

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:

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

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

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 3: Long Answer

10 points

(a) For a correct electron configuration: 1 point

Accept one of the following:

- $1s^2 2s^2 2p^6 3s^2 3p^1$
- $[\text{Ne}] 3s^2 3p^1$

(b) For a correct explanation: 1 point

The highest occupied electron shell ($n=3$) of Al is at a greater average distance from the nucleus than the highest occupied electron shell ($n=2$) of Al^{3+} .

(c) For the correct steps to dissolve the solute in water (steps may be consolidated): 1 point

- Partially fill the volumetric flask with some distilled water
- Add the weighed $\text{AgNO}_3(s)$ to the volumetric flask
- Swirl to dissolve the solid

For the correct step to ensure quantitative dilution: 1 point

- After the solid is dissolved, fill the flask to the calibration (200.00 mL) mark and mix.

Total for part (c) 2 points

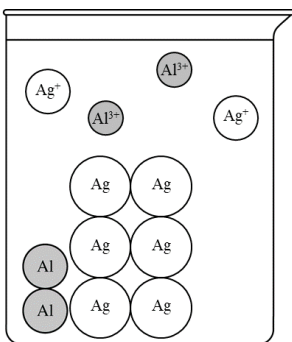
(d) For a drawing that shows product formation and indicates the conservation of matter: 1 point

4 Al and 8 Ag particles in the beaker on right (see sample drawing below)

For a drawing that shows product formation and conservation of charge: 1 point

2 Ag^+ ions and 2 Al^{3+} ions in the beaker on the right (see sample drawing below)

For a drawing that shows product formation and correct phases of matter for all species: 1 point

6 Ag atoms that are solid and 2 Al^{3+} ions that are aqueous in the beaker on the right

Total for part (d) 3 points

(e) For the correct calculated value: 1 point

Accept one of the following:

- $E^\circ = 0.80 \text{ V} + 1.66 \text{ V} = 2.46 \text{ V}$
- $E^\circ_{\text{cell}} = E^\circ_{\text{red}} - E^\circ_{\text{ox}} = 0.80 \text{ V} - (-1.66 \text{ V}) = 2.46 \text{ V}$

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

Negative. The reaction has a positive value of E° , indicating that it is thermodynamically favorable and would therefore have a negative value of ΔG° . ($\Delta G^\circ = -nFE^\circ$)

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

Accept one of the following:

- Zero. The observation that the reaction stops progressing implies that $E_{\text{cell}} = 0$, indicating that there is no longer a driving force for the reaction.
- Zero. The observation that reaction stops progressing implies that equilibrium is established, and $\Delta G = 0$ at equilibrium.

Total for question 3 10 points

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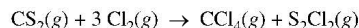
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AP Chemistry

Scoring Guidelines

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Question 1



Carbon tetrachloride, $\text{CCl}_4(\text{g})$, 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, $\text{Cl}_2(\text{g})$, is initially present in the container at a pressure of 0.40 atm.

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

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

$0.31 \text{ mol } \text{Cl}_2 \times \frac{1 \text{ mol } \text{CS}_2}{3 \text{ mol } \text{Cl}_2} \times \frac{76.13 \text{ g } \text{CS}_2}{1 \text{ mol } \text{CS}_2} = 7.9 \text{ g } \text{CS}_2$	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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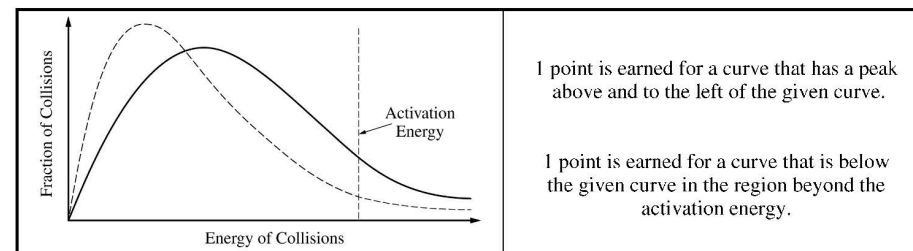
(b) At 30°C the reaction is thermodynamically favorable, but no reaction is observed to occur. However, at 120°C , the reaction occurs at an observable rate.

(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)

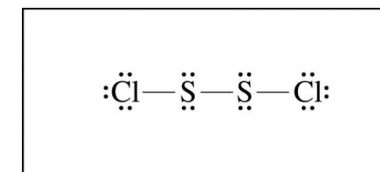


1 point is earned for a curve that has a peak above and to the left of the given curve.

