$$NaHCO_3(s) + HC_2H_3O_2(aq) \rightarrow NaC_2H_3O_2(aq) + H_2O(l) + CO_2(g)$$

2. A student designs an experiment to study the reaction between $NaHCO_3$ and $HC_2H_3O_2$. The reaction is represented by the equation above. The student places 2.24 g of $NaHCO_3$ in a flask and adds 60.0 mL of 0.875 *M* $HC_2H_3O_2$. The student observes the formation of bubbles and that the flask gets cooler as the reaction proceeds.

(a) Identify the reaction represented above as an acid-base reaction, precipitation reaction, or redox reaction. Justify your answer.

(b) Based on the information above, identify the limiting reactant. Justify your answer with calculations.

(c) The student observes that the bubbling is rapid at the beginning of the reaction and gradually slows as the reaction continues. Explain this change in the reaction rate in terms of the collisions between reactant particles.

(d) In thermodynamic terms, a reaction can be driven by enthalpy, entropy, or both.

(i) Considering that the flask gets cooler as the reaction proceeds, what drives the chemical reaction between $NaHCO_3(s)$ and $HC_2H_3O_2(aq)$? Answer by drawing a circle around one of the choices below.

Enthalpy only　　　　Entropy only　　　　Both enthalpy and entropy

(ii) Justify your selection in part (d)(i) in terms of $\Delta G°$.

(e) The HCO_3^- ion has three carbon-to-oxygen bonds. Two of the carbon-to-oxygen bonds have the same length and the third carbon-to-oxygen bond is longer than the other two. The hydrogen atom is bonded to one of the oxygen atoms. In the box below, draw a Lewis electron-dot diagram (or diagrams) for the HCO_3^- ion that is (are) consistent with the given information.

(f) A student prepares a solution containing equimolar amounts of $HC_2H_3O_2$ and $NaC_2H_3O_2$. The pH of the solution is measured to be 4.7. The student adds two drops of 3.0 *M* $HNO_3(aq)$ and stirs the sample, observing that the pH remains at 4.7. Write a balanced, net-ionic equation for the reaction between $HNO_3(aq)$ and the chemical species in the sample that is responsible for the pH remaining at 4.7.

Question 2

$$NaHCO_3(s) + HC_2H_3O_2(aq) \rightarrow NaC_2H_3O_2(aq) + H_2O(l) + CO_2(g)$$

A student designs an experiment to study the reaction between $NaHCO_3$ and $HC_2H_3O_2$. The reaction is represented by the equation above. The student places 2.24 g of $NaHCO_3$ in a flask and adds 60.0 mL of 0.875 *M* $HC_2H_3O_2$. The student observes the formation of bubbles and that the flask gets cooler as the reaction proceeds.

(a) Identify the reaction represented above as an acid-base reaction, precipitation reaction, or redox reaction. Justify your answer.

It is an acid-base reaction. The weak acid $HC_2H_3O_2$ reacts with the weak base HCO_3^- with $HC_2H_3O_2$ donating a proton. OR It is an acid-base reaction. No solid precipitates, so it is not a precipitation reaction. None of the oxidation numbers change, so it is not a redox reaction.	1 point is earned for identifying the reaction as acid-base. 1 point is earned for the justification.

(b) Based on the information above, identify the limiting reactant. Justify your answer with calculations.

$2.24 \text{ g } NaHCO_3 \times \frac{1 \text{ mol } NaHCO_3}{84.0 \text{ g}} = 0.0267 \text{ mol } NaHCO_3$ $60.0 \text{ mL} \times \frac{0.875 \text{ mol } HC_2H_3O_2}{1000 \text{ mL}} = 0.0525 \text{ mol } HC_2H_3O_2$ The $NaHCO_3(s)$ and $HC_2H_3O_2(aq)$ react in a 1:1 ratio, so the limiting reactant is $NaHCO_3(s)$.	1 point is earned for calculating the number of moles of each reactant. 1 point is earned for identifying the limiting reactant consistent with the calculations.

(c) The student observes that the bubbling is rapid at the beginning of the reaction and gradually slows as the reaction continues. Explain this change in the reaction rate in terms of the collisions between reactant particles.

