## Question 2: Long Answer — 10 points

**A** (i) For the correct calculated value: **Point 01**

$$2.883 \text{ g } H_2O \times \frac{1 \text{ mol } H_2O}{18.02 \text{ g } H_2O} = 0.1600 \text{ mol } H_2O$$

(ii) For the correct calculated number of moles of H (may be implicit): **Point 02**

$$0.1600 \text{ mol } H_2O \times \frac{2 \text{ mol H}}{1 \text{ mol } H_2O} = 0.3200 \text{ mol H}$$

For the correct empirical formula. **Point 03**

Examples of acceptable responses may include the following:

- $x : y : z$ = (moles of C):(moles of H):(moles of O)
  $x : y : z = 0.2400 : 0.3200 : 0.2400 = 3 : 4 : 3$
  *Therefore, the empirical formula of ascorbic acid is* $C_3H_4O_3$.
- $0.2400 \text{ mol } CO_2 \times \frac{1 \text{ mol C}}{1 \text{ mol } CO_2} = 0.2400 \text{ mol C}$
  $\frac{0.3200 \text{ mol H}}{0.2400 \text{ mol C}} = \frac{4 \text{ H}}{3 \text{ C}}$
  *Given that the ratio of* C:O *is* 1:1, *the empirical formula of ascorbic acid is* $C_3H_4O_3$.

**B** (i) For the correct calculated value: **Point 04**

$$0.0160 \text{ L NaOH} \times \frac{0.0550 \text{ mol NaOH}}{1 \text{ L NaOH}} \times \frac{1 \text{ mol HAsc}}{1 \text{ mol NaOH}} = 8.80 \times 10^{-4} \text{ mol HAsc}$$

$$\frac{8.80 \times 10^{-4} \text{ mol HAsc}}{0.0100 \text{ L}} = 0.0880 \ M \text{ HAsc}$$

(ii) For the correct $pK_a$: **Point 05**

4.1 (*acceptable range:* 4.0 – 4.3)

(iii) For the correct ratio, consistent with part B (ii): **Point 06**

*Using the Henderson-Hasselbalch equation:*

$$pH = pK_a + \log\left(\frac{[Asc^-]}{[HAsc]}\right)$$

$$4.7 = 4.1 + \log\left(\frac{[Asc^-]}{[HAsc]}\right)$$

$$\frac{[Asc^-]}{[HAsc]} = 10^{0.6} = 4.0$$





**C** (i) For a correct explanation. **Point 07**

Examples of acceptable responses may include the following:

- $\frac{4.914 \times 10^{-4}}{2.457 \times 10^{-4}} = \left(\frac{0.900}{0.450}\right)^a$, thus $a = 1$
- *Comparing trials 1 and 3, the rate doubles when the concentration of ascorbic acid is doubled and the triiodide ion concentration is constant, indicating that the process is first order with respect to ascorbic acid.*

(ii) For the correct calculated value: **Point 08**

$rate = k[HAsc][I_3^-]$

*Using trial 1 data:*

$$k = \frac{rate}{[HAsc][I_3^-]} = \frac{2.457 \times 10^{-4} \ M/s}{(0.450 \ M)(1.200 \ M)} = 4.55 \times 10^{-4} M^{-1} \text{ s}^{-1}$$

For the correct units: **Point 09**

$M^{-1}$ $s^{-1}$

**D** For the correct answer: **Point 10**

*Ion-dipole attractions are present between* $I_3^-$ *ions and water but not between* $I_2$ *molecules and water.*

## Question 2: Long Answer — 10 points

**(a) (i)** For the correct calculated value: **1 point**

$$0.0114 \text{ mol } CO_2 \times \frac{44.01 \text{ g}}{1 \text{ mol}} = 0.502 \text{ g } CO_2$$

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

$PV = nRT$

$$V = \frac{nRT}{P} = \frac{(0.0114 \text{ mol})(0.08206 \ \frac{\text{L·atm}}{\text{mol·K}})(293 \text{ K})}{1.25 \text{ atm}} = 0.219 \text{ L}$$

**Total for part (a)** **2 points**

**(b) (i)** For a correct claim: **1 point**

*The surface area of the solid reactants increases.*

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

*Shorter than. The powdered solids have a larger surface area than the solid chunks, thus collisions between water and the surface particles occur more frequently, resulting in a faster rate of dissolution and a shorter amount of time to dissolve the solids.*

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

*Equal to. Both experiments begin with the same amount of reactants, so they will produce the same number of moles of* $CO_2(g)$ *under the same conditions of pressure and temperature; therefore, the final volume will be the same.*

**Total for part (b)** **3 points**

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

Accept one of the following:

- $NaHCO_3$ *is the limiting reactant because changing the mass of* $NaHCO_3$ *alters the amount of* $CO_2$ *produced.*
- $NaHCO_3$ *is the limiting reactant because the amount present has a smaller theoretical yield of the* $CO_2$ *product.*

$$1.543 \text{ g } H_2C_4H_2O_4 \times \frac{1 \text{ mol } H_2C_4H_2O_4}{116.07 \text{ g}} \times \frac{2 \text{ mol } CO_2}{1 \text{ mol } H_2C_4H_2O_4} = 0.02659 \text{ mol } CO_2$$

$$1.251 \text{ g } NaHCO_3 \times \frac{1 \text{ mol } NaHCO_3}{84.01 \text{ g}} \times \frac{2 \text{ mol } CO_2}{2 \text{ mol } NaHCO_3} = 0.01489 \text{ mol } CO_2$$

**(d)** For a valid explanation: **1 point**

*The entropy change is positive because the aqueous reactants produce 2 moles of gas particles, according to the balanced chemical equation. Gases are far more dispersed (occupy a greater number of microstates) than condensed phases, so the entropy of the products is greater than that of the reactants.*





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

Accept one of the following:

- *Disagree. The reaction is endothermic and has a positive entropy change. Thus, the reaction is only thermodynamically favorable at a high enough temperature such that the magnitude of* $-T\Delta S$ *is greater than that of* $\Delta H$.
- *Disagree. For the reaction to be thermodynamically favorable* $(\Delta G < 0)$ *at all temperatures, the reaction must be exothermic* $(\Delta H < 0)$ *and have a positive entropy change* $(\Delta S > 0)$.

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

$$pK_{a_2} = -\log\left(8.5 \times 10^{-7}\right) = 6.07$$

**(g)** For the correct calculated value: **1 point**

$$\text{pH} = pK_{a_2} + \log\frac{[C_4H_2O_4^{2-}]}{[HC_4H_2O_4^{-}]}$$

$$\frac{[C_4H_2O_4^{2-}]}{[HC_4H_2O_4^{-}]} = 10^{(\text{pH}-pK_{a_2})} = 10^{(7.00-6.07)} = 8.5$$

**Total for question 2** **10 points**



## Question 4: Short Answer — 4 points

**(a)** For the correct calculated value: **1 point**

$$0.00250 \text{ mol } CH_3NH_3Cl \times \frac{67.52 \text{ g}}{1 \text{ mol}} = 0.169 \text{ g}$$

**(b)** For a correct description of step 1: **1 point**

Accept one of the following:

- *Use the spatula, balance, and weighing paper to measure out exactly* $0.169$ g *of* $CH_3NH_3Cl(s)$.
- *Use the balance to weigh out the mass of solid in part (a).*

For a correct description of step 4: **1 point**

*Rinse the buret with a small amount of* $0.100\ M\ CH_3NH_2(aq)$, *drain, and refill with* $0.100\ M\ CH_3NH_2(aq)$.