1 point is earned for a curve that is below the given curve in the region beyond the activation energy.

(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.

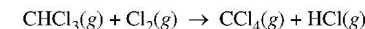
1 point is earned for a correctly drawn diagram.

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



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

- (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.

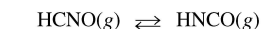
In the diagram on the left, the C atom has a formal charge of zero and the O atom has a formal charge of -1 . In the diagram on the right, the C atom has a formal charge of -1 and the O atom has a formal charge of zero.

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*

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
- $\text{HCNO}(g)$
- to form
- $\text{HNCO}(g)$
- .

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

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

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.)

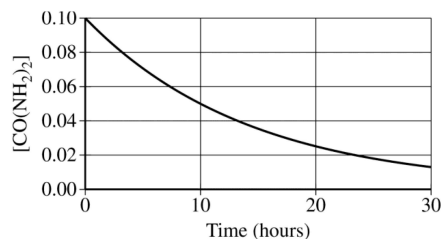
1 point is earned for correctly connecting thermodynamic favorability to the equilibrium constant, K .

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 $\text{rate} = k[\text{CO}(\text{NH}_2)_2]$.

- (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.

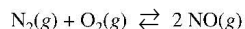
- (f) The student learns that the decomposition reaction was run in a solution with a pH of 13. Briefly describe an experiment, including the initial conditions that you would change and the data you would gather, to determine whether the rate of the reaction depends on the concentration of $\text{OH}^-(aq)$.

Perform the experiment at a different concentration of $\text{OH}^-(aq)$ and measure how the concentration of $\text{CO}(\text{NH}_2)_2$ 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

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

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

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

1 point is earned for the correct calculation of K_p .

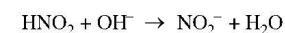
Nitrogen monoxide, $\text{NO}(\text{g})$, can undergo further reactions to produce acids, such as HNO_2 , a weak acid with a K_a of 4.0×10^{-4} and a $\text{p}K_a$ of 3.40.

- (c) A student is asked to make a buffer solution with a pH of 3.40 by using 0.100 M $\text{HNO}_2(\text{aq})$ and 0.100 M $\text{NaOH}(\text{aq})$.
- (i) Explain why the addition of 0.100 M $\text{NaOH}(\text{aq})$ to 0.100 M $\text{HNO}_2(\text{aq})$ 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.



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.

- (ii) Determine the volume, in mL, of 0.100 M $\text{NaOH}(\text{aq})$ the student should add to 100. mL of 0.100 M $\text{HNO}_2(\text{aq})$ 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 $\text{NaOH}(\text{aq})$.

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

$$\text{pH} = \text{p}K_a + \log \frac{[\text{NO}_2^-]}{[\text{HNO}_2]}, \text{ thus } \text{pH} = \text{p}K_a \text{ when } [\text{HNO}_2] = [\text{NO}_2^-]$$

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).

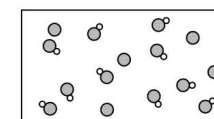
- (d) A second student makes a buffer by dissolving 0.100 mol of $\text{NaNO}_2(\text{s})$ in 100. mL of 1.00 M $\text{HNO}_2(\text{aq})$. Which is more resistant to changes in pH when a strong acid or a strong base is added, the buffer made by the second student or the buffer made by the first student 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.

- (e) A new buffer is made using $\text{HNO}_2(\text{aq})$ 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.

● HNO_2 molecule ● NO_2^- ion



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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

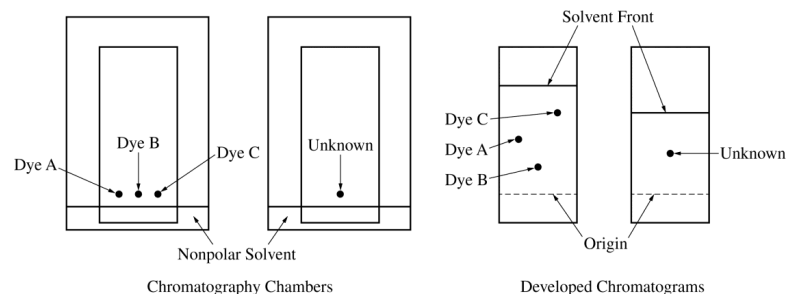
$$\text{pH} = \text{p}K_a + \log \frac{[\text{NO}_2^-]}{[\text{HNO}_2]} \Rightarrow \text{pH} = 3.40 + \log \frac{5}{10} \Rightarrow \text{pH} = 3.10$$

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.

