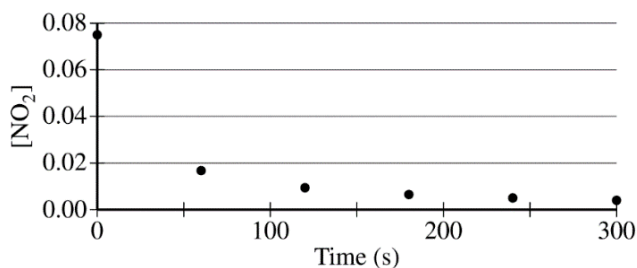
2019 SCORING GUIDELINES

Question 6

Nitrogen dioxide, $\text{NO}_2(g)$, is produced as a byproduct of the combustion of fossil fuels in internal combustion engines. At elevated temperatures $\text{NO}_2(g)$ decomposes according to the equation below.



The concentration of a sample of $\text{NO}_2(g)$ is monitored as it decomposes and is recorded on the graph directly below. The two graphs that follow it are derived from the original data.



Explain how the graphs indicate that the reaction is second order.

The linear graph of $\frac{1}{[\text{NO}_2]}$ vs. time indicates a second-order reaction.

1 point is earned for the correct answer.

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Question 6 (continued)

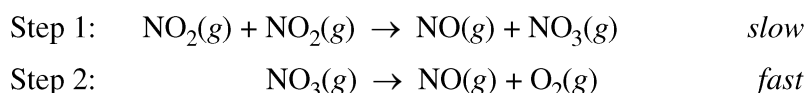
Write the rate law for the decomposition of $\text{NO}_2(g)$.

rate = $k[\text{NO}_2]^2$	1 point is earned for the correct answer.
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Consider two possible mechanisms for the decomposition reaction.

- (i) Is the rate law described by mechanism I shown below consistent with the rate law you wrote in part (b)? Justify your answer.

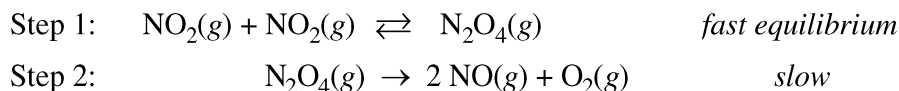
Mechanism I



Step 1 is slow, therefore it is the rate-determining step of this mechanism. The rate law of this elementary reaction is rate = $k[\text{NO}_2][\text{NO}_2] = k[\text{NO}_2]^2$, which is consistent with the second-order rate law in part (b).	1 point is earned for the correct answer with justification.
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- (ii) Is the rate law described by mechanism II shown below consistent with the rate law you wrote in part (b)? Justify your answer.

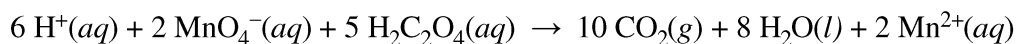
Mechanism II



Step 2 is slow; therefore, it is the rate-determining step of this mechanism. The rate law of this elementary reaction is rate = $k[\text{N}_2\text{O}_4]$. Because N_2O_4 is an intermediate, it cannot appear in the rate law of the overall reaction. Because $K_{eq} = \frac{[\text{N}_2\text{O}_4]}{[\text{NO}_2]^2}$ in step 1, $[\text{N}_2\text{O}_4] = K_{eq}[\text{NO}_2]^2$. Then, substituting $K_{eq}[\text{NO}_2]^2$ for $[\text{N}_2\text{O}_4]$ in the rate law of step 2 gives rate = $(k K_{eq})[\text{NO}_2]^2$, which is consistent with the rate law in part (b).	1 point is earned for the correct answer with justification.
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2019 SCORING GUIDELINES

Question 7



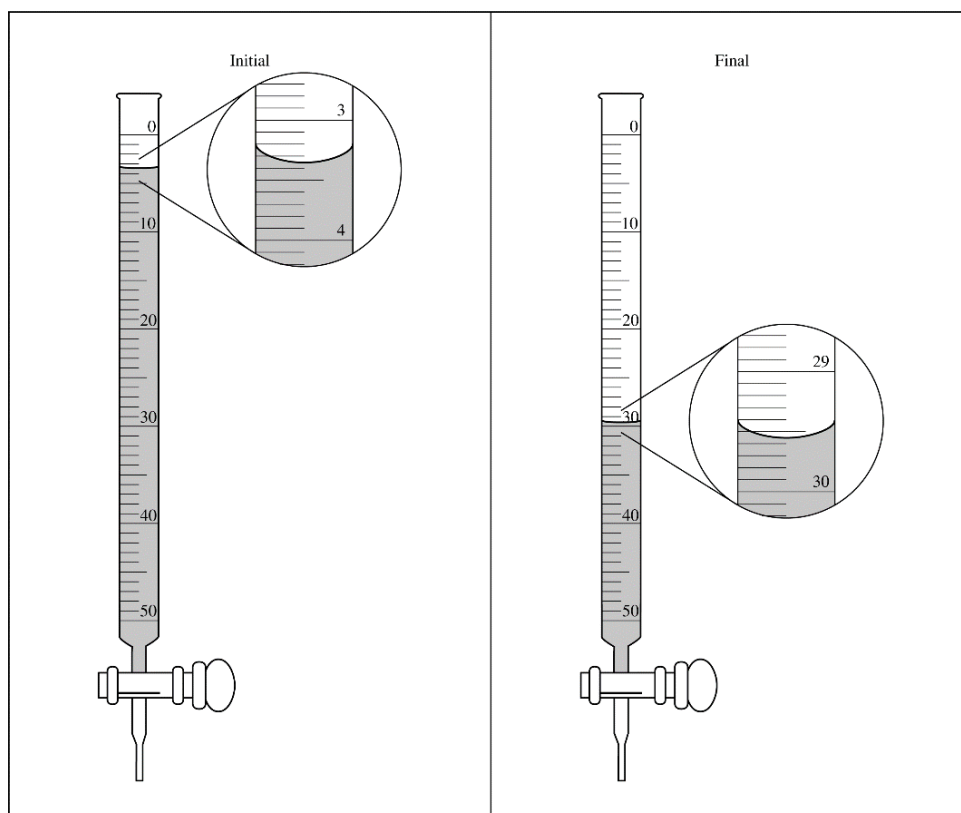
A student dissolved a 0.139 g sample of oxalic acid, $\text{H}_2\text{C}_2\text{O}_4$, in water in an Erlenmeyer flask. Then the student titrated the $\text{H}_2\text{C}_2\text{O}_4$ solution in the flask with a solution of KMnO_4 , which has a dark purple color. The balanced chemical equation for the reaction that occurred during the titration is shown above.

Identify the species that was reduced in the titration reaction. Justify your answer in terms of oxidation numbers.

MnO_4^- is reduced to Mn^{2+} as the oxidation number of Mn changes from +7 to +2, indicating a gain of 5 electrons.

1 point is earned for the correct answer with justification.

The student used a 50.0 mL buret to add the $\text{KMnO}_4(aq)$ to the $\text{H}_2\text{C}_2\text{O}_4(aq)$ until a faint lavender color was observed in the flask, an indication that the end point of the titration had been reached. The initial and final volume readings of the solution in the buret are shown below. Write down the initial reading and the final reading and use them to determine the volume of $\text{KMnO}_4(aq)$ that was added during the titration.



$$29.55 \text{ mL} - 3.35 \text{ mL} = 26.20 \text{ mL}$$

1 point is earned for the correct answer.

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Question 7 (continued)

Given that the concentration of $\text{KMnO}_4(aq)$ was 0.0235 M , calculate the number of moles of MnO^- ions that completely reacted with the $\text{H}_2\text{C}_2\text{O}_4$.

$$(0.02620\text{ L})(0.0235\text{ mol/L}) = 0.000616\text{ mol}$$

1 point is earned for the correct answer.

The student proposes to perform another titration using a 0.139 g sample of $\text{H}_2\text{C}_2\text{O}_4$, but this time using 0.00143 M $\text{KMnO}_4(aq)$ in the buret. Would this titrant concentration be a reasonable choice to use if the student followed the same procedure and used the same equipment as before? Justify your response.

No. The 0.00143 M titrant solution is so diluted that volume of titrant needed to reach the end point would be much greater than the 50 mL capacity of the buret.

1 point is earned for the correct answer with appropriate justification.

2018

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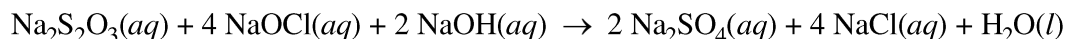
CollegeBoard

AP Chemistry

Scoring Guidelines

2018 SCORING GUIDELINES

Question 1



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

Determine the oxidation number of Cl in NaOCl.

+1	1 point is earned for the correct answer.
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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 $\text{Na}_2\text{S}_2\text{O}_3$.

$100.00 \text{ mL} \times \frac{0.500 \text{ mol Na}_2\text{S}_2\text{O}_3}{1000 \text{ mL}} \times \frac{158.10 \text{ g Na}_2\text{S}_2\text{O}_3}{1 \text{ mol Na}_2\text{S}_2\text{O}_3}$ $= 7.90 \text{ g Na}_2\text{S}_2\text{O}_3$	1 point is earned for the 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.
---	---

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

Solution	Concentration (M)	Volume (mL)
$\text{Na}_2\text{S}_2\text{O}_3(aq)$	0.500	5.00
$\text{NaOCl}(aq)$	0.500	5.00
$\text{NaOH}(aq)$	0.500	5.00

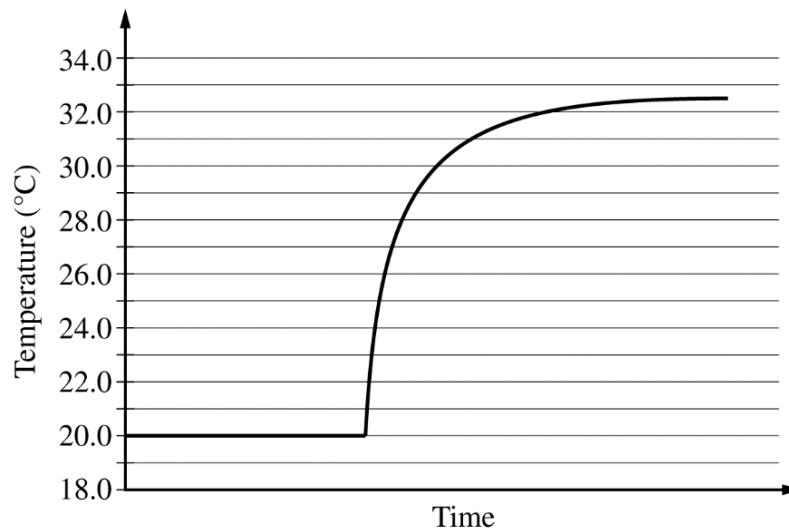
Using the balanced equation for the oxidation-reduction reaction and the information in the table above, determine which reactant is the limiting reactant. Justify your answer.

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 limiting reactant <u>and</u> providing a valid justification.
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2018 SCORING GUIDELINES

Question 1 (continued)

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.



According to the graph, what is the temperature change of the reaction mixture?

From the graph the final temperature is 32.5°C. $\Delta = T_f - T_i = 32.5^\circ\text{C} - 20.0^\circ\text{C} = 12.5^\circ\text{C}$	1 point is earned for the correct value Δ
--	--

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.

$q = mc\Delta T$ $= (15.21 \text{ g})(3.94 \text{ J/(g}\cdot^\circ\text{C)})(12.5^\circ\text{C}) = 749 \text{ J}$	1 point is earned for the correct calculation q consistent with the ΔT value from part (i)
--	--

- (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, $\Delta H_{\text{rxn}}^\circ$, in kJ/mol_{rxn}. Include the appropriate algebraic sign with your answer.