**Total for part (b)** **2 points**

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

*Equal to. The ratio of weak acid to conjugate base is still 1:1.*

**Total for question 4** **4 points**

2019

AP CollegeBoard

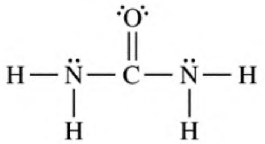
# AP® Chemistry
## Scoring Guidelines





## 2019 SCORING GUIDELINES

### Question 1

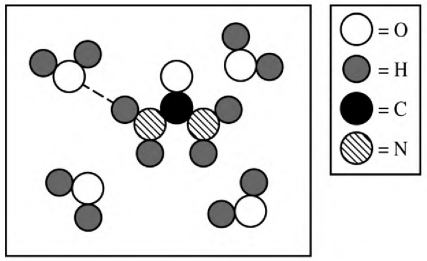


The compound urea, $H_2NCONH_2$, is widely used in chemical fertilizers. The complete Lewis electron-dot diagram for the urea molecule is shown above.

(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. |

(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. |

$$H_2NCONH_2(s) \rightleftarrows H_2NCONH_2(aq)$$

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.

## 2019 SCORING GUIDELINES

### Question 1 (continued)

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

| | |
|---|---|
| $5.39\text{ g } H_2NCONH_2 \times \frac{1\text{ mol}}{60.06\text{ g}} = 0.0897\text{ mol}$<br><br>$\frac{0.0897\text{ mol}}{0.00500\text{ L}} = 17.9\ M$ | 1 point is earned for the correct number of moles of urea (may be implicit).<br><br>1 point is earned for the correct molarity. |

(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. |


(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.<br><br>1 point is earned for the temperatures. |





2019 SCORING GUIDELINES

Question 1 (continued)

| | $S°$ (J/(mol·K)) |
|---|---|
| $H_2NCONH_2(s)$ | 104.6 |
| $H_2NCONH_2(aq)$ | ? |

(f) The entropy change for the dissolution of urea, $\Delta S°_{soln}$, 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.

| | |
|---|---|
| $\Delta S°_{soln} = S°(H_2NCONH_2(aq)) - S°(H_2NCONH_2(s))$<br>$70.1\text{ J/(mol·K)} = S°(H_2NCONH_2(aq)) - 104.6\text{ J/(mol·K)}$<br>$S°(H_2NCONH_2(aq)) = 174.7\text{ J/(mol·K)}$ | 1 point is earned for the correct answer. |

(g) Using particle-level reasoning, explain why $\Delta S°_{soln}$ 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 $\Delta S°_{soln}$. | 1 point is earned for a correct explanation. |

(h) The student claims that $\Delta S°$ 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 $\Delta G°$, with $\Delta G° = \Delta H° - T\Delta S°$. Since $\Delta S°$ is positive, the $T\Delta S°$ term makes the value of $\Delta G°$ smaller and thus makes the dissolution more thermodynamically favorable. | 1 point is earned for the correct answer. |

# 2019 SCORING GUIDELINES

## 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.

$Br_2$ $Cl_2$ $F_2$ $I_2$

| | |
|---|---|
| $I_2$ 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: NaBr($aq$), $Cl_2(g)$, and $I_2(s)$.

| Half-Reaction | $E°$ at 25°C (V) |
|---|---|
| $Br_2 + 2\,e^- \rightarrow 2\,Br^-$ | 1.07 |
| $Cl_2 + 2\,e^- \rightarrow 2\,Cl^-$ | 1.36 |
| $I_2 + 2\,e^- \rightarrow 2\,I^-$ | 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.

| | |
|---|---|
| $2\,Br^- + Cl_2 \rightarrow Br_2 + 2\,Cl^-$<br><br>$E° = E°$(reduced species) $- E°$(oxidized species)<br>$= 1.36\text{ V} - 1.07\text{ V} = +0.29\text{ V}$.<br><br>Because $E°$ for the reaction has a positive value, the reaction is thermodynamically favorable. | 1 point is earned for the correct balanced equation.<br><br>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 <u>each</u> substance.





2019 SCORING GUIDELINES

## Question 2 (continued)

| | |
|---|---|
| The only intermolecular attractions in $Br_2(l)$ are London forces, while those in 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 $Br_2(l)$ are stronger than the combined intermolecular forces in BrCl($l$). Thus, the boiling point of $Br_2(l)$ is greater than that of BrCl($l$). | 1 point is earned for identifying the intermolecular forces in each substance.<br><br>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.

$$2\,BrCl(g) \rightleftarrows Br_2(g) + Cl_2(g) \qquad \Delta H° = 1.6\text{ kJ/mol}_{rxn}$$

A 0.100 mole sample of pure 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.

| | |
|---|---|
| $K_{eq} = \frac{[Br_2][Cl_2]}{[BrCl]^2}$ or $K_{eq} = \frac{P_{Br_2}P_{Cl_2}}{(P_{BrCl})^2}$ | 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.

| | |
|---|---|
| $2\,BrCl(g) \rightleftarrows Br_2(g) + Cl_2(g)$<br><br>I 1.22 0 0<br>C $-2x$ $+x$ $+x$<br>E 0.71 0.26 0.26<br><br>$P_{BrCl}$ decomposed $= (0.42)(1.22\text{ atm}) = 0.51\text{ atm}$<br><br>$2x = 0.51\text{ atm} \Rightarrow x = 0.26\text{ atm}$<br><br>$K_{eq} = \frac{(0.26)(0.26)}{(0.71)^2} = 0.13$<br><br>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.<br><br>1 point is earned for a consistent value of $K_{eq}$. |

## 2019 SCORING GUIDELINES

### Question 2 (continued)

Calculate the bond energy of the Br-Cl bond, in kJ/mol, using $\Delta H°$ 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 | ? |

| | |
|---|---|
| $\Delta$ = $\Sigma$ (bond energies)$_{broken}$ – $\Sigma$ (bond energies)$_{formed}$<br>J/mol = 2(Br–Cl bond energy) – (193 kJ/mol + 243 kJ/mol)<br>36 + 1.6) kJ/mol = 2(Br–Cl bond energy)<br>Cl bond energy = 219 kJ/mol | 1 point is earned for a correct calculation of the Br–Cl bond energy. |