- (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

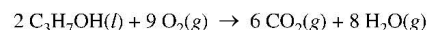
Dye A has a retention factor (R_f) that is close to 0.50 on the chromatogram with the three dyes, and the unknown also has a retention factor close to 0.50.

1 point is earned for the correct choice.

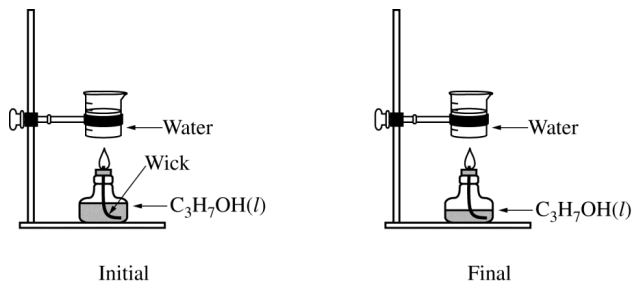
1 point is earned for a valid justification.

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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.)

$q = mc\Delta T$ $= (125.00 \text{ g})(4.18 \text{ J/(g}\cdot\text{°C)})(51.1^\circ\text{C} - 22.0^\circ\text{C})$ $= 15,200 \text{ J} = 15.2 \text{ kJ}$	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.

- (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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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.

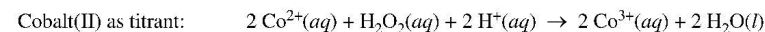
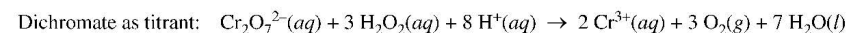
1 point is earned for the correct comparison of cation sizes.

1 point is earned for indicating that smaller interionic distances lead to a greater lattice energy.

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.
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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

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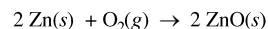
SCORING GUIDELINES

Question

Metal-air cells are a relatively new type of portable energy source consisting of a metal anode, an alkaline electrolyte paste that contains water, and a porous cathode membrane that lets in oxygen from the air. A schematic of the cell is shown above. Reduction potentials for the cathode and three possible metal anodes are given in the table below.

Half Reaction	E at pH 11 and 298 K (V)
$\text{O}_2(\text{g}) + 2 \text{H}_2\text{O}(\text{l}) + 4 \text{e}^- \rightarrow 4 \text{OH}^-(\text{aq})$	+0.34
$\text{ZnO}(\text{s}) + \text{H}_2\text{O}(\text{l}) + 2 \text{e}^- \rightarrow \text{Zn}(\text{s}) + 2 \text{OH}^-(\text{aq})$	-1.31
$\text{Na}_2\text{O}(\text{s}) + \text{H}_2\text{O}(\text{l}) + 2 \text{e}^- \rightarrow 2 \text{Na}(\text{s}) + 2 \text{OH}^-(\text{aq})$	-1.60
$\text{CaO}(\text{s}) + \text{H}_2\text{O}(\text{l}) + 2 \text{e}^- \rightarrow \text{Ca}(\text{s}) + 2 \text{OH}^-(\text{aq})$	-2.78

Early forms of metal-air cells used zinc as the anode. Zinc oxide is produced as the cell operates according to the overall equation below.



(i) Using the data in the table above, calculate the cell potential for the zinc-air cell.

$E_{\text{cell}} = 0.34 \text{ V} - (-1.31 \text{ V}) = 1.65 \text{ V}$	1 point is earned for the correct cell potential.
---	---

(ii) The electrolyte paste contains OH^- ions. On the diagram of the cell above, draw an arrow to indicate the direction of migration of OH^- ions through the electrolyte as the cell operates.

(The arrow should point to the left.)	1 point is earned for indicating the movement of OH^- ions from right to left in the cell.
---------------------------------------	---

A fresh zinc-air cell is weighed on an analytical balance before being placed in a hearing aid for use.

(i) As the cell operates, does the mass of the cell increase, decrease, or remain the same?

The mass increases.	1 point is earned for indicating an increase in cell mass.
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(ii) Justify your answer to part (b)(i) in terms of the equation for the overall cell reaction.