2018 SCORING GUIDELINES

Question 1 (continued)

$\text{NaOCl} = 5.00 \text{ mL} \times \frac{0.500 \text{ mol NaOCl}}{1000 \text{ mL NaOCl}} = 0.00250 \text{ mol NaOCl}$ $= 0.00250 \text{ mol NaOCl} \times \frac{1 \text{ mol}_{rxn}}{4 \text{ mol NaOCl}} = 0.000625 \text{ mol}_{rxn}$ $\Delta H_{rxn}^{\circ} = \frac{-0.749 \text{ kJ}}{0.000625 \text{ mol}_{rxn}} = -1.20 \times 10^3 \text{ kJ/mol}_{rxn}$	1 point is earned for correctly calculating the value of mol consistent with the limiting reactant in part 1 point is earned for a negative ΔH_{rxn}° obtained by dividing the calculated value of q by the calculated value of mol
--	--

→ student repeats the experiment, but this time doubling the volume of each of the reactants, as shown in the table below.

Solution	Concentration (M)	Volume (mL)
$\text{Na}_2\text{S}_2\text{O}_3(aq)$	0.500	10.0
$\text{NaOCl}(aq)$	0.500	10.0
$\text{NaOH}(aq)$	0.500	10.0

The magnitude of the enthalpy change, ΔH_{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.

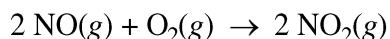
By doubling the volumes, the number of moles of the reactants are doubled, which doubles the amount of energy produced. Therefore the amount of heat per mole will remain the same. OR In the second experiment, $\Delta H_{rxn}^{\circ} = \frac{2mc\Delta T}{2n} = \frac{mc\Delta T}{n} = \Delta H_{rxn}^{\circ}$. Thus the magnitude is the same as calculated in the first experiment.	1 point is earned for valid explanation.
--	---

Write the balanced net ionic equation for the given reaction.

$\text{S}_3^{2-}(aq) + 4 \text{ OCl}^{-}(aq) + 2 \text{ OH}^{-}(aq) \rightarrow 2 \text{ SO}_4^{2-}(aq) + 4 \text{ Cl}^{-}(aq) + \text{H}_2\text{O}(l)$	1 point is earned for the correct net ionic equation.
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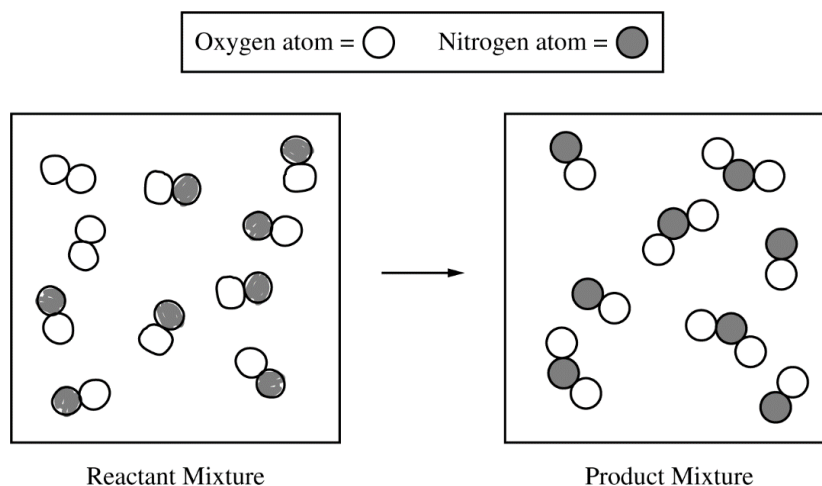
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Question 2



A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $\text{NO}(g)$ and $\text{NO}_2(g)$, which the student produces by using the reaction represented above.

- (The particle-level representation of the equimolar mixture of $\text{NO}(g)$ and $\text{NO}_2(g)$ in the flask at the completion of the reaction between $\text{NO}(g)$ and $\text{O}_2(g)$ 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 $\text{NO}(g)$ and O_2 would yield the product mixture shown in the box on the right. In your drawing, represent oxygen atoms and nitrogen atoms as indicated below.

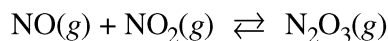


See sample student response above.
(8 molecules of NO and 2 molecules of O_2)

1 point is earned for correctly
representing molecules of NO and O

1 point is earned for correctly
representing atom conservation.

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



ΔH_{298}°	ΔS_{298}°	ΔG_{298}°
$-40.4 \text{ kJ/mol}_{\text{rxn}}$	$-138.5 \text{ J/(K}\cdot\text{mol}_{\text{rxn}})$	$0.87 \text{ kJ/mol}_{\text{rxn}}$

2018 SCORING GUIDELINES

Question 2 (continued)

The student begins with an equimolar mixture of $\text{NO}(g)$ and $\text{NO}_2(g)$ 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 .
--	--

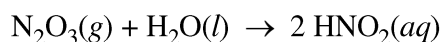
(ii) If both P_{NO} and P_{NO_2} in the vessel are initially 1.0 atm, will $P_{\text{N}_2\text{O}_3}$ at equilibrium be equal to 1.0 atm? Justify your answer.

No, the pressure will not equal 1.0 atm. $P_{\text{N}_2\text{O}_3}$ would only equal 1.0 atm if the reaction goes to completion. 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
---	--

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.

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 <u>and</u> a correct justification.
---	--

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.



2018 SCORING GUIDELINES

Question 2 (continued)

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.

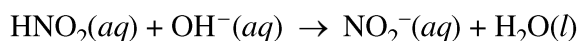


See sample response above. (Line segments can be used to represent electron pairs.)	1 point is earned for a valid diagram.
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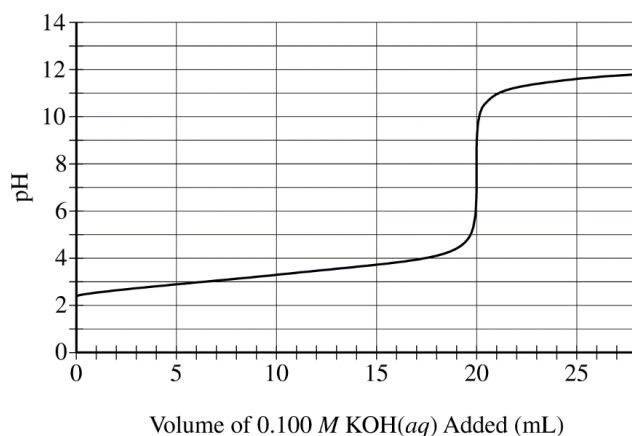
- (ii) Based on your completed diagram above, identify the hybridization of the nitrogen atom in the HNO_2 molecule.

sp^2	1 point is earned for the correct answer.
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To produce an aqueous solution of HNO_2 , the student bubbles $\text{N}_2\text{O}_3(g)$ into distilled water. Assume that the reaction goes to completion and that HNO_2 is the only species produced. To determine the concentration of $\text{HNO}_2(aq)$ in the resulting solution, the student titrates a 100. mL sample of the solution with 0.100 $\text{KOH}(aq)$. The neutralization reaction is represented below.



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



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Question 2 (continued)

Use the titration curve and the information above to

- (i) determine the initial concentration of the $\text{HNO}_2(aq)$ solution

$\text{mL KOH} \times \frac{0.100 \text{ mol KOH}}{1000 \text{ mL KOH}} = 0.0020 \text{ mol KOH added}$ $\Rightarrow 0.0020 \text{ mol HNO}_2 \text{ in } 100. \text{ mL of solution because the stoichiometry of the neutralization reaction is 1 to 1.}$ $\frac{0.0020 \text{ mol HNO}_2}{0.100 \text{ L}} = 0.020 \text{ M HNO}_2$	1 point is earned for the correct calculation of the initial concentration.
---	--

- (ii) estimate the value of $\text{p}K_a$ for $\text{HNO}_2(aq)$

The value of $\text{p}K_a$ is about 3.4.	1 point is earned for an acceptable estimate for the value of $\text{p}K_a$.
--	---

During the titration, after a volume of 15 mL of 0.100 M $\text{KOH}(aq)$ has been added, which species, $\text{HNO}_2(aq)$ or $\text{NO}_2^-(aq)$, is present at a higher concentration in the solution? Justify your answer.

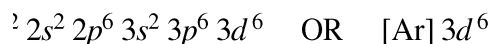
(aq) The titration is past the half-equivalence point; therefore, there will be more conjugate base present than acid.	1 point is earned for the correct choice <u>and</u> a valid justification.
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2018 SCORING GUIDELINES

Question 3

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

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



1 point is earned for a correct electron configuration.

Ion	Ionic Radius (pm)
Fe^{2+}	92
Fe^{3+}	79

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.

Both ions have the same nuclear charge; however, the greater number of electrons in the outermost shell of Fe^{2+} results in greater electron-electron repulsion within that shell, leading to a larger radius.

1 point is earned for a valid explanation.

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.

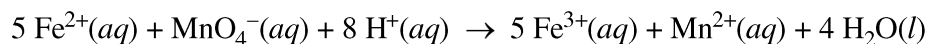
Coulomb's law: $F \propto \frac{q_1 q_2}{r^2}$ (need not be explicitly stated)

In comparison to the Fe^{2+} ion, the Fe^{3+} ion has a higher charge.

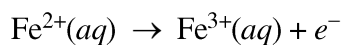
The smaller size of Fe^{3+} allows it to get closer to a water molecule.

1 point is earned for a valid explanation.

A student obtains a solution that contains an unknown concentration of $\text{Fe}^{2+}(aq)$. To determine the concentration of $\text{Fe}^{2+}(aq)$ in the solution, the student titrates a sample of the solution with MnO_4^- (which converts $\text{Fe}^{2+}(aq)$ to $\text{Fe}^{3+}(aq)$), as represented by the following equation.



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



1 point is earned for the correct half-reaction.

2018 SCORING GUIDELINES

Question 3 (continued)

The student titrates a 10.0 mL sample of the $\text{Fe}^{2+}(\text{aq})$ solution. Calculate the value of $[\text{Fe}^{2+}]$ in solution if it takes 17.48 mL of added $0.0350\text{ M KMnO}_4(\text{aq})$ to reach the equivalence point of the titration.

$17.48\text{ mL} \times \frac{0.0350\text{ mol KMnO}_4}{1000\text{ mL}} = 0.000612\text{ mol KMnO}_4$ $0.000612\text{ mol KMnO}_4 \times \frac{5\text{ mol Fe}^{2+}}{1\text{ mol KMnO}_4} = 0.003059\text{ mol Fe}^{2+}$ $\frac{0.003059\text{ mol Fe}^{2+}}{0.0100\text{ L}} = 0.306\text{ M Fe}^{2+}$	1 point is earned for calculating the number of moles of KMnO_4 (may be implicit). 1 point is earned for the correct concentration of Fe^{2+}.
---	--

To deliver the 10.0 mL sample of the $\text{Fe}^{2+}(\text{aq})$ 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

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

The volumetric flask is designed to contain only 25.00 mL precisely.	1 point is earned for a valid explanation.
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2018 SCORING GUIDELINES

Question 3 (continued)

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.

Mass of Fe(s) with inert impurity	6.724 g
Mass of Fe ₂ O ₃ (s) produced	7.531 g

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

$7.531 \text{ g Fe}_2\text{O}_3 \times \frac{1 \text{ mol Fe}_2\text{O}_3}{159.70 \text{ g Fe}_2\text{O}_3} = 0.04716 \text{ mol Fe}_2\text{O}_3$ $0.04716 \text{ mol Fe}_2\text{O}_3 \times \frac{2 \text{ mol Fe}}{1 \text{ mol Fe}_2\text{O}_3} = 0.09431 \text{ mol Fe}$	1 point is earned for correct calculation.
--	--

Calculate the percent by mass of Fe in the original sample of powdered Fe(s) with the inert impurity.