## 2019 SCORING GUIDELINES

### Question 3

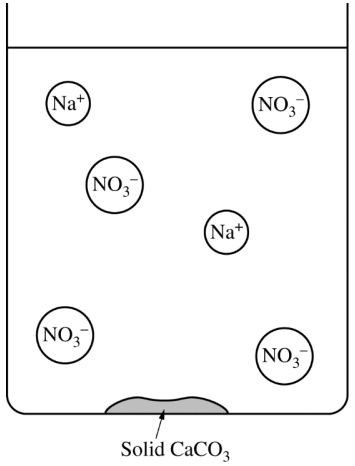
A student is given 50.0 mL of a solution of $Na_2CO_3$ of unknown concentration. To determine the concentration of the solution, the student mixes the solution with excess 1.0 *M* $Ca(NO_3)_2(aq)$, causing a precipitate to form. The balanced equation for the reaction is shown below.

$$Na_2CO_3(aq) + Ca(NO_3)_2(aq) \rightarrow 2\ NaNO_3(aq) + CaCO_3(s)$$

Write the net ionic equation for the reaction that occurs when the solutions of $Na_2CO_3$ and Ca(NO mixed.

| | |
|---|---|
| $Ca^{2+}(aq) + CO_3^{2-}(aq) \rightarrow CaCO_3(s)$ | 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. |

## 2019 SCORING GUIDELINES

### 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* $Ca(NO_3)_2$ 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.

| | |
|---|---|
| $0.93\text{ g } CaCO_3 \times \frac{1\text{ mol } CaCO_3}{100.1\text{ g}} = 0.0093\text{ mol } CaCO_3$<br>$0.0093\text{ mol } CaCO_3 \times \frac{1\text{ mol } Na_2CO_3}{1\text{ mol } CaCO_3} = 0.0093\text{ mol } Na_2CO_3$ | 1 point is earned for the correct answer. |

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 $Na_2CO_3(aq)$ will be too high. | 1 point is earned for the correct answer with valid justification. |

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 ($Na^+(aq)$, $Cl^-(aq)$, and $NO_3^-(aq)$) are present in the solution. | 1 point is earned for the correct answer with valid justification. |

The student decides to determine the molarity of the same $Na_2CO_3$ solution using a second method. When $Na_2CO_3$ is dissolved in water, $CO_3^{2-}(aq)$ hydrolyzes to form $HCO_3^-(aq)$, as shown by the following equation.

$$CO_3^{2-}(aq) + H_2O(l) \rightleftarrows HCO_3^-(aq) + OH^-(aq) \qquad K_b = \frac{[HCO_3^-][OH^-]}{[CO_3^{2-}]} = 2.1 \quad 10^{-4}$$





2019 SCORING GUIDELINES

Question 3 (continued)

The student decides to first determine $[OH^-]$ in the solution, then use that result to calculate the initial concentration of $CO_3^{2-}(aq)$.

(i) Identify a laboratory method (not titration) that the student could use to collect data to determine $[OH^-]$ 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 $CO_3^{2-}(aq)$. (Do not do any numerical calculations.)

| | |
|---|---|
| First determine $[OH^-]$ using pOH = 14 − pH, then $[OH^-] = 10^{-pOH}$.<br><br>use the $K_b$ expression and an ICE table (see example below) to determine $[CO_3^{2-}]$ and $[HCO_3^-]$ 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 $HCO_3^-$.<br><br>$CO_3^{2-}(aq) + H_2O(l) \rightleftarrows HCO_3^-(aq) + OH^-(aq)$<br>$c_i$ --- 0 0<br>$-x$ --- $+x$ $+x$<br>$c_i - x$ --- $x$ $x$<br><br>$K_b = \frac{(x)(x)}{c_i - x} \Rightarrow c_i = \frac{(x)(x)}{K_b} + x$ | 1 point is earned for a valid method of determining $[OH^-]$ from the measured value.<br><br>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 $HCO_3^-(aq)$ greater than, less than, or equal to the concentration of $CO_3^{2-}(aq)$? Justify your answer.

| | |
|---|---|
| Less than. The small value of $K_b$, $2.1 \times 10^{-4}$, indicates the reactants are favored. | 1 point is earned for the correct answer with a valid justification. |

The student needs to make a $CO_3^{2-}/HCO_3^-$ 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 $pK_a$ of $HCO_3^-$ is 10.32. Buffers are effective when the required pH is approximately equal to the $pK_a$ of the weak acid. An acid with a $pK_a$ 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

dent is doing experiments with $CO_2(g)$. 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 $CO_2(g)$ in the container to 425 K.

Describe the effect of raising the temperature on the motion of the $CO_2(g)$ molecules.

| | |
|---|---|
| e average speed of the molecules increases as temperature increases. | 1 point is earned for the correct answer. |

Calculate the pressure of the $CO_2(g)$ in the container at 425 K.

| | |
|---|---|
| Both the volume and the number of molecules are constant, therefore<br>$\frac{P_1}{T_1} = \frac{P_2}{T_2} \Rightarrow \frac{0.70 \text{ atm}}{299 \text{ K}} = \frac{P_2}{425 \text{ K}} \Rightarrow P_2 = 0.99 \text{ atm}$ | 1 point is earned for the correct answer. |

In terms of kinetic molecular theory, briefly explain why the pressure of the $CO_2(g)$ 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.<br><br>ster-moving gas particles collide more forcefully with the walls of the container, thus increasing the pressure. | 1 point is earned for a correct explanation. |

The student measures the actual pressure of the $CO_2(g)$ 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. |

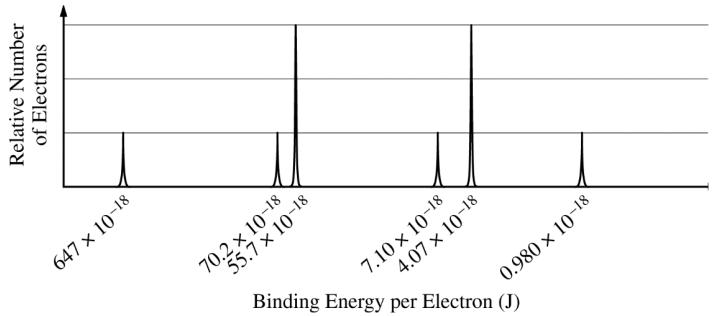




## 2019 SCORING GUIDELINES

### 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 [Ar] $4s^2$ | 1 point is earned for the correct answer. |

(ii) identify the element.

| | |
|---|---|
| Ca | 1 point is earned for the correct answer. |

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

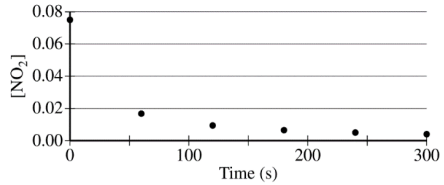
# 2019 SCORING GUIDELINES

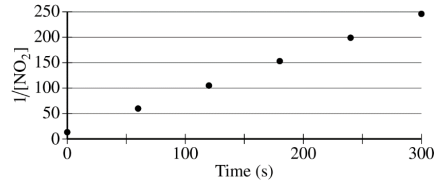
## Question 6

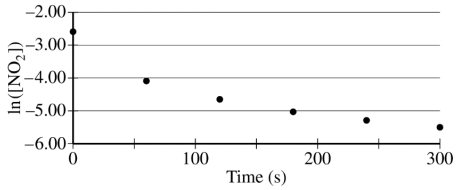
Nitrogen dioxide, $NO_2(g)$, is produced as a byproduct of the combustion of fossil fuels in internal combustion engines. At elevated temperatures $NO_2(g)$ decomposes according to the equation below.