As the reaction proceeds, both reactants are consumed and their concentrations decrease. Collisions between reactant particles become less likely as their concentations decrease, thus the reaction rate slows.	1 point is earned for a valid explanation.

(d) In thermodynamic terms, a reaction can be driven by enthalpy, entropy, or both.

(i) Considering that the flask gets cooler as the reaction proceeds, what drives the chemical reaction between $NaHCO_3(s)$ and $HC_2H_3O_2(aq)$? Answer by drawing a circle around one of the choices below.

Enthalpy only   Entropy only   Both enthalpy and entropy

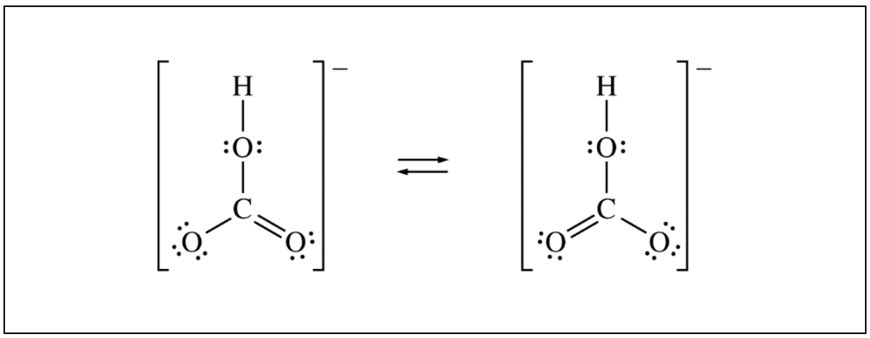
Entropy only should be circled.	1 point is earned for circling Entropy only.

Question 2 (continued)

(ii) Justify your selection in part (d)(i) in terms of $\Delta G°$.

$\Delta G° = \Delta H° - T\Delta S°$ Reactions are thermodynamically favorable when $\Delta G°$ is negative. Since the reaction is endothermic (the flask gets cooler, $\Delta H°$ is positive), the reaction is not driven by enthalpy, because enthalpy does not help make $\Delta G°$ negative. Because there are no gases in the reactants and one of the products is a gas, $\Delta S°$ must be positive, which helps make $\Delta G°$ negative.	1 point is earned for a valid justification.

(e) The HCO_3^- ion has three carbon-to-oxygen bonds. Two of the carbon-to-oxygen bonds have the same length and the third carbon-to-oxygen bond is longer than the other two. The hydrogen atom is bonded to one of the oxygen atoms. In the box below, draw a Lewis electron-dot diagram (or diagrams) for the HCO_3^- ion that is (are) consistent with the given information.



See diagram above.	1 point is earned for a correct Lewis structure of HCO_3^-. 1 point is earned for indicating resonance (e.g., two diagrams, or one diagram with an arrow between the two appropriate oxygen atoms).

(f) A student prepares a solution containing equimolar amounts of $HC_2H_3O_2$ and $NaC_2H_3O_2$. The pH of the solution is measured to be 4.7. The student adds two drops of 3.0 *M* $HNO_3(aq)$ and stirs the sample, observing that the pH remains at 4.7. Write a balanced, net-ionic equation for the reaction between $HNO_3(aq)$ and the chemical species in the sample that is responsible for the pH remaining at 4.7.

$C_2H_3O_2^- + H_3O^+ \rightarrow HC_2H_3O_2 + H_2O$ OR $C_2H_3O_2^- + H^+ \rightarrow HC_2H_3O_2$	1 point is earned for a correct equation.

$$NaHCO_3(s) + HC_2H_3O_2(aq) \rightarrow NaC_2H_3O_2(aq) + H_2O(l) + CO_2(g)$$

2. A student designs an experiment to study the reaction between $NaHCO_3$ and $HC_2H_3O_2$. The reaction is represented by the equation above. The student places 2.24 g of $NaHCO_3$ in a flask and adds 60.0 mL of 0.875 M $HC_2H_3O_2$. The student observes the formation of bubbles and that the flask gets cooler as the reaction proceeds. endothermic

(a) Identify the reaction represented above as an acid-base reaction, precipitation reaction, or redox reaction. Justify your answer.

(b) Based on the information above, identify the limiting reactant. Justify your answer with calculations.