$0.09431 \text{ mol Fe} \times \frac{55.85 \text{ g Fe}}{1 \text{ mol}} = 5.267 \text{ g Fe}$ $\frac{5.267 \text{ g Fe}}{6.724 \text{ g sample}} \times 100 = 78.33\%$	1 point is earned for correct calculation of the mass percent based on the answer to part (g).
--	--

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.

The calculated mass percent of Fe would be lower than the actual mass percent of Fe. A sample that contains any FeO (rather than Fe₂O₃) will have a lower <u>actual</u> 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 Fe₂O₃) the <u>calculated</u> number of moles of Fe, and hence the <u>calculated</u> mass percent of Fe, will be lower.	1 point is earned for the correct answer and a valid explanation.
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2018 SCORING GUIDELINES

Question 4

Sulfur atom =  Carbon atom =  Oxygen atom = 

Compound	Molecular Structure	Boiling Point at 1 atm (K)
CS ₂		319
COS		223

The table above gives the molecular structures and boiling points for the compounds CS₂ and COS.

In terms of the types and relative strengths of all the intermolecular forces in each compound, explain why the boiling point of CS₂(*l*) is higher than that of COS(*l*).

has only London dispersion forces, while COS has London dispersion forces and dipole-dipole forces.

The London dispersion forces in CS₂ are stronger than the combination of London dispersion forces and dipole-dipole forces in COS.

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

1 point is earned for a valid explanation.

A 10.0 g sample of CS₂(*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 CS₂(*l*) has vaporized. What is the pressure in the container once all of the CS₂(*l*) has vaporized?

$$10.0 \text{ g CS}_2 \times \frac{1 \text{ mol CS}_2}{76.13 \text{ g CS}_2} = 0.131 \text{ mol CS}_2$$

$$: \frac{nRT}{V} = \frac{(0.131 \text{ mol})(0.08206 \text{ L atm mol}^{-1} \text{ K}^{-1})(325 \text{ K})}{5.0 \text{ L}}$$

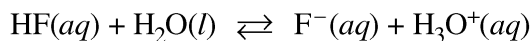
$$= 0.70 \text{ atm}$$

1 point is earned for the correct number of moles of

1 point is earned for the correct calculation of pressure with appropriate units.

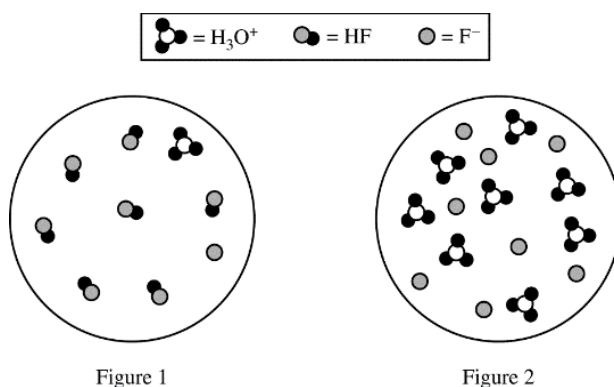
2018 SCORING GUIDELINES

Question 5



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

Two particulate representations of the ionization of HF molecules in the 0.0350 M $\text{HF}(aq)$ solution 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.)



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Question 5 (continued)

If 50.0 mL of distilled water is added to 50.0 mL of 0.035 M HF(aq), will the percent ionization 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,

$$\frac{(\frac{1}{2}[\text{H}_3\text{O}^+]_i)(\frac{1}{2}[\text{F}^-]_i)}{\frac{1}{2}[\text{HF}]_i} = \frac{1}{2}K_a \Rightarrow Q < K_a.$$

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

New volume = twice original volume, thus new $[\text{HF}]_i = \frac{0.035}{2} = 0.0175 M$

$$= \frac{[\text{H}_3\text{O}^+][\text{F}^-]}{[\text{HF}]} = 6.81 \times 10^{-4} \text{ (value from part (b))}$$

Let $[\text{H}_3\text{O}^+] = [\text{F}^-] = x$

$$\text{Then } 6.81 \times 10^{-4} = \frac{(x)(x)}{(0.0175 - x)} \approx \frac{x^2}{(0.0175)} \Rightarrow x \approx 0.00345 M$$

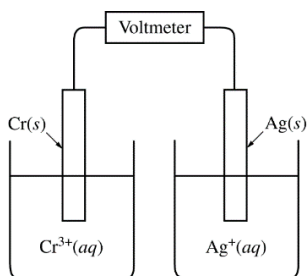
$$\text{Percent ionization} = \frac{0.00345 M}{0.0175 M} \times 100 = 20.0\%$$

$\% > 13.0\%$; therefore, the percent ionization increases.

1 point is earned for correct answer
valid explanation or calculation.

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Question 6



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.

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.

A 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.

Half-Reaction	E° (V)
$\text{Ag}^+(aq) + e^- \rightarrow \text{Ag}(s)$	+ 0.80
$\text{Cr}^{3+}(aq) + 3 e^- \rightarrow \text{Cr}(s)$	?

The student adds the missing component to the cell and measures E°_{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° for the half-reaction $\text{Cr}^{3+}(aq) + 3 e^- \rightarrow \text{Cr}(s)$.

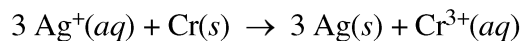
$$E^\circ_{\text{cell}} = E^\circ_{\text{red}}(\text{cathode}) - E^\circ_{\text{red}}(\text{anode})$$

$$+1.54 \text{ V} = +0.80 \text{ V} - x$$

$$= +0.80 \text{ V} - (+1.54 \text{ V}) = -0.74 \text{ V}$$

1 point is earned for a correct calculation of E°_{red} .

(ii) Write the balanced net-ionic equation for the overall reaction that occurs as the cell operates.



1 point is earned for the correctly balanced equation.

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Question 6 (continued)

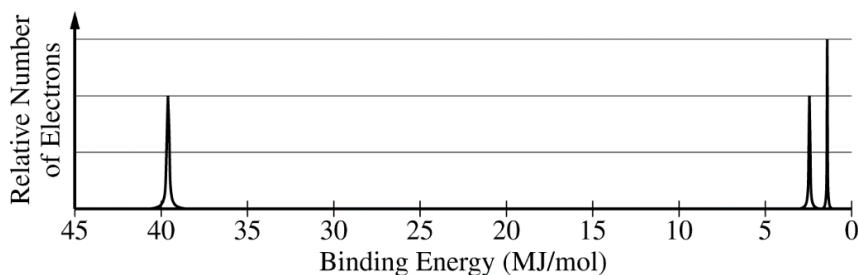
(iii) Calculate the value of ΔG° for the overall cell reaction in $\text{J/mol}_{\text{rxn}}$.

$$\begin{aligned}\Delta G^\circ &= -nFE^\circ = -\left(\frac{3 \text{ mol } e^-}{1 \text{ mol}_{\text{rxn}}}\right)\left(96,485 \frac{\text{C}}{\text{mol } e^-}\right)\left(1.54 \frac{\text{J}}{\text{C}}\right) \\ &= -4.46 \times 10^5 \text{ J/mol}_{\text{rxn}}\end{aligned}$$

1 point is earned for the correct calculation of the value of Δ

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Question 7



The complete photoelectron spectrum of an element is represented above.

Identify the element.

The element is nitrogen, N.	1 point is earned for correctly identifying the element.
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A radioactive isotope of the element decays with a half-life of 10. minutes.

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

$k = \frac{0.693}{t_{1/2}} = \frac{0.693}{10. \text{ min}} = 0.069 \text{ min}^{-1}$	1 point is earned for the correct numerical answer. 1 point is earned for the correct unit.
--	---

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.

$64 \rightarrow 32 \rightarrow 16 \rightarrow 8 \rightarrow 4 \rightarrow 2 \rightarrow 1$ 6 half-lives are required. $6 \times 10. \text{ min} = 60. \text{ min}$ 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 <u>and</u> a valid method.
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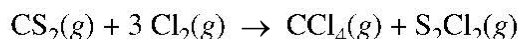
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AP Chemistry

Scoring Guidelines

2017 SCORING GUIDELINES

Question 1



Carbon tetrachloride, $\text{CCl}_4(g)$, can be synthesized according to the reaction represented above. A chemist runs the reaction at a constant temperature of 120°C in a rigid 25.0 L container.

(a) Chlorine gas, $\text{Cl}_2(g)$, is initially present in the container at a pressure of 0.40 atm.

(i) How many moles of $\text{Cl}_2(g)$ are in the container?

$n = \frac{PV}{RT} = \frac{0.40 \text{ atm} \times 25.0 \text{ L}}{0.08206 \text{ (L} \cdot \text{atm)} / (\text{mol} \cdot \text{K}) \times 393 \text{ K}} = 0.31 \text{ mol Cl}_2(g)$	1 point is earned for the correct answer with supporting work.
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(ii) How many grams of carbon disulfide, $\text{CS}_2(g)$, are needed to react completely with the $\text{Cl}_2(g)$?

$0.31 \text{ mol Cl}_2 \times \frac{1 \text{ mol CS}_2}{3 \text{ mol Cl}_2} \times \frac{76.13 \text{ g CS}_2}{1 \text{ mol CS}_2} = 7.9 \text{ g CS}_2$	1 point is earned for using the correct mole ratio (may be implicit). 1 point is earned for the mass of CS_2.
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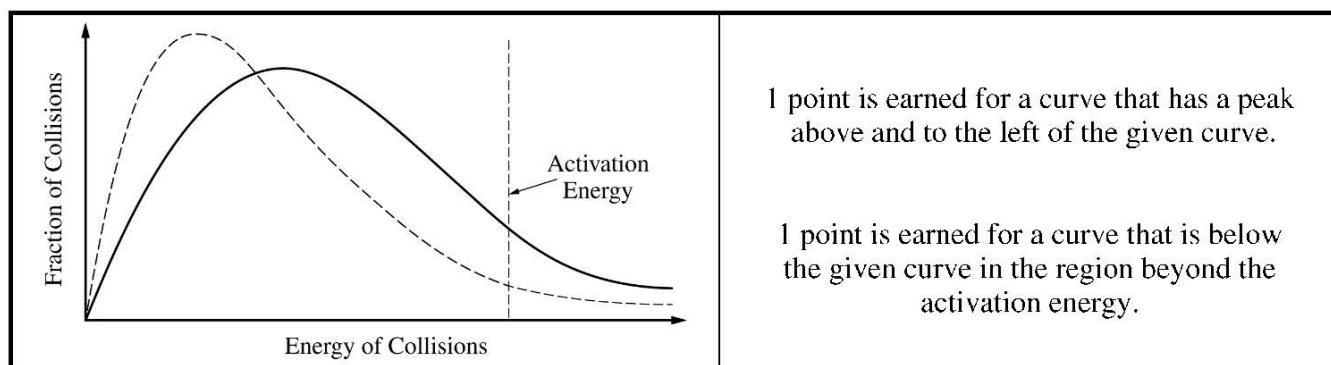
(b) At 30°C the reaction is thermodynamically favorable, but no reaction is observed to occur. However, at 120°C , the reaction occurs at an observable rate.

(i) Explain how the higher temperature affects the collisions between the reactant molecules so that the reaction occurs at an observable rate at 120°C .