$$2\ NO_2(g) \rightarrow 2\ NO(g) + O_2(g)$$

The concentration of a sample of $NO_2(g)$ 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 $\frac{1}{[NO_2]}$ vs. time indicates a second-order reaction. | 1 point is earned for the correct answer. |





2019 SCORING GUIDELINES

## Question 6 (continued)

Write the rate law for the decomposition of $NO_2(g)$.

| | |
|---|---|
| rate = $k[NO_2]^2$ | 1 point is earned for the correct answer. |

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: $NO_2(g) + NO_2(g) \rightarrow NO(g) + NO_3(g)$ *slow*

Step 2: $NO_3(g) \rightarrow NO(g) + O_2(g)$ *fast*

| | |
|---|---|
| Step 1 is slow, therefore it is the rate-determining step of this mechanism. The rate law of this elementary reaction is rate = $k[NO_2][NO_2] = k[NO_2]^2$, which is consistent with the second-order rate law in part (b). | 1 point is earned for the correct answer with justification. |

(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 1: $NO_2(g) + NO_2(g) \rightleftarrows N_2O_4(g)$ *fast equilibrium*

Step 2: $N_2O_4(g) \rightarrow 2\ NO(g) + O_2(g)$ *slow*

| | |
|---|---|
| Step 2 is slow; therefore, it is the rate-determining step of this mechanism. The rate law of this elementary reaction is rate = $k[N_2O_4]$. Because $N_2O_4$ is an intermediate, it cannot appear in the rate law of the overall reaction. Because $K_{eq} = \frac{[N_2O_4]}{[NO_2]^2}$ in step 1, $[N_2O_4] = K_{eq}[NO_2]^2$. Then, substituting $K_{eq}[NO_2]^2$ for $[N_2O_4]$ in the rate law of step 2 gives rate = $(k\ K_{eq})[NO_2]^2$, which is consistent with the rate law in part (b). | 1 point is earned for the correct answer with justification. |

## 2019 SCORING GUIDELINES

### Question 7

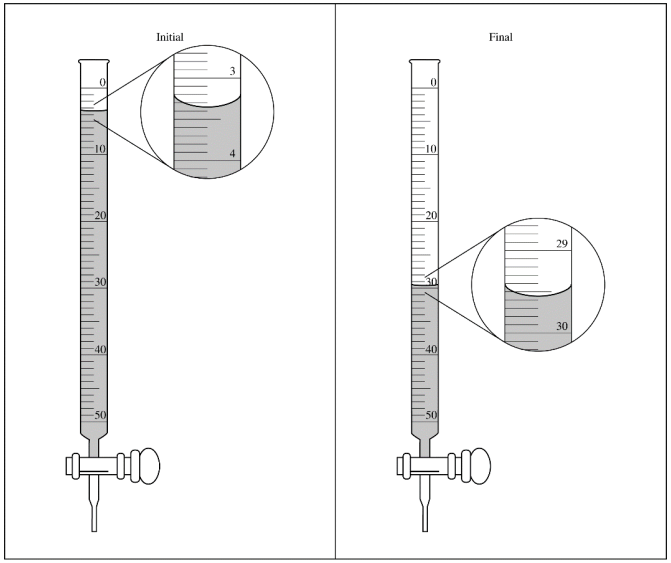
$$6\ H^+(aq) + 2\ MnO_4^-(aq) + 5\ H_2C_2O_4(aq) \rightarrow 10\ CO_2(g) + 8\ H_2O(l) + 2\ Mn^{2+}(aq)$$

A student dissolved a 0.139 g sample of oxalic acid, $H_2C_2O_4$, in water in an Erlenmeyer flask. Then the student titrated the $H_2C_2O_4$ 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 $KMnO_4(aq)$ to the $H_2C_2O_4(aq)$ 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 $KMnO_4(aq)$ that was added during the titration.




| | |
|---|---|
| 29.55 mL – 3.35 mL = 26.20 mL | 1 point is earned for the correct answer. |





2019 SCORING GUIDELINES

### Question 7 (continued)

Given that the concentration of $KMnO_4(aq)$ was 0.0235 *M*, calculate the number of moles of $MnO^-$ ions that completely reacted with the $H_2C_2O_4$.

| | |
|---|---|
| (0.02620 L)(0.0235 mol/L) = 0.000616 mol | 1 point is earned for the correct answer. |

The student proposes to perform another titration using a 0.139 g sample of $H_2C_2O_4$, but this time using 0.00143 *M* $KMnO_4(aq)$ 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 olume 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. |



**2017**

AP® CollegeBoard

# AP Chemistry
## Scoring Guidelines

# 2017 SCORING GUIDELINES

## Question 1

$$CS_2(g) + 3\ Cl_2(g) \rightarrow CCl_4(g) + S_2Cl_2(g)$$

Carbon tetrachloride, $CCl_4(g)$, 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, $Cl_2(g)$, is initially present in the container at a pressure of 0.40 atm.

(i) How many moles of $Cl_2(g)$ 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. |

(ii) How many grams of carbon disulfide, $CS_2(g)$, are needed to react completely with the $Cl_2(g)$ ?

| | |
|---|---|
| $0.31\ \text{mol}\ Cl_2 \times \frac{1\ \text{mol}\ CS_2}{3\ \text{mol}\ Cl_2} \times \frac{76.13\ \text{g}\ CS_2}{1\ \text{mol}\ CS_2} = 7.9\ \text{g}\ CS_2$ | 1 point is earned for using the correct mole ratio (may be implicit).<br><br>1 point is earned for the mass of $CS_2$. |

(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.

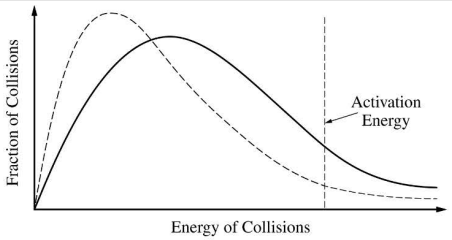
| | |
|---|---|
| At the higher temperature the particles have a greater average kinetic energy than at the lower temperature. Thus there are more collisions with sufficient energy to overcome the activation energy. | 1 point is earned for an appropriate explanation that includes a reference to molecular collisions. |

(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)

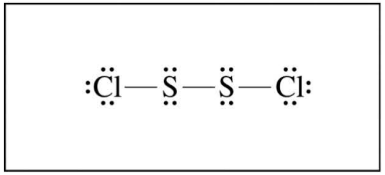



1 point is earned for a curve that has a peak above and to the left of the given curve.