Oxygen gas from the air reacts with $\text{Zn}(\text{s})$ in the cell, producing $\text{ZnO}(\text{s})$, which has more mass than the original $\text{Zn}(\text{s})$.	1 point is earned for the justification.
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SCORING GUIDELINES

Question 1 (continued)

The zinc-air cell is taken to the top of a mountain where the air pressure is lower.

(i) Will the cell potential be higher, lower, or the same as the cell potential at the lower elevation?

The cell potential will be lower.	1 point is earned for indicating a lower cell potential.
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(ii) Justify your answer to part (c)(i) based on the equation for the overall cell reaction and the information above.

$\text{O}_2(\text{g})$, a reactant in the cell reaction, will be at a lower partial pressure at the higher elevation; thus the reaction has a greater value of Q (closer to K). Deviations in partial pressure that take the cell closer to equilibrium will decrease the magnitude of the cell potential.	1 point is earned for a justification that relates lower pressure (or concentration) of O_2 or a qualitative approach using the Nernst equation.
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Metal-air cells need to be lightweight for many applications. In order to transfer more electrons with a smaller mass, Na and Ca are investigated as potential anodes. A 1.0 g anode of which of these metals would transfer more electrons, assuming that the anode is totally consumed during the lifetime of a cell? Justify your answer with calculations.

$\text{Na, } 1.0 \text{ g Na} \times \frac{1.0 \text{ mol Na}}{22.99 \text{ g Na}} \times \frac{1.0 \text{ mol e}^-}{1.0 \text{ mol Na}} = 0.043 \text{ mol e}^-$	1 point is earned for the correct calculation of moles for Na
$\text{Ca, } 1.0 \text{ g Ca} \times \frac{1.0 \text{ mol Ca}}{40.08 \text{ g Ca}} \times \frac{2.0 \text{ mol e}^-}{1.0 \text{ mol Ca}} = 0.050 \text{ mol e}^-$	1 point is earned for taking 1 vs. 2 moles of electrons into account the correct answer.
The cell with the Ca anode would transfer more electrons.	

The only common oxide of zinc has the formula ZnO .

(i) Write the electron configuration for a Zn atom in the ground state.

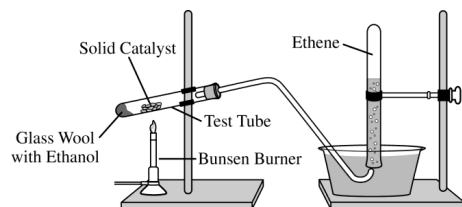
$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10}$ or $[\text{Ar}] 4s^2 3d^{10}$	1 point is earned for a correct configuration.
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(ii) From which sublevel are electrons removed when a Zn atom in the ground state is oxidized?

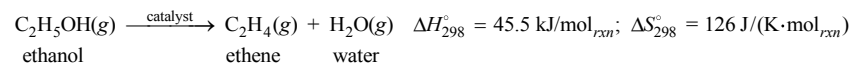
4s sublevel	1 point is earned for the correct answer.
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2015 SCORING GUIDELINES

Question



Ethene, $\text{C}_2\text{H}_4(\text{g})$ (molar mass 28.1 g/mol), may be prepared by the dehydration of ethanol, $\text{C}_2\text{H}_5\text{OH}(\text{l})$ (molar mass 46.1 g/mol), using a solid catalyst. A setup for the lab synthesis is shown in the diagram above. The equation for the dehydration reaction is given below.



A student added a 0.200 g sample of $\text{C}_2\text{H}_5\text{OH}(\text{l})$ to a test tube using the setup shown above. The student heated the test tube gently with a Bunsen burner until all of the $\text{C}_2\text{H}_5\text{OH}(\text{l})$ evaporated and gas generation stopped. When the reaction stopped, the volume of collected gas was 0.0854 L at 0.822 atm and 305 K. (The vapor pressure of water at 305 K is 35.7 torr.)

Calculate the number of moles of $\text{C}_2\text{H}_4(\text{g})$

(i) that are actually produced in the experiment and measured in the gas collection tube and

$35.7 \text{ torr} \times \frac{1 \text{ atm}}{760 \text{ torr}} = 0.0470 \text{ atm}$ $P_{\text{ethene}} = P_{\text{total}} - P_{\text{water}} = 0.822 \text{ atm} - 0.0470 \text{ atm} = 0.775 \text{ atm}$ $n = \frac{PV}{RT} = \frac{(0.775 \text{ atm})(0.0854 \text{ L})}{(0.08206 \text{ L atm mol}^{-1} \text{ K}^{-1})(305 \text{ K})} = 0.00264 \text{ mol}$	1 point is earned for the calculation the pressure of the dry ethene. 1 point is earned for the correct number of moles of ethene gas.
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(ii) that would be produced if the dehydration reaction went to completion.