At the higher temperature the particles have a greater average kinetic energy than at the lower temperature. Thus there are more collisions with sufficient energy to overcome the activation energy.	1 point is earned for an appropriate explanation that includes a reference to molecular collisions.
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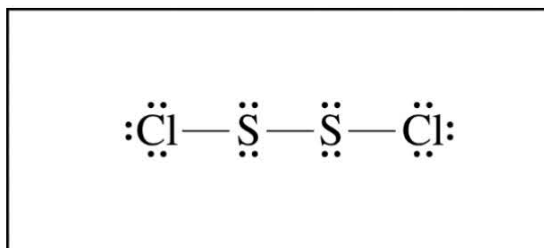
(ii) The graph below shows a distribution for the collision energies of reactant molecules at 120°C . Draw a second curve on the graph that shows the distribution for the collision energies of reactant molecules at 30°C .

Question 1 (continued)



(c) S_2Cl_2 is a product of the reaction.

- (i) In the box below, complete the Lewis electron-dot diagram for the S_2Cl_2 molecule by drawing in all of the electron pairs.



See correct diagram above.

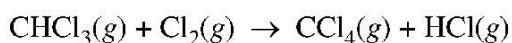
1 point is earned for a correctly drawn diagram.

- (ii) What is the approximate value of the $\text{Cl}-\text{S}-\text{S}$ bond angle in the S_2Cl_2 molecule that you drew in part (c)(i)? (If the two $\text{Cl}-\text{S}-\text{S}$ bond angles are not equal, include both angles.)

Any value between 104° and 110°

1 point is earned for an acceptable angle that is consistent with the Lewis diagram.

(d) $\text{CCl}_4(g)$ can also be produced by reacting $\text{CHCl}_3(g)$ with $\text{Cl}_2(g)$ at 400°C , as represented by the equation below.



At the completion of the reaction a chemist successfully separates the $\text{CCl}_4(g)$ from the $\text{HCl}(g)$ by cooling the mixture to 70°C , at which temperature the $\text{CCl}_4(g)$ condenses while the $\text{HCl}(g)$ remains in the gaseous state.

Question 1 (continued)

- (i) Identify all types of intermolecular forces present in $\text{HCl}(l)$.

Dipole-dipole forces, London dispersion forces	1 point is earned for both types of forces.
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- (ii) What can be inferred about the relative strengths of the intermolecular forces in $\text{CCl}_4(l)$ and $\text{HCl}(l)$? Justify your answer in terms of the information above.

The intermolecular forces among CCl_4 molecules must be stronger than those among HCl molecules because the CCl_4 condenses at a higher temperature than HCl .	1 point is earned for the correct answer with a valid justification.
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Question 2

Answer the following questions about the isomers fulminic acid and isocyanic acid.

Two possible Lewis electron-dot diagrams for fulminic acid, HCNO, are shown below.



- (a) Explain why the diagram on the left is the better representation for the bonding in fulminic acid. Justify your choice based on formal charges.

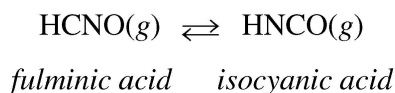
In the diagram on the left, the C atom has a formal charge of zero and the O atom has a formal charge of -1 . In the diagram on the right, the C atom has a formal charge of -1 and the O atom has a formal charge of zero.

The diagram on the left is the better representation because it puts the negative formal charge on oxygen, which is more electronegative than carbon.

1 point is earned for a correct assignment of formal charges in the two diagrams.

1 point is earned for a correct explanation.

Fulminic acid can convert to isocyanic acid according to the equation below.



Fulminic Acid	Isocyanic Acid
$\text{H} - \text{C} \equiv \text{N} - \ddot{\text{O}}:$	$\text{H} - \ddot{\text{N}} = \text{C} = \ddot{\text{O}}:$

- (b) Using the Lewis electron-dot diagrams of fulminic acid and isocyanic acid shown in the boxes above and the table of average bond enthalpies below, determine the value of ΔH° for the reaction of HCNO(g) to form HNCO(g).

Bond	Enthalpy (kJ/mol)	Bond	Enthalpy (kJ/mol)	Bond	Enthalpy (kJ/mol)
N–O	201	C=N	615	H–C	413
C=O	745	C≡N	891	H–N	391

Compound	HCNO	HNCO
Bond Enthalpies (kJ/mol)	$413 + 891 + 201$	$391 + 615 + 745$
Total Bond Enthalpy (kJ/mol)	1505	1751

$$\begin{aligned} \Delta H^\circ &= \sum(\text{enthalpies of bonds broken}) - \sum(\text{enthalpies of bonds formed}) \\ &= 1505 \text{ kJ/mol} - 1751 \text{ kJ/mol} \\ &= -246 \text{ kJ/mol}_{\text{rxn}} \end{aligned}$$

1 point is earned for subtracting the enthalpies of bonds formed from the enthalpies of bonds broken.

1 point is earned for the correct determination of ΔH° .

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Question 2 (continued)

- (c) A student claims that ΔS° for the reaction is close to zero. Explain why the student's claim is accurate.

The change from fulminic acid to isocyanic acid is a rearrangement of atoms with no change in phase or number of molecules.

1 point is earned for a correct explanation.

- (d) Which species, fulminic acid (HCNO) or isocyanic acid (HNCO), is present in higher concentration at equilibrium at 298 K? Justify your answer in terms of thermodynamic favorability and the equilibrium constant.

Isocyanic acid (HNCO) will be present in higher concentration.

ΔG° is essentially equal to ΔH° because ΔS° is essentially zero, so $\Delta G^\circ \approx -246 \text{ kJ/mol}_{rxn}$, indicating the forward reaction is thermodynamically favorable.

Since ΔG° is negative, $K > 1$ ($\Delta G^\circ = -RT \ln K$), resulting in a higher concentration of product than reactant at equilibrium.

1 point is earned for the correct choice **with** a valid justification.

(Calculation of ΔG° is a sufficient justification.)

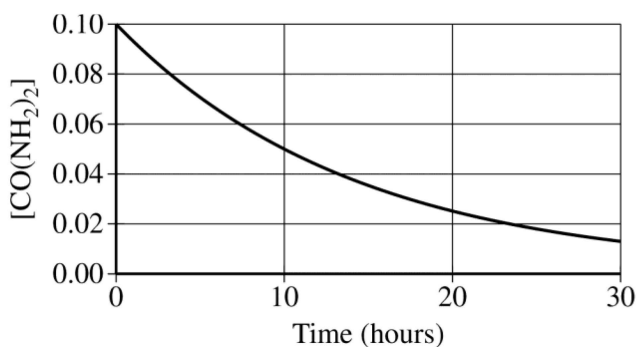
1 point is earned for correctly connecting thermodynamic favorability to the equilibrium constant, K .

The ammonium salt of isocyanic acid is a product of the decomposition of urea, $\text{CO}(\text{NH}_2)_2$, represented below.



A student studying the decomposition reaction runs the reaction at 90°C . The student collects data on the concentration of urea as a function of time, as shown by the data table and the graph below.

Time (hours)	$[\text{CO}(\text{NH}_2)_2]$
0	0.1000
5	0.0707
10	0.0500
15	0.0354
20	0.0250
25	0.0177
30	0.0125



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Question 2 (continued)

(e) The student proposes that the rate law is $rate = k[CO(NH_2)_2]$.

(i) Explain how the data support the student's proposed rate law.

From inspecting the data table or the graph, it is evident that the decomposition reaction has a constant half-life, which indicates that the reaction is a first-order reaction.

1 point is earned for a correct explanation.

(ii) Using the proposed rate law and the student's results, determine the value of the rate constant, k . Include units with your answer.

Since the reaction is first order,

$$k = \frac{0.693}{t_{1/2}} = \frac{0.693}{10. \text{ h}} = 0.069 \text{ h}^{-1}$$

OR

$$k = \frac{\ln[A]_0 - \ln[A]_t}{t} = \frac{\ln(0.1000) - \ln(0.0500)}{10. \text{ h}} = 0.069 \text{ h}^{-1}$$

1 point is earned for the correct value of k with correct units.

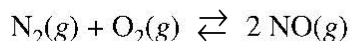
(f) The student learns that the decomposition reaction was run in a solution with a pH of 13. Briefly describe an experiment, including the initial conditions that you would change and the data you would gather, to determine whether the rate of the reaction depends on the concentration of $OH^-(aq)$.

Perform the experiment at a different concentration of $OH^-(aq)$ and measure how the concentration of $CO(NH_2)_2$ changes over time.
(Other variables, such as temperature, should be held constant.)

1 point is earned for the description of a valid experiment.

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Question 3



At high temperatures, $\text{N}_2(\text{g})$ and $\text{O}_2(\text{g})$ can react to produce nitrogen monoxide, $\text{NO}(\text{g})$, as represented by the equation above.

- (a) Write the expression for the equilibrium constant, K_p , for the forward reaction.

$$K_p = \frac{(P_{\text{NO}})^2}{(P_{\text{N}_2})(P_{\text{O}_2})}$$

1 point is earned for a correct K_p expression.

- (b) A student injects $\text{N}_2(\text{g})$ and $\text{O}_2(\text{g})$ into a previously evacuated, rigid vessel and raises the temperature of the vessel to 2000°C . At this temperature the initial partial pressures of $\text{N}_2(\text{g})$ and $\text{O}_2(\text{g})$ are 6.01 atm and 1.61 atm, respectively. The system is allowed to reach equilibrium. The partial pressure of $\text{NO}(\text{g})$ at equilibrium is 0.122 atm. Calculate the value of K_p .

	$\text{N}_2(\text{g}) + \text{O}_2(\text{g}) \rightleftharpoons 2 \text{NO}(\text{g})$		
Initial	6.01	1.61	0
Change	$-x$	$-x$	$+2x$
Equilibrium	$6.01-x$	$1.61-x$	0.122

$$2x = 0.122 \text{ atm} \Rightarrow x = 0.0610 \text{ atm}$$

$$K_p = \frac{(0.122)^2}{(5.95)(1.55)} = 0.00161$$

1 point is earned for the correct equilibrium partial pressures of reactants and products (may be implicit).

1 point is earned for the correct calculation of K_p .

Nitrogen monoxide, $\text{NO}(\text{g})$, can undergo further reactions to produce acids, such as HNO_2 , a weak acid with a K_a of 4.0×10^{-4} and a $\text{p}K_a$ of 3.40.

- (c) A student is asked to make a buffer solution with a pH of 3.40 by using $0.100 \text{ M HNO}_2(\text{aq})$ and $0.100 \text{ M NaOH}(\text{aq})$.
- (i) Explain why the addition of $0.100 \text{ M NaOH}(\text{aq})$ to $0.100 \text{ M HNO}_2(\text{aq})$ can result in the formation of a buffer solution. Include the net ionic equation for the reaction that occurs when the student adds the $\text{NaOH}(\text{aq})$ to the $\text{HNO}_2(\text{aq})$.

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Question 3 (continued)

NaOH will neutralize some of the HNO_2 to produce NO_2^-. The resulting solution contains a mixture of a weak acid and its conjugate base, which is a buffer solution. $\text{HNO}_2 + \text{OH}^- \rightarrow \text{NO}_2^- + \text{H}_2\text{O}$	1 point is earned for the recognition that the solution produced is a mixture of a weak acid and its conjugate base. 1 point is earned for the correct net ionic equation.
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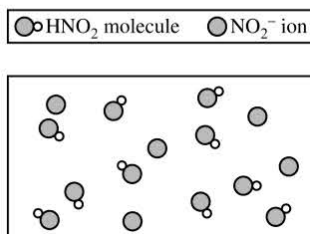
- (ii) Determine the volume, in mL, of 0.100 M NaOH(aq) the student should add to 100. mL of 0.100 M HNO_2 (aq) to make a buffer solution with a pH of 3.40. Justify your answer.