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 Cl–S–S bond angle in the $S_2Cl_2$ molecule that you drew in part (c)(i) ? (If the two Cl–S–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) $CCl_4(g)$ can also be produced by reacting $CHCl_3(g)$ with $Cl_2(g)$ at 400°C, as represented by the equation below.

$$CHCl_3(g) + Cl_2(g) \rightarrow CCl_4(g) + HCl(g)$$

At the completion of the reaction a chemist successfully separates the $CCl_4(g)$ from the $HCl(g)$ by cooling the mixture to 70°C, at which temperature the $CCl_4(g)$ condenses while the $HCl(g)$ remains in the gaseous state.

## Question 1 (continued)

(i) Identify all types of intermolecular forces present in $HCl(l)$.

| | |
|---|---|
| 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 $CCl_4(l)$ and $HCl(l)$? 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. |





# 2017 SCORING GUIDELINES

## 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.

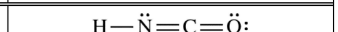
(a) Explain why the diagram on the left is the better representation for the bonding in fulminic acid. Justify your choice based on formal charges.

| | |
|---|---|
| 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.<br><br>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.<br><br>1 point is earned for a correct explanation. |

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

$$HCNO(g) \rightleftarrows HNCO(g)$$

*fulminic acid* *isocyanic acid*

| Fulminic Acid | Isocyanic Acid |
|---|---|
|  |  |

(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 $\Delta H^\circ$ 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 |

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

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 $\Delta H^\circ$.

## 2017 SCORING GUIDELINES

### Question 2 (continued)

(c) A student claims that $\Delta S^\circ$ 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.

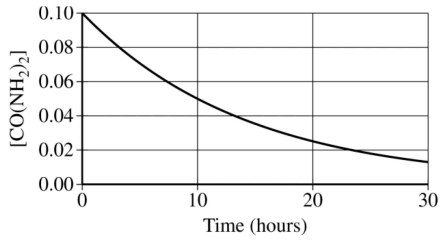
| | |
|---|---|
| Isocyanic acid (HNCO) will be present in higher concentration.<br><br>$\Delta G^\circ$ is essentially equal to $\Delta H^\circ$ because $\Delta S^\circ$ is essentially zero, so $\Delta G^\circ \approx -246$ kJ/mol$_{rxn}$, indicating the forward reaction is thermodynamically favorable.<br><br>Since $\Delta G^\circ$ 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 $\Delta G^\circ$ is a sufficient justification.)<br><br>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, $CO(NH_2)_2$, represented below.

$$CO(NH_2)_2(aq) \rightleftarrows NH_4^+(aq) + OCN^-(aq)$$

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) | $[CO(NH_2)_2]$ |
|---|---|
| 0 | 0.1000 |
| 5 | 0.0707 |
| 10 | 0.0500 |
| 15 | 0.0354 |
| 20 | 0.0250 |
| 25 | 0.0177 |
| 30 | 0.0125 |








## 2017 SCORING GUIDELINES

### 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,<br>$k = \frac{0.693}{t_{1/2}} = \frac{0.693}{10.\text{ h}} = 0.069\text{ h}^{-1}$<br>OR<br>$k = \frac{\ln[A]_0 - \ln[A]_t}{t} = \frac{\ln(0.1000) - \ln(0.0500)}{10.\text{ h}} = 0.069\text{ h}^{-1}$ | 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. |

# AP® CHEMISTRY
# 2017 SCORING GUIDELINES

## Question 3

$$N_2(g) + O_2(g) \rightleftarrows 2\,NO(g)$$

At high temperatures, $N_2(g)$ and $O_2(g)$ can react to produce nitrogen monoxide, $NO(g)$, as represented by the equation above.

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

| | |
|---|---|
| $K_p = \dfrac{(P_{NO})^2}{(P_{N_2})(P_{O_2})}$ | 1 point is earned for a correct $K_p$ expression. |

(b) A student injects $N_2(g)$ and $O_2(g)$ into a previously evacuated, rigid vessel and raises the temperature of the vessel to 2000°C. At this temperature the initial partial pressures of $N_2(g)$ and $O_2(g)$ are 6.01 atm and 1.61 atm, respectively. The system is allowed to reach equilibrium. The partial pressure of $NO(g)$ at equilibrium is 0.122 atm. Calculate the value of $K_p$.

| | | | |
|---|---|---|---|
| | $N_2(g) + O_2(g) \rightleftarrows$ | | $2\,NO(g)$ |
| Initial | 6.01 | 1.61 | 0 |
| Change | $-x$ | $-x$ | $+2x$ |
| Equilibrium | $6.01-x$ | $1.61-x$ | 0.122 |

$2x = 0.122$ atm $\Rightarrow$ $x = 0.0610$ atm

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

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

(c) A student is asked to make a buffer solution with a pH of 3.40 by using 0.100 *M* $HNO_2(aq)$ and 0.100 *M* $NaOH(aq)$.

(i) Explain why the addition of 0.100 *M* $NaOH(aq)$ to 0.100 *M* $HNO_2(aq)$ can result in the formation of a buffer solution. Include the net ionic equation for the reaction that occurs when the student adds the $NaOH(aq)$ to the $HNO_2(aq)$.





2017 SCORING GUIDELINES

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.<br>$HNO_2 + OH^- \rightarrow NO_2^- + H_2O$ | 1 point is earned for the recognition that the solution produced is a mixture of a weak acid and its conjugate base.<br>1 point is earned for the correct net ionic equation. |

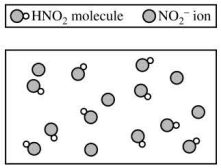
(ii) Determine the volume, in mL, of 0.100 *M* $NaOH(aq)$ the student should add to 100. mL of 0.100 *M* $HNO_2(aq)$ to make a buffer solution with a pH of 3.40. Justify your answer.

| | |
|---|---|
| The student should add 50.0 mL of 0.100 *M* $NaOH(aq)$.<br>When half of the $HNO_2$ is converted to the conjugate base, $[HNO_2] = [NO_2^-]$, therefore the buffer has a pH equal to $pK_a$.<br>OR<br>$pH = pK_a + \log\dfrac{[NO_2^-]}{[HNO_2]}$, thus pH = $pK_a$ when $[HNO_2] = [NO_2^-]$ | 1 point is earned for the correct volume.<br>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 $NaNO_2(s)$ 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. |

(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)

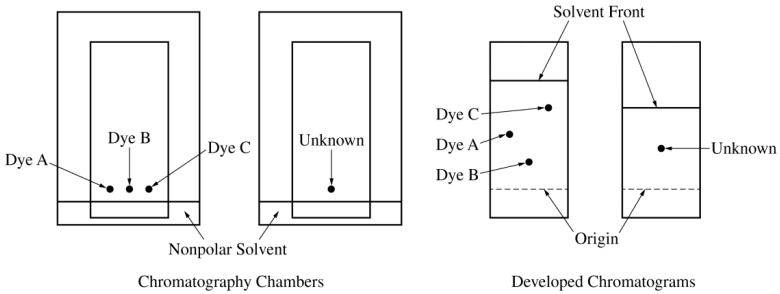
| | |
|---|---|
| The pH of the solution is less than 3.40. | 1 point is earned for the correct choice. |
| If $[HNO_2] = [NO_2^-]$, pH = $pK_a$, and the pH of the solution would be 3.40. Since $[HNO_2] > [NO_2^-]$, as represented in the diagram, the solution has a pH less than 3.40.<br>OR<br>$pH = pK_a + \log\frac{[NO_2^-]}{[HNO_2]} \Rightarrow pH = 3.40 + \log\frac{5}{10} \Rightarrow pH = 3.10$ | 1 point is earned for a valid justification. |





## 2017 SCORING GUIDELINES

### Question 4




Chromatography Chambers — Developed Chromatograms

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. | 1 point is earned for the correct choice **and** reference to the chromatogram. |
| Nonpolar dyes are more strongly attracted to the nonpolar solvent.<br>AND/OR<br>Nonpolar dyes are least strongly retained by the polar paper. | 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.