$0.200 \text{ g C}_2\text{H}_5\text{OH} \times \frac{1 \text{ mol C}_2\text{H}_5\text{OH}}{46.1 \text{ g C}_2\text{H}_5\text{OH}} \times \frac{1 \text{ mol C}_2\text{H}_4}{1 \text{ mol C}_2\text{H}_5\text{OH}}$ $= 0.00434 \text{ mol C}_2\text{H}_4 \text{ produced}$	1 point is earned for the correct number of moles of ethene produced.
---	--

Calculate the percent yield of $\text{C}_2\text{H}_4(\text{g})$ in the experiment.

$\% \text{ yield} = \frac{\text{actual yield}}{\text{maximum possible yield}} \times 100 = \frac{0.00264 \text{ mol}}{0.00434 \text{ mol}} \times 100 = 60.8\%$	1 point is earned for the correct percent yield.
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2015 SCORING GUIDELINES

Question 2 (continued)

Because the dehydration reaction is not observed to occur at 298 K, the student claims that the reaction has an equilibrium constant less than 1.00 at 298 K.

Do the thermodynamic data for the reaction support the student's claim? Justify your answer, including a calculation of ΔG_{298}° for the reaction.

Yes, the data support the student's claim.

$$\begin{aligned} \Delta G^\circ &= \Delta H^\circ - T\Delta S^\circ \\ &= 45.5 \text{ kJ/mol}_{\text{rxn}} - (298 \text{ K})(0.126 \text{ kJ/(K}\cdot\text{mol}_{\text{rxn}})) = 8.0 \text{ kJ/mol}_{\text{rxn}} \end{aligned}$$

Because $\Delta G^\circ > 0$, the value of $K_p = e^{\frac{-\Delta G^\circ}{RT}} < 1.00$.

1 point is earned for the correct calculation of Δ

1 point is earned for a valid justification.

The Lewis electron-dot diagram for C_2H_4 is shown below in the box on the left. In the box on the right, complete the Lewis electron-dot diagram for $\text{C}_2\text{H}_5\text{OH}$ by drawing in all of the electron pairs.

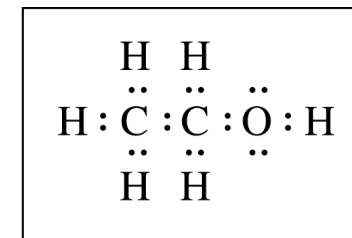
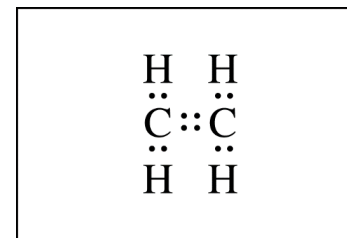


Diagram should include all bonding pairs plus two nonbonding pairs on the O atom. (A line may be used to represent an electron pair.)

1 point is earned for a correct diagram.

What is the approximate value of the C–O–H bond angle in the ethanol molecule?

The bond angle is approximately 109° .

1 point is earned for an angle from 100° to 115° .

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Question continued)

During the dehydration experiment, $\text{C}_2\text{H}_4(g)$ and unreacted $\text{C}_2\text{H}_5\text{OH}(g)$ passed through the tube into the water. The C_2H_4 was quantitatively collected as a gas, but the unreacted $\text{C}_2\text{H}_5\text{OH}$ was not. Explain this observation in terms of the intermolecular forces between water and each of the two gases.

Ethene is only slightly soluble in water because the weak dipole/induced dipole intermolecular attractions between nonpolar ethene molecules and polar water molecules are weaker than the hydrogen bonds between water molecules. Ethanol molecules are soluble in water because they are polar and form hydrogen bonds with water molecules as they dissolve.

1 point is earned for comparing the solubility of ethene in water with the solubility of ethanol in water in terms of differences in polarity.

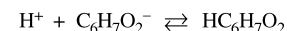
1 point is earned for describing the intermolecular forces between ethene and water as weak dipole/induced dipole forces and attributing the solubility of ethanol in water to the hydrogen bonds formed between ethanol molecules and water molecules.