The student should add 50.0 mL of 0.100 M NaOH(aq). When half of the HNO_2 is converted to the conjugate base, $[\text{HNO}_2] = [\text{NO}_2^-]$, therefore the buffer has a pH equal to $\text{p}K_a$. OR $\text{pH} = \text{p}K_a + \log \frac{[\text{NO}_2^-]}{[\text{HNO}_2]}$, thus $\text{pH} = \text{p}K_a$ when $[\text{HNO}_2] = [\text{NO}_2^-]$	1 point is earned for the correct volume. 1 point is earned for clearly indicating a 1 to 1 ratio of HNO_2 and NO_2^- (calculation not required).
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- (d) A second student makes a buffer by dissolving 0.100 mol of NaNO_2 (s) in 100. mL of 1.00 M HNO_2 (aq). Which is more resistant to changes in pH when a strong acid or a strong base is added, the buffer made by the second student or the buffer made by the first student in part (c)? Justify your answer.

The buffer made by the second student is more resistant to changes in pH because it contains a higher concentration of HNO_2 and NO_2^- to react with added H^+ or OH^- ions.	1 point is earned for the correct choice and a valid justification.
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- (e) A new buffer is made using HNO_2 (aq) as one of the ingredients. A particulate representation of a small representative portion of the buffer solution is shown below. (Cations and water molecules are not shown.) Is the pH of the buffer represented in the diagram greater than, less than, or equal to 3.40? Justify your answer.

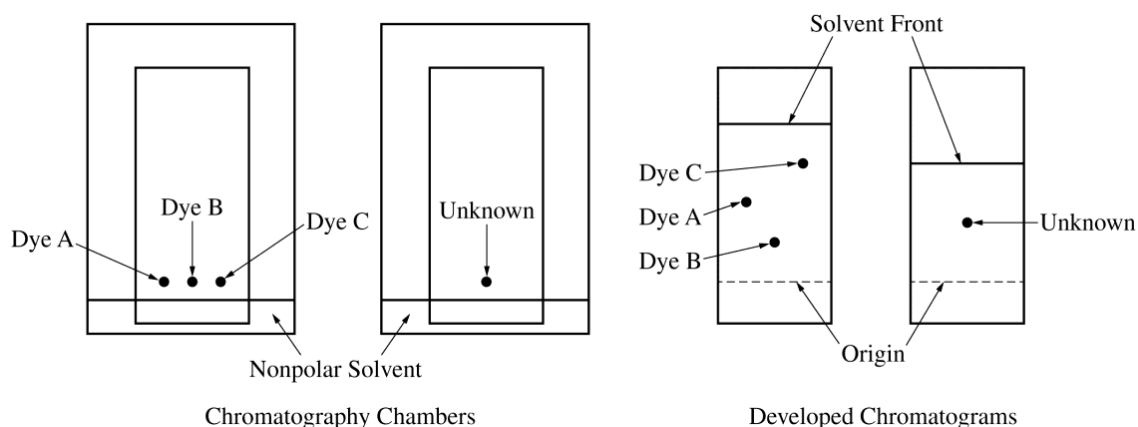


2017 SCORING GUIDELINES**Question 3 (continued)**

The pH of the solution is less than 3.40. If $[\text{HNO}_2] = [\text{NO}_2^-]$, $\text{pH} = \text{p}K_a$, and the pH of the solution would be 3.40. Since $[\text{HNO}_2] > [\text{NO}_2^-]$, as represented in the diagram, the solution has a pH less than 3.40. OR $\text{pH} = \text{p}K_a + \log \frac{[\text{NO}_2^-]}{[\text{HNO}_2]} \Rightarrow \text{pH} = 3.40 + \log \frac{5}{10} \Rightarrow \text{pH} = 3.10$	1 point is earned for the correct choice. 1 point is earned for a valid justification.
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Question 4



A student investigates various dyes using paper chromatography. The student has samples of three pure dyes, labeled A, B, and C, and an unknown sample that contains one of the three dyes. The student prepares the chromatography chambers shown above on the left by putting a drop of each dye at the indicated position on the chromatography paper (a polar material) and standing the paper in a nonpolar solvent. The developed chromatograms are shown above on the right.

- (a) Which dye (A, B, or C) is the least polar? Justify your answer in terms of the interactions between the dyes and the solvent or between the dyes and the paper.

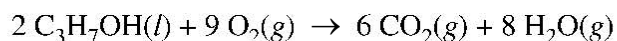
Dye C is the least polar because it moved the farthest. Nonpolar dyes are more strongly attracted to the nonpolar solvent. AND/OR Nonpolar dyes are least strongly retained by the polar paper.	1 point is earned for the correct choice and reference to the chromatogram. 1 point is earned for a correct description of dye-solvent and/or dye-paper interactions.
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- (b) Which dye is present in the unknown sample? Justify your answer.

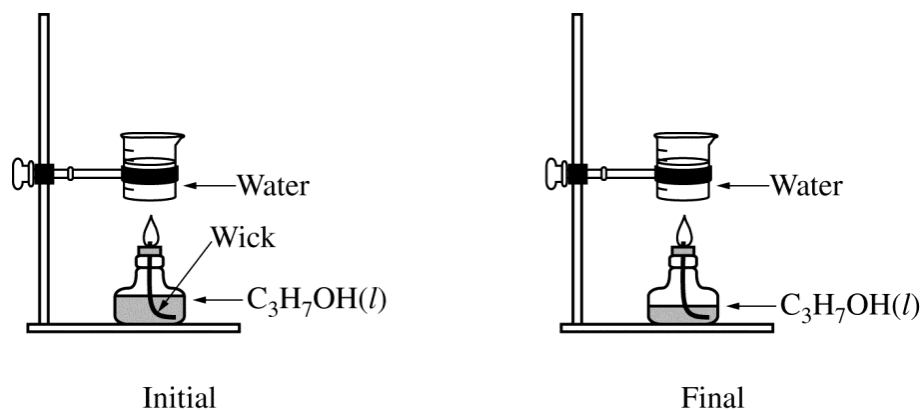
Dye A is present in the unknown sample. The unknown sample moves to a position that is midway between the origin and the solvent front, and so does dye A. OR Dye A has a retention factor (R_f) that is close to 0.50 on the chromatogram with the three dyes, and the unknown also has a retention factor close to 0.50.	1 point is earned for the correct choice. 1 point is earned for a valid justification.
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2017 SCORING GUIDELINES

Question 5



A student performs an experiment to determine the enthalpy of combustion of 2-propanol, $\text{C}_3\text{H}_7\text{OH}(l)$, which combusts in oxygen according to the equation above. The student heats a sample of water by burning some of the $\text{C}_3\text{H}_7\text{OH}(l)$ that is in an alcohol burner, as represented below. The alcohol burner uses a wick to draw liquid up into the flame. The mass of $\text{C}_3\text{H}_7\text{OH}(l)$ combusted is determined by weighing the alcohol burner before and after combustion.



Data from the experiment are given in the table below.

Mass of $\text{C}_3\text{H}_7\text{OH}(l)$ combusted	0.55 g
Mass of water heated	125.00 g
Initial temperature of water	22.0°C
Final temperature of water	51.1°C
Specific heat of water	4.18 J/(g·°C)

- (a) Calculate the magnitude of the heat energy, in kJ, absorbed by the water. (Assume that the energy released from the combustion is completely transferred to the water.)

$q = mc\Delta T$ $= (125.00 \text{ g})(4.18 \text{ J/(g}\cdot\text{°C)})(51.1\text{°C} - 22.0\text{°C})$ $= 15,200 \text{ J} = 15.2 \text{ kJ}$	1 point is earned for the correct calculation.
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Question 5 (continued)

- (b) Based on the experimental data, if one mole of $\text{C}_3\text{H}_7\text{OH}(l)$ is combusted, how much heat, in kJ, is released? Report your answer with the correct number of significant figures.

$1 \text{ mol C}_3\text{H}_7\text{OH} \times \frac{60.09 \text{ g C}_3\text{H}_7\text{OH}}{1 \text{ mol C}_3\text{H}_7\text{OH}} \times \frac{15.2 \text{ kJ}}{0.55 \text{ g C}_3\text{H}_7\text{OH}} = 1661 \text{ kJ}$ $= 1.7 \times 10^3 \text{ kJ}$	1 point is earned for the correct amount of heat released. 1 point is earned for reporting the answer to the appropriate number of significant figures based on the experimental data.
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- (c) A second student performs the experiment using the same mass of water at the same initial temperature. However, the student uses an alcohol burner containing $\text{C}_3\text{H}_7\text{OH}(l)$ that is contaminated with water, which is miscible with $\text{C}_3\text{H}_7\text{OH}(l)$. The difference in mass of the alcohol burner before and after the combustion in this experiment is also 0.55 g. Would the final temperature of the water in the beaker heated by the alcohol burner in this experiment be greater than, less than, or equal to the final temperature of the water in the beaker in the first student's experiment? Justify your answer.

The final temperature measured by the second student would be less than that measured by the first student because: the actual mass of $\text{C}_3\text{H}_7\text{OH}(l)$ combusted will be less than 0.55 g OR combustion of the contaminated sample will also require vaporization of the water in the sample.	1 point is earned for the correct choice with a valid explanation.
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2017 SCORING GUIDELINES

Question 6

Answer the following questions about $\text{Mg}(\text{OH})_2$. At 25°C , the value of the solubility product constant, K_{sp} , for $\text{Mg}(\text{OH})_2(s)$ is 1.8×10^{-11} .

- (a) Calculate the number of grams of $\text{Mg}(\text{OH})_2$ (molar mass 58.32 g/mol) that is dissolved in $100. \text{ mL}$ of a saturated solution of $\text{Mg}(\text{OH})_2$ at 25°C .

$1.8 \times 10^{-11} = [\text{Mg}^{2+}][\text{OH}^-]^2 = (x)(2x)^2 = 4x^3$ $x = \sqrt[3]{\frac{1.8 \times 10^{-11}}{4}} = 1.65 \times 10^{-4} \text{ M} = [\text{Mg}^{2+}] = [\text{Mg}(\text{OH})_2]$ $0.100 \text{ L} \times \frac{1.65 \times 10^{-4} \text{ mol}}{1 \text{ L}} \times \frac{58.32 \text{ g Mg}(\text{OH})_2}{1 \text{ mol Mg}(\text{OH})_2} = 9.6 \times 10^{-4} \text{ g Mg}(\text{OH})_2$	1 point is earned for calculating the solubility of $\text{Mg}(\text{OH})_2$. 1 point is earned for calculating the correct mass based on the solubility of $\text{Mg}(\text{OH})_2$.
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- (b) The energy required to separate the ions in the $\text{Mg}(\text{OH})_2$ crystal lattice into individual $\text{Mg}^{2+}(g)$ and $\text{OH}^-(g)$ ions, as represented in the table below, is known as the lattice energy of $\text{Mg}(\text{OH})_2(s)$. As shown in the table, the lattice energy of $\text{Sr}(\text{OH})_2(s)$ is less than the lattice energy of $\text{Mg}(\text{OH})_2(s)$. Explain why in terms of periodic properties and Coulomb's law.