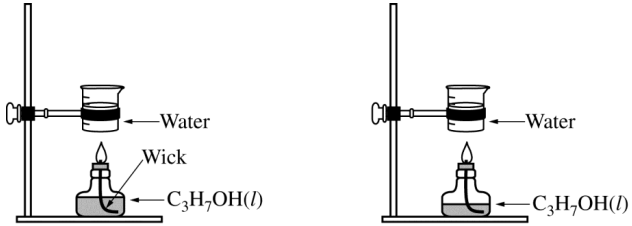
| | |
|---|---|
| Dye A is present in the unknown sample. | 1 point is earned for the correct choice. |
| The unknown sample moves to a position that is midway between the origin and the solvent front, and so does dye A.<br>OR<br>Dye A has a retention factor ($R_f$) that is close to 0.50 on the chromatogram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

## 2017 SCORING GUIDELINES

### Question 5

$$2\ C_3H_7OH(l) + 9\ O_2(g) \rightarrow 6\ CO_2(g) + 8\ H_2O(g)$$

A student performs an experiment to determine the enthalpy of combustion of 2-propanol, $C_3H_7OH(l)$, which combusts in oxygen according to the equation above. The student heats a sample of water by burning some of the $C_3H_7OH(l)$ 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 $C_3H_7OH(l)$ combusted is determined by weighing the alcohol burner before and after combustion.




Initial Final

Data from the experiment are given in the table below.

| | |
|---|---|
| Mass of $C_3H_7OH(l)$ 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.)

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





## AP® CHEMISTRY
## 2017 SCORING GUIDELINES

### Question 5 (continued)

(b) Based on the experimental data, if one mole of $C_3H_7OH(l)$ is combusted, how much heat, in kJ, is released? Report your answer with the correct number of significant figures.

| | |
|---|---|
| $1\ mol\ C_3H_7OH \times \frac{60.09\ g\ C_3H_7OH}{1\ mol\ C_3H_7OH} \times \frac{15.2\ kJ}{0.55\ g\ C_3H_7OH} = 1661\ kJ$<br>$= 1.7 \times 10^3\ kJ$ | 1 point is earned for the correct amount of heat released.<br><br>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 $C_3H_7OH(l)$ that is contaminated with water, which is miscible with $C_3H_7OH(l)$. 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:<br><br>the actual mass of $C_3H_7OH(l)$ combusted will be less than 0.55 g<br><br>OR<br><br>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. |

## 2017 SCORING GUIDELINES

### Question 6

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

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

| | |
|---|---|
| $1.8 \times 10^{-11} = [Mg^{2+}][OH^-]^2 = (x)(2x)^2 = 4x^3$<br><br>$x = \sqrt[3]{\frac{1.8 \times 10^{-11}}{4}} = 1.65 \times 10^{-4}\ M = [Mg^{2+}] = [Mg(OH)_2]$<br><br>$0.100\ \text{L} \times \frac{1.65 \times 10^{-4}\ \text{mol}}{1\ \text{L}} \times \frac{58.32\ \text{g Mg(OH)}_2}{1\ \text{mol Mg(OH)}_2} = 9.6 \times 10^{-4}\ \text{g Mg(OH)}_2$ | 1 point is earned for calculating the solubility of $Mg(OH)_2$.<br><br>1 point is earned for calculating the correct mass based on the solubility of $Mg(OH)_2$. |

(b) The energy required to separate the ions in the $Mg(OH)_2$ crystal lattice into individual $Mg^{2+}(g)$ and $OH^-(g)$ ions, as represented in the table below, is known as the lattice energy of $Mg(OH)_2(s)$. As shown in the table, the lattice energy of $Sr(OH)_2(s)$ is less than the lattice energy of $Mg(OH)_2(s)$. Explain why in terms of periodic properties and Coulomb's law.

| Reaction | Lattice Energy (kJ/mol) |
|---|---|
| $Mg(OH)_2(s) \rightarrow Mg^{2+}(g) + 2\ OH^-(g)$ | 2900 |
| $Sr(OH)_2(s) \rightarrow Sr^{2+}(g) + 2\ OH^-(g)$ | 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 $Mg(OH)_2$ are stronger and, therefore, its lattice energy is greater. | 1 point is earned for the correct comparison of cation sizes.<br><br>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 $H_2O_2(aq)$. The student can use one of two titrants, either dichromate ion, $Cr_2O_7^{2-}(aq)$, or cobalt(II) ion, $Co^{2+}(aq)$. The balanced chemical equations for the two titration reactions are shown below.

Dichromate as titrant: $Cr_2O_7^{2-}(aq) + 3\ H_2O_2(aq) + 8\ H^+(aq) \rightarrow 2\ Cr^{3+}(aq) + 3\ O_2(g) + 7\ H_2O(l)$

Cobalt(II) as titrant: $2\ Co^{2+}(aq) + H_2O_2(aq) + 2\ H^+(aq) \rightarrow 2\ Co^{3+}(aq) + 2\ H_2O(l)$

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 |
|---|---|
| $Co^{3+}(aq) + e^- \rightarrow Co^{2+}(aq)$ | 1.84 |
| $H_2O_2(aq) + 2\ H^+(aq) + 2\ e^- \rightarrow 2\ H_2O(l)$ | 1.77 |
| $Cr_2O_7^{2-}(aq) + 14\ H^+(aq) + 6\ e^- \rightarrow 2\ Cr^{3+}(aq) + 7\ H_2O(l)$ | 1.33 |
| $O_2(g) + 2\ H^+(aq) + 2\ e^- \rightarrow H_2O_2(aq)$ | 0.70 |

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

(i) $E°$ for the reaction between $Cr_2O_7^{2-}(aq)$ and $H_2O_2(aq)$ at 298 K

| | |
|---|---|
| $E° = 1.33 - 0.70 = 0.63$ V | 1 point is earned for correctly combining $E°$ values. |