2015 SCORING GUIDELINES

Question

Potassium sorbate, $\text{KC}_6\text{H}_7\text{O}_2$ (molar mass 150. g/mol) is commonly added to diet soft drinks as a preservative. A stock solution of $\text{KC}_6\text{H}_7\text{O}_2(aq)$ of known concentration must be prepared. A student titrates 45.00 mL of the stock solution with 1.25 M $\text{HCl}(aq)$ using both an indicator and a pH meter. The value of K_a for sorbic acid, I_7O_2 , is 1.7×10^{-5} .

Write the net-ionic equation for the reaction between $\text{KC}_6\text{H}_7\text{O}_2(aq)$ and $\text{HCl}(aq)$.



1 point is earned the net-ionic equation.

A total of 29.95 mL of 1.25 M $\text{HCl}(aq)$ is required to reach the equivalence point. Calculate [KC the stock solution.

$$\frac{1.25 \text{ mol HCl}}{1000 \text{ mL}} = \frac{x \text{ mol HCl}}{29.95 \text{ mL}} \quad x = 0.0374 \text{ mol HCl}$$

$$\frac{0.0374 \text{ mol C}_6\text{H}_7\text{O}_2^-}{45.0 \text{ mL}} = \frac{x \text{ mol C}_6\text{H}_7\text{O}_2^-}{1000 \text{ mL}} \Rightarrow 0.832 \text{ M}$$

1 point is earned for the moles of HCl at the equivalence point.

1 point is earned for the correct answer.

The pH at the equivalence point of the titration is measured to be 2.54. Which of the following indicators would be the best choice for determining the end point of the titration? Justify your answer.

Indicator	$\text{p}K_a$
Phenolphthalein	9.3
Bromothymol blue	7.0
Methyl red	5.0
Thymol blue	2.0
Methyl violet	0.80

Thymol blue; it has a $\text{p}K_a$ close to the pH at the equivalence point, so it will change color near the equivalence point.

1 point is earned for the correct indicator.

1 point is earned for correct justification.

Calculate the pH at the half-equivalence point.

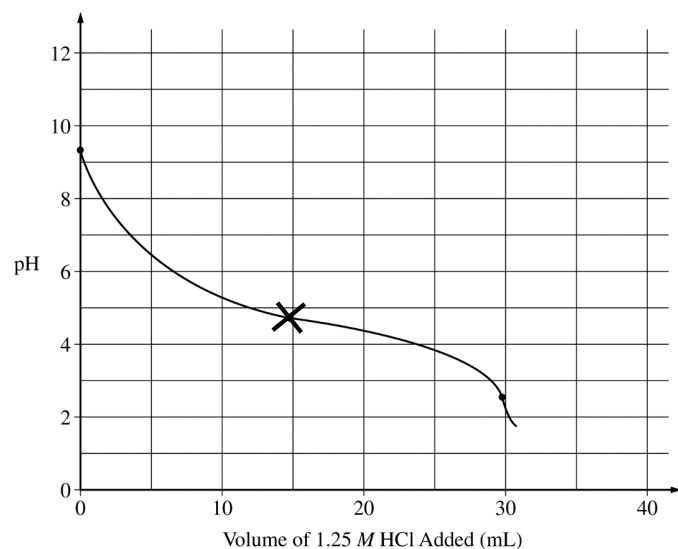
$$\text{pH} = \text{p}K_a = -\log(1.7 \times 10^{-5}) = 4.77$$

1 point is earned for the correct pH.

2015 SCORING GUIDELINES

Question 3 (continued)

The initial pH and the equivalence point are plotted on the graph below. Accurately sketch the titration curve on the graph below. Mark the position of the half-equivalence point on the curve with an



The pH curve should have the correct shape.]

- 1 point is earned for a half-equivalence point consistent with the answer to part (d) and at the correct volume.
- 1 point is earned for a curve that levels off to a relatively horizontal slope through the half-equivalence point.
- 1 point is earned for a relatively steep negative slope through the equivalence point.