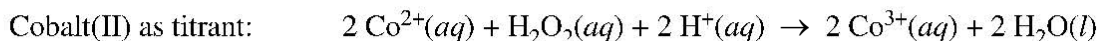
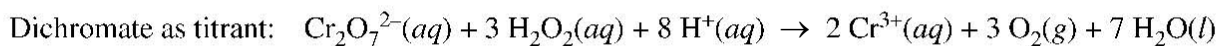
Reaction	Lattice Energy (kJ/mol)
$\text{Mg}(\text{OH})_2(s) \rightarrow \text{Mg}^{2+}(g) + 2 \text{ OH}^-(g)$	2900
$\text{Sr}(\text{OH})_2(s) \rightarrow \text{Sr}^{2+}(g) + 2 \text{ OH}^-(g)$	2300

The Sr^{2+} ion is larger than the Mg^{2+} ion because it has additional occupied energy levels (or shells). Coulomb's law states that the force of attraction between cation and anion is inversely proportional to the square of the distance between them. Since the distance between Mg^{2+} and OH^- is shorter than the distance between Sr^{2+} and OH^-, the attractive forces in $\text{Mg}(\text{OH})_2$ are stronger and, therefore, its lattice energy is greater.	1 point is earned for the correct comparison of cation sizes. 1 point is earned for indicating that smaller interionic distances lead to a greater lattice energy.
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2017 SCORING GUIDELINES

Question 7

A student wants to determine the concentration of H_2O_2 in a solution of $\text{H}_2\text{O}_2(aq)$. The student can use one of two titrants, either dichromate ion, $\text{Cr}_2\text{O}_7^{2-}(aq)$, or cobalt(II) ion, $\text{Co}^{2+}(aq)$. The balanced chemical equations for the two titration reactions are shown below.



The half-reactions and the E° values for the systems related to the titrations above are given in the following table.

Half-Reaction	E° (V) at 298 K
$\text{Co}^{3+}(aq) + e^- \rightarrow \text{Co}^{2+}(aq)$	1.84
$\text{H}_2\text{O}_2(aq) + 2 \text{H}^+(aq) + 2 e^- \rightarrow 2 \text{H}_2\text{O}(l)$	1.77
$\text{Cr}_2\text{O}_7^{2-}(aq) + 14 \text{H}^+(aq) + 6 e^- \rightarrow 2 \text{Cr}^{3+}(aq) + 7 \text{H}_2\text{O}(l)$	1.33
$\text{O}_2(g) + 2 \text{H}^+(aq) + 2 e^- \rightarrow \text{H}_2\text{O}_2(aq)$	0.70

(a) Use the information in the table to calculate the following.

(i) E° for the reaction between $\text{Cr}_2\text{O}_7^{2-}(aq)$ and $\text{H}_2\text{O}_2(aq)$ at 298 K

$$E^\circ = 1.33 - 0.70 = 0.63 \text{ V}$$

1 point is earned for correctly combining E° values.

(ii) E° for the reaction between $\text{Co}^{2+}(aq)$ and $\text{H}_2\text{O}_2(aq)$ at 298 K

$$E^\circ = -1.84 + 1.77 = -0.07 \text{ V}$$

1 point is earned for correctly combining E° values.

2017 SCORING GUIDELINES

Question 7 (continued)

- (b) Based on the calculated values of E° , the student must choose the titrant for which the titration reaction is thermodynamically favorable at 298 K.

(i) Which titrant should the student choose? Explain your reasoning.

The student should use the dichromate ion for the titration because, for the reaction, the value of E° is positive, which means that the reaction is thermodynamically favorable.

OR

$\Delta G^\circ = -nFE^\circ$ and n , F , and E° are all positive numbers, therefore $\Delta G^\circ < 0$, which means that the reaction is thermodynamically favorable.

1 point is earned for choosing the correct titrant **and** for understanding that a positive E° or a negative ΔG° is required.

(ii) Calculate the value of ΔG° , in $\text{kJ/mol}_{\text{rxn}}$, for the reaction between the chosen titrant and $\text{H}_2\text{O}_2(aq)$.

$$\Delta G^\circ = -nFE^\circ = -6(96,485 \frac{\text{C}}{\text{mol}})(0.63 \frac{\text{J}}{\text{C}})(\frac{1 \text{ kJ}}{1000 \text{ J}}) = -360 \text{ kJ/mol}_{\text{rxn}}$$

1 point is earned for calculating the value of ΔG° .

AP[®] Chemistry

2014 Scoring Guidelines

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4 SCORING GUIDELINES

Question 1
(10 points)

Mass of KI tablet	0.425 g
Mass of thoroughly dried filter paper	1.462 g
Mass of filter paper + precipitate after first drying	1.775 g
Mass of filter paper + precipitate after second drying	1.699 g
Mass of filter paper + precipitate after third drying	1.698 g

A student is given the task of determining the I^- content of tablets that contain KI and an inert, water-soluble sugar as a filler. A tablet is dissolved in 50.0 mL of distilled water, and an excess of 0.20 M $\text{Pb}(\text{NO}_3)_2(aq)$ is added to the solution. A yellow precipitate forms, which is then filtered, washed, and dried. The data from the experiment are shown in the table above.

(a) For the chemical reaction that occurs when the precipitate forms,

(i) write a balanced, net-ionic equation for the reaction, and

$\text{Pb}^{2+} + 2 \text{I}^- \rightarrow \text{PbI}_2$	1 point is earned for a balanced net-ionic equation.
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(ii) explain why the reaction is best represented by a net-ionic equation.

The net-ionic equation shows the formation of the $\text{PbI}_2(s)$ from $\text{Pb}^{2+}(aq)$ and $\text{I}^-(aq)$ ions, omitting the non-reacting species (spectator ions), $\text{K}^+(aq)$ and $\text{NO}_3^-(aq)$.	1 point is earned for a valid explanation.
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(b) Explain the purpose of drying and weighing the filter paper with the precipitate three times.

The filter paper and precipitate must be dried several times (to a constant mass) to ensure that all the water has been driven off.	1 point is earned for a valid explanation.
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(c) In the filtrate solution, is $[\text{K}^+]$ greater than, less than, or equal to $[\text{NO}_3^-]$? Justify your answer.

$[\text{K}^+]$ is less than $[\text{NO}_3^-]$ because the source of the NO_3^- , the 0.20 M $\text{Pb}(\text{NO}_3)_2(aq)$, was added in excess.	1 point is earned for a correct comparison with a valid explanation.
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4 SCORING GUIDELINES

Question 1 (continued)

(d) Calculate the number of moles of precipitate that is produced in the experiment.

$1.698 \text{ g} - 1.462 \text{ g} = 0.236 \text{ g PbI}_2(s)$ $0.236 \text{ g PbI}_2 \times \frac{1 \text{ mol PbI}_2}{461.0 \text{ g PbI}_2} = 5.12 \times 10^{-4} \text{ mol PbI}_2$	1 point is earned for the correct number of moles of $\text{PbI}_2(s)$ precipitate.
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(e) Calculate the mass percent of I^- in the tablet.

$5.12 \times 10^{-4} \text{ mol PbI}_2 \times \frac{2 \text{ mol I}^-}{1 \text{ mol PbI}_2} = 1.02 \times 10^{-3} \text{ mol I}^-$ $1.02 \times 10^{-3} \text{ mol I}^- \times \frac{126.91 \text{ g I}^-}{1 \text{ mol I}^-} = 0.130 \text{ g I}^- \text{ in one tablet}$ $\frac{0.130 \text{ g I}^-}{0.425 \text{ g KI tablet}} = 0.306 = 30.6\% \text{ I}^- \text{ per KI tablet}$	1 point is earned for determining the number of moles of I^- in one tablet. 1 point is earned for calculating the mass percent of I^- in the KI tablet.
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(f) In another trial, the student dissolves a tablet in 55.0 mL of water instead of 50.0 mL of water. Predict whether the experimentally determined mass percent of I^- will be greater than, less than, or equal to the amount calculated in part (e). Justify your answer.

The mass percent of I^- will be the same. $\text{Pb}^{2+}(aq)$ was added in excess, ensuring that essentially no I^- remained in solution. The additional water is removed by filtration and drying, leaving the same mass of dried precipitate.	1 point is earned for correct comparison with a valid justification.
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(g) A student in another lab also wants to determine the I^- content of a KI tablet but does not have access to $\text{Pb}(\text{NO}_3)_2$. However, the student does have access to 0.20 M AgNO_3 , which reacts with $\text{I}^-(aq)$ to produce $\text{AgI}(s)$. The value of K_{sp} for AgI is 8.5×10^{-17} .

(i) Will the substitution of AgNO_3 for $\text{Pb}(\text{NO}_3)_2$ result in the precipitation of the I^- ion from solution? Justify your answer.

Yes. Addition of an excess of $0.20 \text{ M AgNO}_3(aq)$ will precipitate all of the I^- ion present in the solution because AgI is insoluble, as evidenced by its low value of K_{sp} .	1 point is earned for the correct answer with a valid justification.
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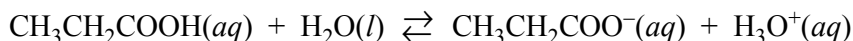
(ii) The student only has access to one KI tablet and a balance that can measure to the nearest 0.01 g. Will the student be able to determine the mass of AgI produced to three significant figures? Justify your answer.

4 SCORING GUIDELINES**Question 1 (continued)**

No. If masses can be measured to ± 0.01 g, then the mass of the dry $\text{AgI}(s)$ precipitate (which is less than 1 g) will be known to only two significant figures.

1 point is earned for a correct answer with a valid justification.

2014 SCORING GUIDELINES

Question
(10 points)

Propanoic acid, $\text{CH}_3\text{CH}_2\text{COOH}$, is a carboxylic acid that reacts with water according to the equation above. At 25°C the pH of a 50.0 mL sample of 0.20 M $\text{CH}_3\text{CH}_2\text{COOH}$ is 2.79.

- (a) Identify a Brønsted-Lowry conjugate acid-base pair in the reaction. Clearly label which is the acid and which is the base.

$\text{CH}_3\text{CH}_2\text{COOH}$ and $\text{CH}_3\text{CH}_2\text{COO}^-$ <i>acid</i> <i>base</i> OR H_3O^+ and H_2O <i>acid</i> <i>base</i>	1 point is earned for writing (or naming) either of the Brønsted-Lowry conjugate acid-base pairs with a clear indication of which is the acid and which is the base.
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- (b) Determine the value of K_a for propanoic acid at 25°C .

$[\text{H}_3\text{O}^+] = 10^{-\text{pH}} = 10^{-2.79} = 1.6 \times 10^{-3} \text{ M}$ $[\text{CH}_3\text{CH}_2\text{COO}^-] = [\text{H}_3\text{O}^+]$ AND $[\text{CH}_3\text{CH}_2\text{COOH}] = 0.20 \text{ M} - [\text{H}_3\text{O}^+]$, OR $[\text{CH}_3\text{CH}_2\text{COOH}] \approx 0.20 \text{ M}$ (state or assume that $[\text{H}_3\text{O}^+] \ll 0.20 \text{ M}$) $K_a = \frac{[\text{CH}_3\text{CH}_2\text{COO}^-][\text{H}_3\text{O}^+]}{[\text{CH}_3\text{CH}_2\text{COOH}]} = \frac{(1.6 \times 10^{-3} \text{ M})^2}{0.20 \text{ M}} = 1.3 \times 10^{-5}$	1 point is earned for correctly solving for $[\text{H}_3\text{O}^+]$. 1 point is earned for the K_a expression for propanoic acid OR 1 point is earned for substituting values into the K_a expression. 1 point is earned for correctly solving for the value of K_a .
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- (c) For each of the following statements, determine whether the statement is true or false. In each case, explain the reasoning that supports your answer.

- (i) The pH of a solution prepared by mixing the 50.0 mL sample of 0.20 M $\text{CH}_3\text{CH}_2\text{COOH}$ with a 50.0 mL sample of 0.20 M NaOH is 7.00.