(ii) $E°$ for the reaction between $Co^{2+}(aq)$ and $H_2O_2(aq)$ at 298 K

| | |
|---|---|
| $E° = -1.84 + 1.77 = -0.07$ 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.<br>OR<br>$\Delta G° = -nFE°$ and $n$, $F$, and $E°$ are all positive numbers, therefore $\Delta G° < 0$, 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 $\Delta G°$ is required. |

(ii) Calculate the value of $\Delta G°$, in $kJ/mol_{rxn}$, for the reaction between the chosen titrant and $H_2O_2(aq)$.

| | |
|---|---|
| $\Delta G° = -nFE° = -6(96{,}485 \frac{C}{mol})(0.63 \frac{J}{C})(\frac{1\ kJ}{1000\ J}) = -360\ kJ/mol_{rxn}$ | 1 point is earned for calculating the value of $\Delta G°$. |





# AP® Chemistry
# 2015 Scoring Guidelines

## 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) |
|---|---|
| $O_2(g) + 2\,H_2O(l) + 4\,e^- \rightarrow 4\,OH^-(aq)$ | +0.34 |
| $ZnO(s) + H_2O(l) + 2\,e^- \rightarrow Zn(s) + 2\,OH^-(aq)$ | −1.31 |
| $Na_2O(s) + H_2O(l) + 2\,e^- \rightarrow 2\,Na(s) + 2\,OH^-(aq)$ | −1.60 |
| $CaO(s) + H_2O(l) + 2\,e^- \rightarrow Ca(s) + 2\,OH^-(aq)$ | −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.

$$2\,Zn(s) + O_2(g) \rightarrow 2\,ZnO(s)$$

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

| | |
|---|---|
| $E_{cell} = 0.34\text{ V} - (-1.31\text{ V}) = 1.65\text{ V}$ | 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. |

(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 Zn($s$) in the cell, producing ZnO($s$), which has more mass than the original Zn($s$). | 1 point is earned for the justification. |





## 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. |

(ii) Justify your answer to part (c)(i) based on the equation for the overall cell reaction and the information above.

| | |
|---|---|
| $O_2(g)$, 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. |

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.

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

The only common oxide of zinc has the formula ZnO.

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

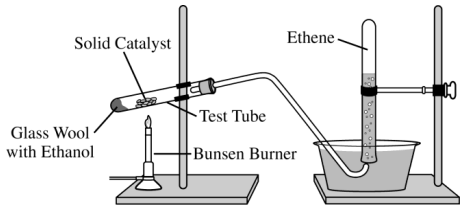
| | |
|---|---|
| $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^2\ 3d^{10}$ or $[Ar]\ 4s^2\ 3d^{10}$ | 1 point is earned for a correct configuration. |

(ii) From which sublevel are electrons removed when a Zn atom in the ground state is oxidized?

| | |
|---|---|
| 4$s$ sublevel | 1 point is earned for the correct answer. |

# 2015 SCORING GUIDELINES

## Question




Ethene, $C_2H_4(g)$ (molar mass 28.1 g/mol), may be prepared by the dehydration of ethanol, $C_2H_5OH($ (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.

$$\underset{\text{ethanol}}{C_2H_5OH(g)} \xrightarrow{\text{catalyst}} \underset{\text{ethene}}{C_2H_4(g)} + \underset{\text{water}}{H_2O(g)} \quad \Delta H^\circ_{298} = 45.5 \text{ kJ/mol}_{rxn};\ \Delta S^\circ_{298} = 126 \text{ J/(K·mol}_{rxn})$$

A student added a 0.200 g sample of $C_2H_5OH(l)$ to a test tube using the setup shown above. The student heated the test tube gently with a Bunsen burner until all of the $C_2H_5OH(l)$ 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 $C_2H_4(g)$

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

| | |
|---|---|
| $35.7 \text{ torr} \times \frac{1 \text{ atm}}{760 \text{ torr}} = 0.0470 \text{ atm}$<br>$_{\text{ene}} = P_{\text{total}} - P_{\text{water}} = 0.822 \text{ atm} - 0.0470 \text{ atm} = 0.775 \text{ atm}$<br>$n = \frac{PV}{RT} = \frac{(0.775 \text{ atm})(0.0854 \text{ L})}{(0.08206 \text{ L atm mol}^{-1} \text{ K}^{-1})(305 \text{ K})} = 0.00264 \text{ mol}$ | 1 point is earned for the calculation the pressure of the dry ethene.<br>1 point is earned for the correct number of moles of ethene gas. |

(ii) that would be produced if the dehydration reaction went to completion.

| | |
|---|---|
| $0.200 \text{ g } C_2H_5OH \times \frac{1 \text{ mol } C_2H_5OH}{46.1 \text{ g } C_2H_5OH} \times \frac{1 \text{ mol } C_2H_4}{1 \text{ mol } C_2H_5OH}$<br>$= 0.00434 \text{ mol } C_2H_4 \text{ produced}$ | 1 point is earned for the correct number of moles of ethene produced. |

Calculate the percent yield of $C_2H_4(g)$ 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. |





# 2015 SCORING GUIDELINES

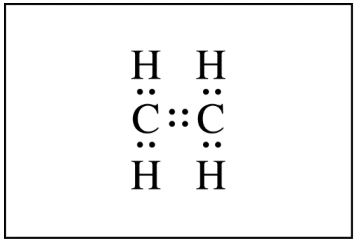
## Question 2 (continued)

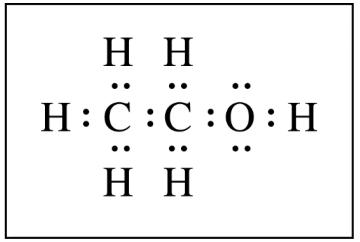
Because the dehydration reaction is not observed to occur at 298 K, the student claims that the reaction has an equilibrium constant less than 1.00 at 298 K.

Do the thermodynamic data for the reaction support the student's claim? Justify your answer, including a calculation of $\Delta G^\circ_{298}$ for the reaction.

| | |
|---|---|
| Yes, the data support the student's claim.<br>$\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$<br>$= 45.5 \text{ kJ/mol}_{rxn} - (298 \text{ K})(0.126 \text{ kJ/(K·mol}_{rxn})) = 8.0 \text{ kJ/mol}_{rxn}$<br>:ause $\Delta G^\circ > 0$, the value of $K_p = e^{\left(\frac{-\Delta G^\circ}{RT}\right)} < 1.00$. | 1 point is earned for the correct calculation of Δ<br>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 $C_2H_5OH$ 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°. |

## 2015 SCORING GUIDELINES

### Question (continued)

During the dehydration experiment, $C_2H_4(g)$ and unreacted $C_2H_5OH(g)$ passed through the tube into the water. The $C_2H_4$ was quantitatively collected as a gas, but the unreacted $C_2H_5OH$ 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.<br><br>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, $KC_6H_7O_2$ (molar mass 150. g/mol) is commonly added to diet soft drinks as a preservative. A stock solution of $KC_6H_7O_2(aq)$ of known concentration must be prepared. A student titrates 45.00 mL of the stock solution with 1.25 $M$ $HCl(aq)$ using both an indicator and a pH meter. The value of $K_a$ for sorbic acid, $H_7O_2$, is $1.7 \times 10^{-5}$.