2015 SCORING GUIDELINES

Question 3 (continued)

The pH of the soft drink is 3.37 after the addition of the $\text{KC}_6\text{H}_7\text{O}_2(aq)$. Which species, $\text{HC}_6\text{H}_7\text{O}_2$ or $\text{C}_6\text{H}_7\text{O}_2^-$, has a higher concentration in the soft drink? Justify your answer.

$$\text{For sorbic acid, } K_a = \frac{[\text{H}^+][\text{C}_6\text{H}_7\text{O}_2^-]}{[\text{HC}_6\text{H}_7\text{O}_2]},$$

$$\text{thus } \frac{[\text{C}_6\text{H}_7\text{O}_2^-]}{[\text{HC}_6\text{H}_7\text{O}_2]} = \frac{K_a}{[\text{H}^+]} = \frac{1.7 \times 10^{-5}}{10^{-3.37}} \approx 0.04$$

$$\Rightarrow [\text{HC}_6\text{H}_7\text{O}_2] > [\text{C}_6\text{H}_7\text{O}_2^-]$$

The concentrations of $\text{HC}_6\text{H}_7\text{O}_2$ and $\text{C}_6\text{H}_7\text{O}_2^-$ are equal at the half-equivalence point. A pH of 3.37 is lower than that at the half-equivalence point, so the protonated form, $\text{HC}_6\text{H}_7\text{O}_2$, has a higher concentration in the soft drink.

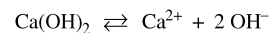
1 point is earned for identifying the correct species and for making a comparison involving the pH (with or without calculation).

2015 SCORING GUIDELINES

Question

Answer the following questions about the solubility of Ca(OH)_2 ($K_{sp} = 1.3 \times 10^{-6}$).

Write a balanced chemical equation for the dissolution of $\text{Ca(OH)}_2(s)$ in pure water.



1 point is earned for the correct equation.

Calculate the molar solubility of Ca(OH)_2 in $0.10 \text{ M Ca(NO}_3)_2$.

$$= [\text{Ca}^{2+}] [\text{OH}^-]^2$$

$$: 10^{-6} = (0.10 + x) (2x)^2 \approx (0.10) 4x^2 \quad [\text{assuming } x \ll 0.10]$$

$$: 10^{-5} = 4x^2$$

$$= 0.0018 \text{ M}$$

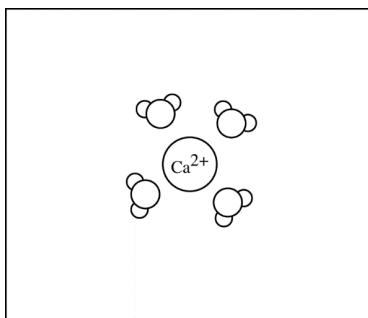
$$\text{Molar solubility of Ca(OH)}_2 = 0.0018 \text{ M}$$

1 point is earned for the correct stoichiometry and setup.

1 point is earned for the final answer.

In the box below, complete a particle representation diagram that includes four water molecules with proper orientation around the Ca^{2+} ion.

Represent water molecules as 

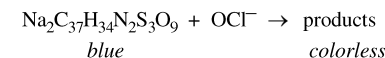


[The diagram should show the oxygen side of the water molecules oriented closer to the Ca^{2+} ion.]

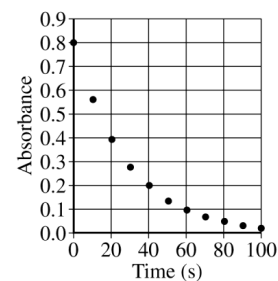
1 point is earned for a correct diagram that shows at least three of the four water molecules oriented as described.

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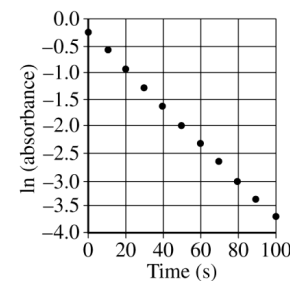
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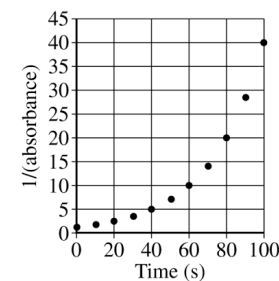
Blue food coloring can be oxidized by household bleach (which contains OCl^-) to form colorless products, as represented by the equation above. A student used a spectrophotometer set at a wavelength of 635 nm to study the absorbance of the food coloring over time during the bleaching process. In the study, bleach is present in large excess so that the concentration of OCl^- is essentially constant throughout the reaction. The student used data from the study to generate the graphs below.