False. The conjugate base of a weak acid undergoes hydrolysis (see equation below) at equivalence to form a solution with a $\text{pH} > 7$. $(\text{CH}_3\text{CH}_2\text{COO}^- + \text{H}_2\text{O} \rightleftharpoons \text{CH}_3\text{CH}_2\text{COOH} + \text{OH}^-)$	1 point is earned for noting that the statement is false AND providing a supporting explanation.
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2014 SCORING GUIDELINES

Question 2 (continued)

- (ii) If the pH of a hydrochloric acid solution is the same as the pH of a propanoic acid solution, then the molar concentration of the hydrochloric acid solution must be less than the molar concentration of the propanoic acid solution.

True. HCl is a strong acid that ionizes completely. Fewer moles of HCl are needed to produce the same $[\text{H}_3\text{O}^+]$ as the propanoic acid solution, which only partially ionizes.	1 point is earned for noting that the statement is true and providing a supporting explanation.
--	---

A student is given the task of determining the concentration of a propanoic acid solution of unknown concentration. A 0.173 M NaOH solution is available to use as the titrant. The student uses a 25.00 mL volumetric pipet to deliver the propanoic acid solution to a clean, dry flask. After adding an appropriate indicator to the flask, the student titrates the solution with the 0.173 M NaOH, reaching the end point after 20.52 mL of the base solution has been added.

- (d) Calculate the molarity of the propanoic acid solution.

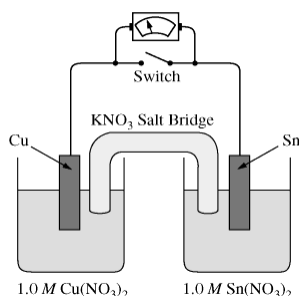
Let x = moles of propanoic acid then $x = (0.02052 \text{ L NaOH}) \times \frac{0.173 \text{ mol NaOH}}{1 \text{ L NaOH}} \times \frac{1 \text{ mol acid}}{1 \text{ mol NaOH}}$ $= 3.55 \times 10^{-3} \text{ mol propanoic acid}$ $\frac{3.55 \times 10^{-3} \text{ mol acid}}{0.02500 \text{ L acid}} = 0.142 \text{ M}$ OR Since $\text{CH}_3\text{CH}_2\text{COOH}$ is monoprotic and, at the equivalence point, moles $\text{H}^+ = \text{moles OH}^-$, then $M_A V_A = M_B V_B$ $M_A = \frac{M_B V_B}{V_A} = \frac{(0.173 \text{ M NaOH})(20.52 \text{ mL NaOH})}{25.00 \text{ mL acid}} = 0.142 \text{ M}$	1 point is earned for correctly calculating the number of moles of acid that reacted at the equivalence point. 1 point is earned for the correct molarity of acid.
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- (e) The student is asked to redesign the experiment to determine the concentration of a butanoic acid solution instead of a propanoic acid solution. For butanoic acid the value of $\text{p}K_a$ is 4.83. The student claims that a different indicator will be required to determine the equivalence point of the titration accurately. Based on your response to part (b), do you agree with the student's claim? Justify your answer.

2014 SCORING GUIDELINES**Question 2 (continued)**

<u>Disagree</u> with the student's claim From part (b) above, pK_a for propanoic acid is $\log(1.3 \times 10^{-5}) = 4.89$. Because 4.83 is so close to 4.89, the pH at the equivalence point in the titration of butanoic acid should be close enough to the pH in the titration of propanoic acid to make the original indicator appropriate for the titration of butanoic acid.	1 point is earned for disagreeing with the student's claim and making a valid justification using pK_a, K_a, or pH arguments. 1 point is earned for numerically comparing either: the two pK_a values, the two K_a values, or the two pH values at the equivalence point.
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SCORING GUIDELINES

Question
(10 points)

A student is given a standard galvanic cell, represented above, that has a Cu electrode and a Sn electrode. As current flows through the cell, the student determines that the Cu electrode increases in mass and the Sn electrode decreases in mass.

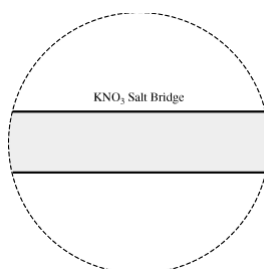
- (a) Identify the electrode at which oxidation is occurring. Explain your reasoning based on the student's observations.

Since the Sn electrode is losing mass, Sn atoms must be forming $\text{Sn}^{2+}(\text{aq})$. This process is oxidation. OR because the cell operates, E° must be positive and, based on the E° values from the table, it must be Sn that is oxidized.	1 point is earned for the correct answer with justification.
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- (b) As the mass of the Sn electrode decreases, where does the mass go?

The atoms on the Sn electrode are going into the solution as Sn^{2+} ions.	1 point is earned for the correct answer.
---	--

- (c) In the expanded view of the center portion of the salt bridge shown in the diagram below, draw and label a particle view of what occurs in the salt bridge as the cell begins to operate. Omit solvent molecules and use arrows to show the movement of particles.



The response should show at least one K^+ ion moving toward the Cu compartment on the left and at least one NO_3^- ion moving in the opposite direction.	1 point is earned for correct representation of both K^+ and NO_3^- ions. (Including free electrons loses this point.) 1 point is earned for correctly indicating the direction of movement of both ions.
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SCORING GUIDELINES

Question 3 (continued)

(d) A nonstandard cell is made by replacing the 1.0 *M* solutions of $\text{Cu}(\text{NO}_3)_2$ and $\text{Sn}(\text{NO}_3)_2$ in the standard cell with 0.50 *M* solutions of $\text{Cu}(\text{NO}_3)_2$ and $\text{Sn}(\text{NO}_3)_2$. The volumes of solutions in the nonstandard cell are identical to those in the standard cell.

(i) Is the cell potential of the nonstandard cell greater than, less than, or equal to the cell potential of the standard cell? Justify your answer.

It is the same. In the cell reaction $Q = \frac{[\text{Sn}^{2+}]}{[\text{Cu}^{2+}]}$, and the concentrations of Sn^{2+} and Cu^{2+} are equal to each other in both cases.	1 point is earned for the correct answer with justification.
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(ii) Both the standard and nonstandard cells can be used to power an electronic device. Would the nonstandard cell power the device for the same time, a longer time, or a shorter time as compared with the standard cell? Justify your answer.

The nonstandard cell would power the device for a shorter time because the supply of Cu^{2+} ions will be exhausted more quickly. OR The nonstandard cell would power the device for a shorter time because the reaction will reach $E = 0$ more quickly.	1 point is earned for the correct answer with justification.
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(e) In another experiment, the student places a new Sn electrode into a fresh solution of 1.0 *M* $\text{Cu}(\text{NO}_3)_2$.

Half-Reaction	E° (V)
$\text{Cu}^+ + e^- \rightarrow \text{Cu}(s)$	0.52
$\text{Cu}^{2+} + 2 e^- \rightarrow \text{Cu}(s)$	0.34
$\text{Sn}^{4+} + 2 e^- \rightarrow \text{Sn}^{2+}$	0.15
$\text{Sn}^{2+} + 2 e^- \rightarrow \text{Sn}(s)$	-0.14

(i) Using information from the table above, write a net-ionic equation for the reaction between the Sn electrode and the $\text{Cu}(\text{NO}_3)_2$ solution that would be thermodynamically favorable. Justify that the reaction is thermodynamically favorable.

SCORING GUIDELINES

Question 3 (continued)

$\text{Cu}^{2+}(\text{aq}) + \text{Sn}(\text{s}) \rightarrow \text{Cu}(\text{s}) + \text{Sn}^{2+}(\text{aq})$ E° is positive ($0.34 \text{ V} + 0.14 \text{ V} = 0.48 \text{ V}$), therefore the reaction is thermodynamically favorable. OR The cell observations from earlier parts of the question are evidence that the Sn is oxidized and Cu is reduced, therefore E° must be positive.	1 point is earned for the correct net-ionic equation. 1 point is earned for a correct justification (unit not needed in calculation).
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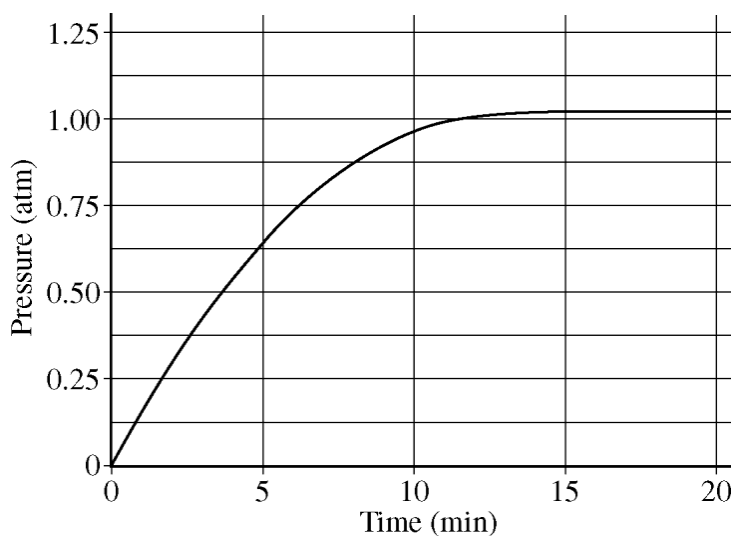
(ii) Calculate the value of ΔG° for the reaction. Include units with your answer.

$\Delta G^\circ = -nFE^\circ$ $\Delta G^\circ = -\frac{2 \text{ mol } e^-}{\text{mol}_{\text{rxn}}} \times \frac{96,485 \text{ C}}{\text{mol } e^-} \times \frac{0.48 \text{ J}}{\text{C}} = -93,000 \text{ J/mol}_{\text{rxn}} = -93 \text{ kJ/mol}_{\text{rxn}}$	1 point is earned for the correct number of electrons. 1 point is earned for the correct answer with unit.
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SCORING GUIDELINES

Question
(4 points)

When heated, calcium carbonate decomposes according to the equation above. In a study of the decomposition of calcium carbonate, a student added a 50.0 g sample of powdered $\text{CaCO}_3(s)$ to a 1.00 L rigid container. The student sealed the container, pumped out all the gases, then heated the container in an oven at 1100 K. As the container was heated, the total pressure of the $\text{CO}_2(g)$ in the container was measured over time. The data are plotted in the graph below.



The student repeated the experiment, but this time the student used a 100.0 g sample of powdered $\text{CaCO}_3(s)$. In this experiment, the final pressure in the container was 1.04 atm, which was the same final pressure as in the first experiment.

- (a) Calculate the number of moles of $\text{CO}_2(g)$ present in the container after 20 minutes of heating.

$$PV = nRT$$

$$\frac{PV}{RT} = n = \frac{(1.04 \text{ atm})(1.00 \text{ L})}{(0.0821 \frac{\text{L atm}}{\text{mol K}})(1100 \text{ K})} = 0.0115 \text{ mol CO}_2$$

1 point is earned for the proper setup using the ideal gas law and an answer that is consistent with the setup.

SCORING GUIDELINES

Question continued)

- (b) The student claimed that the final pressure in the container in each experiment became constant because all of the $\text{CaCO}_3(s)$ had decomposed. Based on the data in the experiments, do you agree with this claim? Explain.