Write the net-ionic equation for the reaction between $KC_6H_7O_2(aq)$ and $HCl(aq)$.

| | |
|---|---|
| $H^+ + C_6H_7O_2^- \rightleftarrows HC_6H_7O_2$ | 1 point is earned the net-ionic equation. |

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

| | |
|---|---|
| $\frac{1.25 \text{ mol HCl}}{1000 \text{ mL}} = \frac{x \text{ mol HCl}}{29.95 \text{ mL}}$ $x = 0.0374$ mol HCl<br><br>$\frac{0.0374 \text{ mol } C_6H_7O_2^-}{45.0 \text{ mL}} = \frac{x \text{ mol } C_6H_7O_2^-}{1000 \text{ mL}} \Rightarrow 0.832\ M$ | 1 point is earned for the moles of HCl at the equivalence point.<br><br>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 | 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 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.<br><br>1 point is earned for correct justification. |

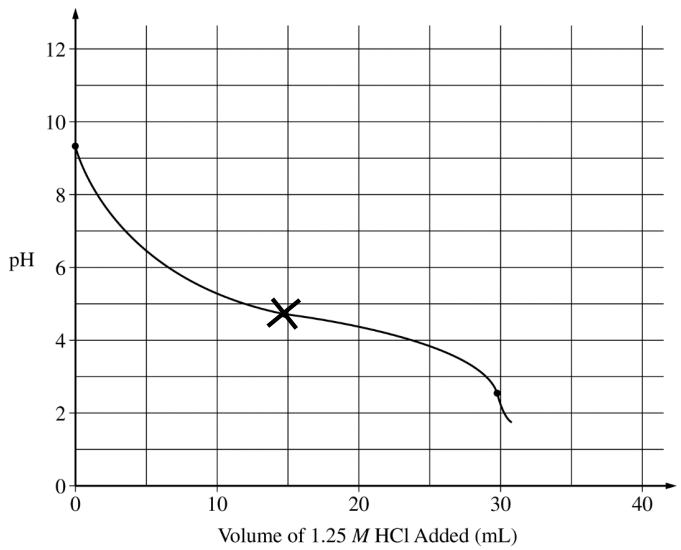
Calculate the pH at the half-equivalence point.

| | |
|---|---|
| pH = 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.<br>1 point is earned for a curve that levels off to a relatively horizontal slope through the half-equivalence point.<br>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 $KC_6H_7O_2(aq)$. Which species, $HC_6H_7O_2$ or $C_6H_7O_2^-$, has a higher concentration in the soft drink? Justify your answer.

| | |
|---|---|
| For sorbic acid, $K_a = \frac{[H^+][C_6H_7O_2^-]}{[HC_6H_7O_2]}$,<br><br>thus $\frac{[C_6H_7O_2^-]}{[HC_6H_7O_2]} = \frac{K_a}{[H^+]} = \frac{1.7 \times 10^{-5}}{10^{-3.37}} \approx 0.04$<br><br>$\Rightarrow [HC_6H_7O_2] > [C_6H_7O_2^-]$<br><br>The concentrations of $HC_6H_7O_2$ and $C_6H_7O_2^-$ 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, $HC_6H_7O_2$, 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 $Ca(OH)_2(s)$ in pure water.

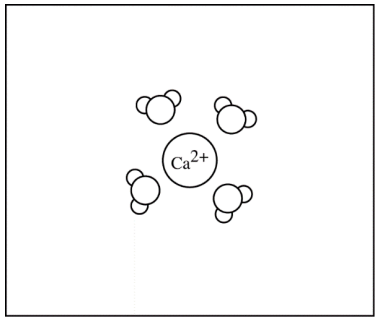
| | |
|---|---|
| $Ca(OH)_2 \rightleftarrows Ca^{2+} + 2\ OH^-$ | 1 point is earned for the correct equation. |

Calculate the molar solubility of $Ca(OH)_2$ in 0.10 *M* $Ca(NO_3)_2$.

| | |
|---|---|
| $= [Ca^{2+}]\,[OH^-]^2$<br>$\therefore 10^{-6} = (0.10 + x)\,(2x)^2 \approx (0.10)\,4x^2$ [assuming $x << 0.10$]<br>$\therefore 10^{-5} = 4x^2$<br>$= 0.0018\ M$<br>Molar solubility of $Ca(OH)_2 = 0.0018\ M$ | 1 point is earned for the correct stoichiometry and setup.<br><br>1 point is earned for the fi 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. |



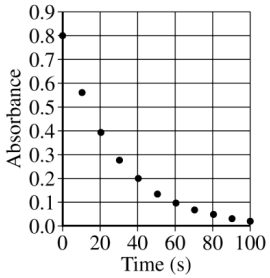


## 2015 SCORING GUIDELINES

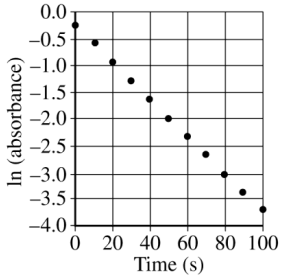
### Question

$$Na_2C_{37}H_{34}N_2S_3O_9 + OCl^- \rightarrow \text{products}$$
*blue* *colorless*

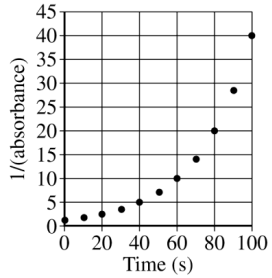
Blue food coloring can be oxidized by household bleach (which contains $OCl^-$) to form colorless products, as represented by the equation above. A student used a spectrophotometer set at a wavelength of 635 nm to study the absorbance of the food coloring over time during the bleaching process. In the 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. |





## 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. |
| $+ H_2O \rightleftarrows HF + OH^-$ | 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:<br>$= \frac{24\ \text{J}}{\text{mol K}} \times 1.00\ \text{mol} \times 635\ \text{K} = 15{,}000\ \text{J} = 15\ \text{kJ}$<br>It takes 10.7 kJ to melt the Al at 933 K.<br>J + 10.7 kJ = 26 kJ | 1 point is earned for calculating the amount heat needed to raise the temperature to 933 K.<br>1 point is earned for adding the heat of fusion to the previous result to get a final answer. |

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.

$$Al_2O_3(s) \rightarrow 2\ Al(s) + \frac{3}{2}\ O_2(g) \qquad \Delta H^\circ = 1675\ \text{kJ/mol}_{rxn}$$

| | |
|---|---|
| For extracting Al from ore:<br>$1675\ \text{kJ/mol}_{rxn} \times \frac{1\ \text{mol of reaction}}{2\ \text{mol Al}} = 837.5\ \text{kJ per mol of Al}$<br>Producing 1.00 mol of Al from $Al_2O_3$ requires 837.5 kJ.<br>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.<br>1 point is earned for a correct comparison. |