Graph I



Graph II



Graph III

Based on the graphs above, what is the order of the reaction with respect to the blue food coloring?

First order

1 point is earned for the correct order.

The reaction is known to be first order with respect to bleach. In a second experiment, the student prepares solutions of food coloring and bleach with concentrations that differ from those used in the first experiment. When the solutions are combined, the student observes that the reaction mixture reaches an absorbance near zero too rapidly. In order to correct the problem, the student proposes the following three possible modifications to the experiment.

- Increasing the temperature
- Increasing the concentration of the food coloring
- Increasing the concentration of the bleach

Circle the one proposed modification above that could correct the problem and explain how that modification increases the time for the reaction mixture to reach an absorbance near zero.

2015 SCORING GUIDELINES

Question (continued)

["Increasing the concentration of the food coloring" should be circled.]	1 point is earned for the correct choice.
If the initial concentration of blue food coloring is increased, then more time is required (regardless of reaction order indicated in part (a)) for the bleach to oxidize the additional blue food coloring.	1 point is earned for a correct explanation.

In another experiment, a student wishes to study the oxidation of red food coloring with bleach. How would the student need to modify the original experimental procedure to determine the order of the reaction with respect to the red food coloring?

The spectrophotometer should be set to a different wavelength.	1 point is earned for a correct answer.
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2015 SCORING GUIDELINES

Question

Compound	Melting Point (°C)
LiI	449
KI	686
LiF	845
NaF	993

A student learns that ionic compounds have significant covalent character when a cation has a polarizing effect on a large anion. As a result, the student hypothesizes that salts composed of small cations and large anions should have relatively low melting points.

Select two compounds from the table and explain how the data support the student's hypothesis.

LiI and KI. LiI has a small cation and a large anion and KI has a large cation and the same large anion. The melting point of LiI (with its smaller cation) is lower than that of KI.	1 point is earned for choosing an appropriate pair of compounds (LiI/KI, LiI/LiF, or LiI/NaF)
LiI and LiF. LiI has a small cation and a large anion and LiF has the same small cation and a small anion. The melting point of LiI (with its larger anion) is lower than that of LiF.	1 point is earned for an explanation that supports the hypothesis.
LiI and NaF. LiI has a small cation and a large anion and NaF has a relatively small cation and a small anion. The melting point of LiI (with its larger anion) is lower than that of NaF.	

Identify a compound from the table that can be dissolved in water to produce a basic solution. Write the net ionic equation for the reaction that occurs to cause the solution to be basic.

Either LiF or NaF is acceptable.	1 point is earned for choosing one of the correct compounds.
$+ \text{H}_2\text{O} \rightleftharpoons \text{HF} + \text{OH}^-$	1 point is earned for writing a correct balanced equation.

2015 SCORING GUIDELINES

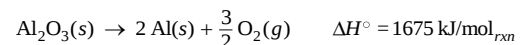
Question

Aluminum metal can be recycled from scrap metal by melting the metal to evaporate impurities.

Calculate the amount of heat needed to purify 1.00 mole of Al originally at 298 K by melting it. The melting point of Al is 933 K. The molar heat capacity of Al is 24 J/(mol·K), and the heat of fusion of Al is 10.7 kJ/mol.

To raise the temperature from 298 K to 933 K: $= \frac{24 \text{ J}}{\text{mol K}} \times 1.00 \text{ mol} \times 635 \text{ K} = 15,000 \text{ J} = 15 \text{ kJ}$ It takes 10.7 kJ to melt the Al at 933 K. $\text{J} + 10.7 \text{ kJ} = 26 \text{ kJ}$	1 point is earned for calculating the amount heat needed to raise the temperature to 933 K. 1 point is earned for adding the heat of fusion to the previous result to get a final answer.
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The equation for the overall process of extracting Al from Al_2O_3 is shown below. Which requires less energy, recycling existing Al or extracting Al from Al_2O_3 ? Justify your answer with a calculation.



For extracting Al from ore: $1675 \text{ kJ/mol}_{\text{rxn}} \times \frac{1 \text{ mol of reaction}}{2 \text{ mol Al}} = 837.5 \text{ kJ per mol of Al}$ Producing 1.00 mol of Al from Al_2O_3 requires 837.5 kJ. Because 26 kJ < 837.5 kJ, recycling requires less energy.	1 point is earned for a calculation to get equal numbers of moles for comparison. 1 point is earned for a correct comparison.
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