Do not agree with claim Explanation I: In experiment 1, the moles of $\text{CaCO}_3 = 50.0 \text{ g}/100.09 \text{ g/mol} = 0.500 \text{ mol CaCO}_3$. If the reaction had gone to completion, 0.500 mol of CO_2 would have been produced. From part (a) only 0.0115 mol was produced. Hence, the student's claim was false. Explanation II: The two different experiments (one with 50.0 g of CaCO_3 and one with 100.0 g of CaCO_3) reached the same constant, final pressure of 1.04 atm. Since increasing the amount of reactant did not produce more product, there is no way that all of the CaCO_3 reacted. Instead, an equilibrium condition has been achieved and there must be some solid CaCO_3 in the container.	1 point is earned for disagreement with the claim <u>and</u> for a correct justification using stoichiometry or a discussion of the creation of an equilibrium condition.
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- (c) After 20 minutes some $\text{CO}_2(g)$ was injected into the container, initially raising the pressure to 1.5 atm. Would the final pressure inside the container be less than, greater than, or equal to 1.04 atm? Explain your reasoning.

The final pressure would be equal to 1.04 atm. Equilibrium was reached in both experiments; the equilibrium pressure at this temperature is 1.04 atm. As the reaction shifts toward the reactant, the amount of $\text{CO}_2(g)$ in the container will decrease until the pressure returns to 1.04 atm.	1 point is earned for the correct answer with justification.
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- (d) Are there sufficient data obtained in the experiments to determine the value of the equilibrium constant, K_p , for the decomposition of $\text{CaCO}_3(s)$ at 1100 K? Justify your answer.

SCORING GUIDELINES**Question continued)**

Yes. For the equilibrium reaction represented by the chemical equation in this problem, at a given temperature the equilibrium pressure of CO_2 determines the equilibrium constant. Since the measured pressure of CO_2 is also the equilibrium pressure of CO_2, $K_p = P_{\text{CO}_2} = 1.04$. Note: If the response in part (b) indicates “yes”, that all of the $\text{CaCO}_3(s)$ had decomposed, then the point can be earned by stating that the system did not reach equilibrium in either experiment and hence the value of K_p cannot be calculated from the data.	1 point is earned for correct explanation that is consistent with the student’s answer to part (b).
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SCORING GUIDELINES

Question 5
(4 points)

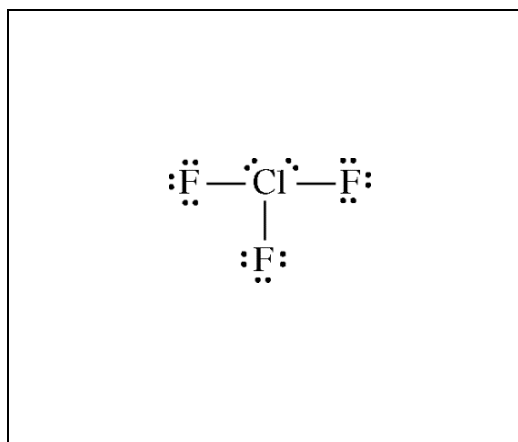
Nonmetal	C	N	O	Ne	Si	P	S	Ar
Formula of Compound	CF ₄	NF ₃	OF ₂	No compound	SiF ₄	PF ₃	SF ₂	No compound

Some binary compounds that form between fluorine and various nonmetals are listed in the table above. A student examines the data in the table and poses the following hypothesis: the number of F atoms that will bond to a nonmetal is always equal to 8 minus the number of valence electrons in the nonmetal atom.

- (a) Based on the student's hypothesis, what should be the formula of the compound that forms between chlorine and fluorine?

ClF	1 point is earned for the correct formula.
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- (b) In an attempt to verify the hypothesis, the student researches the fluoride compounds of the other halogens and finds the formula ClF₃. In the box below, draw a complete Lewis electron-dot diagram for a molecule of ClF₃.



See diagram above.	1 point is earned for a central Cl atom surrounded by three bonding pairs with F atoms and two nonbonding (lone) pairs of electrons. F atoms must have three nonbonding pairs each. Electron pairs can be depicted as dots or line segments.
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SCORING GUIDELINES

Question 5 (continued)

- (c) Two possible geometric shapes for the ClF_3 molecule are trigonal planar and T-shaped. The student does some research and learns that the molecule has a dipole moment. Which of the two shapes is consistent with the fact that the ClF_3 molecule has a dipole moment? Justify your answer in terms of bond polarity and molecular structure.

The molecule is T-shaped because a T-shaped structure is asymmetric with dipoles that do not cancel out, but produce a net dipole (i.e., a polar molecule). OR because, if the molecule had a trigonal planar structure, the molecule would be symmetric with dipoles that cancel out and produce a net dipole of zero (i.e., a nonpolar molecule), which is not consistent with the observation that the ClF_3 molecule does have a dipole moment.	1 point is earned for indicating that the molecule is T-shaped with an acceptable explanation.
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In an attempt to resolve the existence of the ClF_3 molecule with the hypothesis stated above, the student researches the compounds that form between halogens and fluorine, and assembles the following list.

Halogen	Formula(s)
F	F_2
Cl	
Br	BrF , BrF_3 , BrF_5
I	IF , IF_3 , IF_5 , IF_7

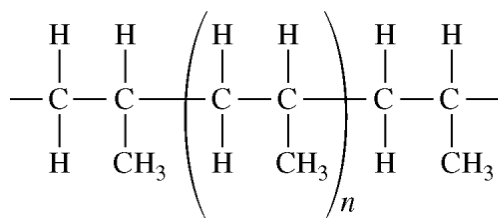
- (d) Based on concepts of atomic structure and periodicity, propose a modification to the student's previous hypothesis to account for the compounds that form between halogens and fluorine.

An acceptable hypothesis (descriptive or formulaic) must include the following ideas: 1. Atomic Structure: e.g., odd number of F atoms 2. Periodicity: e.g., as the atomic number of the central halogen atom increases, the number of F atoms increases.	1 point is earned for an acceptably modified hypothesis that addresses both atomic structure and periodicity.
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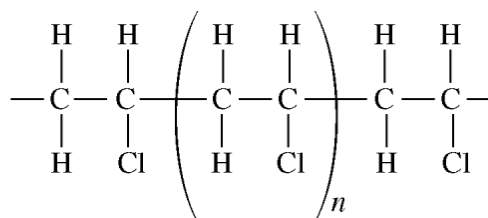
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Question
(4 points)

A student places a mixture of plastic beads consisting of polypropylene (PP) and polyvinyl chloride (PVC) in a 1.0 L beaker containing distilled water. After stirring the contents of the beaker vigorously, the student observes that the beads of one type of plastic sink to the bottom of the beaker and the beads of the other type of plastic float on the water. The chemical structures of PP and PVC are represented by the diagrams below, which show segments of each polymer.



PP



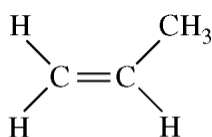
PVC

- (a) Given that the spacing between polymer chains in PP and PVC is similar, the beads that sink are made of which polymer? Explain.

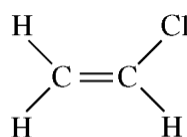
The PVC beads sink. The spacing between chains is similar, but a Cl atom has a greater mass than CH₃.

1 point is earned for the correct polymer with a correct explanation.

PP is synthesized from propene, C₃H₆, and PVC is synthesized from vinyl chloride, C₂H₃Cl. The structures of the molecules are shown below.



Propene



Vinyl Chloride (chloroethene)

- (b) The boiling point of liquid propene (226 K) is lower than the boiling point of liquid vinyl chloride (260 K). Account for this difference in terms of the types and strengths of intermolecular forces present in each liquid.

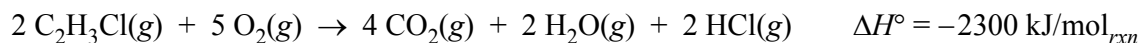
Both substances have dipole-dipole interactions and London dispersion forces (or propene is essentially nonpolar with only LDFs while vinyl chloride has both LDFs and dipole-dipole forces). Propene contains a CH₃ group, but vinyl chloride contains a Cl atom. Vinyl chloride thus has a larger electron cloud, is more polarizable, and has a larger dipole moment. Thus intermolecular attractions are stronger in vinyl chloride, which results in it having the higher boiling point.

1 point is earned for a discussion of intermolecular forces and for a comparison of their relative strengths.

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Question 6 (continued)

In a separate experiment, the student measures the enthalpies of combustion of propene and vinyl chloride. The student determines that the combustion of 2.00 mol of vinyl chloride releases 2300 kJ of energy, according to the equation below.



- (c) Using the table of standard enthalpies of formation below, determine whether the combustion of 2.00 mol of propene releases more, less, or the same amount of energy that 2.00 mol of vinyl chloride releases. Justify your answer with a calculation. The balanced equation for the combustion of 2.00 mol of propene is $2 \text{C}_3\text{H}_6(g) + 9 \text{O}_2(g) \rightarrow 6 \text{CO}_2(g) + 6 \text{H}_2\text{O}(g)$.

Substance	$\text{C}_2\text{H}_3\text{Cl}(g)$	$\text{C}_3\text{H}_6(g)$	$\text{CO}_2(g)$	$\text{H}_2\text{O}(g)$	$\text{HCl}(g)$	$\text{O}_2(g)$
Standard Enthalpy of Formation (kJ/mol)	37	21	-394	-242	-92	0

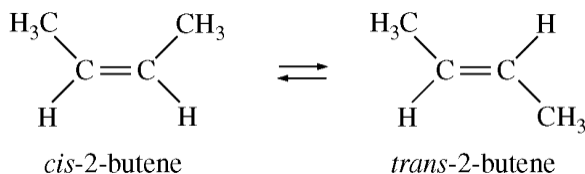
$$\Delta H^\circ = 6(-394) + 6(-242) - 2(21) = -3858 \text{ kJ/mol}_{\text{rxn}}$$

The combustion of 2.00 mol of propene releases more energy.

1 point is earned for the calculation of the enthalpy of combustion of propene.

1 point is earned for the comparison of propene to vinyl chloride that is consistent with the calculated value.

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Question 7
(4 points)

The half-life ($t_{1/2}$) of the catalyzed isomerization of *cis*-2-butene gas to produce *trans*-2-butene gas, represented above, was measured under various conditions, as shown in the table below.

Trial Number	Initial $P_{\text{cis-2-butene}}$ (torr)	V (L)	T (K)	$t_{1/2}$ (s)
1	300.	2.00	350.	100.
2	600.	2.00	350.	100.
3	300.	4.00	350.	100.
4	300.	2.00	365	50.

- (a) The reaction is first order. Explain how the data in the table are consistent with a first-order reaction.

For a first-order reaction, the half-life is independent of reactant concentration (or pressure) at constant T , as shown in trials 1, 2, and 3.	1 point is earned for a correct explanation.
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- (b) Calculate the rate constant, k , for the reaction at 350. K. Include appropriate units with your answer.

$k = \frac{0.693}{t_{1/2}} = \frac{0.693}{100. \text{ s}} = 0.00693 \text{ s}^{-1}$	1 point is earned for correct numerical answer with units.
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- (c) Is the initial rate of the reaction in trial 1 greater than, less than, or equal to the initial rate in trial 2 ? Justify your answer.

The initial rate in trial 1 is less than that in trial 2 because $\text{rate} = k[\text{cis-2-butene}]$ or $\text{rate} = kP_{\text{cis-2-butene}}$ (with reference to values from both trials). OR because the initial concentration of <i>cis</i>-2-butene in trial 1 is less than that in trial 2 and k is constant.	1 point is earned for the correct answer with justification.
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- (d) The half-life of the reaction in trial 4 is less than the half-life in trial 1. Explain why, in terms of activation energy.

The temperature is higher in trial 4, meaning that the KE_{avg} of the molecules is greater. Consequently, in this trial a greater fraction of collisions have sufficient energy to overcome the activation energy barrier, thus the rate is greater.	1 point is earned for a correct answer with justification.
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