(c) The student observes that the bubbling is rapid at the beginning of the reaction and gradually slows as the reaction continues. Explain this change in the reaction rate in terms of the collisions between reactant particles.

(d) In thermodynamic terms, a reaction can be driven by enthalpy, entropy, or both.

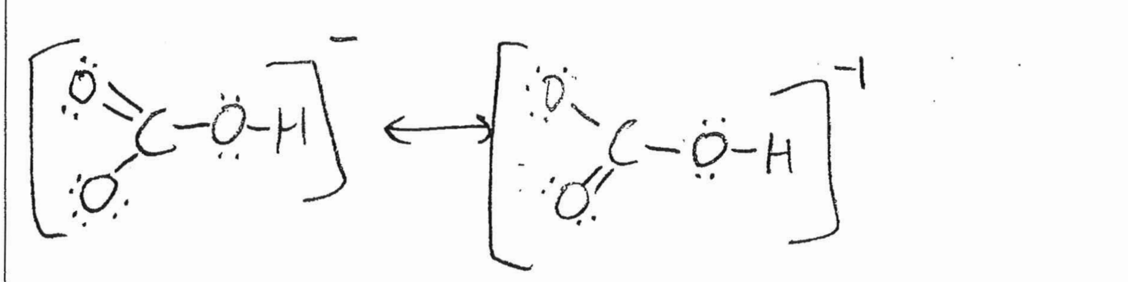
(i) Considering that the flask gets cooler as the reaction proceeds, what drives the chemical reaction between $NaHCO_3(s)$ and $HC_2H_3O_2(aq)$? Answer by drawing a circle around one of the choices below.

Enthalpy only | Entropy only | Both enthalpy and entropy

(ii) Justify your selection in part (d)(i) in terms of $\Delta G°$.

(e) The HCO_3^- ion has three carbon-to-oxygen bonds. Two of the carbon-to-oxygen bonds have the same length and the third carbon-to-oxygen bond is longer than the other two. The hydrogen atom is bonded to one of the oxygen atoms. In the box below, draw a Lewis electron-dot diagram (or diagrams) for the HCO_3^- ion that is (are) consistent with the given information.

1+4+3(6)+1
24⁻ valence e⁻



(f) A student prepares a solution containing equimolar amounts of $HC_2H_3O_2$ and $NaC_2H_3O_2$. The pH of the solution is measured to be 4.7. The student adds two drops of 3.0 M $HNO_3(aq)$ and stirs the sample, observing that the pH remains at 4.7. Write a balanced, net-ionic equation for the reaction between $HNO_3(aq)$ and the chemical species in the sample that is responsible for the pH remaining at 4.7.

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PAGE FOR ANSWERING QUESTION 2

a) The reaction is an acid-base reaction. $HC_2H_3O_2$, an acid, reacts with HCO_3^-, a base, to form CO_2, water, and a salt ($NaC_2H_3O_2$).

b) $2.24\,g\ NaHCO_3 \left(\frac{1\ mol\ NaHCO_3}{22.99g + 1.008g + 12.01g + 3(16.00g)}\right) = 0.02666\ mol\ NaHCO_3$

$60.0\,mL\ HC_2H_3O_2 \left(\frac{1\,L}{1000\,mL}\right)\left(\frac{0.875\ mol}{1\,L}\right) = 0.0525\,mol\ HC_2H_3O_2$

The molar ratio of $NaHCO_3 : HC_2H_3O_2$ is 1:1, and there are fewer moles of $NaHCO_3$, so $NaHCO_3$ is the limiting reactant.

c) As the reaction progresses, there are fewer reactant molecules in the same amount of solution, so fewer collisions occur because there are fewer molecules to collide. Fewer collisions leads to a slower reaction rate

d) ii) The flask cools as the reaction progresses, indicating that it is endothermic and $\Delta H > 0$. $\Delta G = \Delta H - T\Delta S$, so for ΔG to be negative, indicating a thermodynamically favored reaction, $T\Delta S$ must be greater than 0. T is in Kelvin, so is always positive, so ΔS must be positive.

f) $H^+ + C_2H_3O_2^- \rightarrow HC_2H_3O_2$

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$$NaHCO_3(s) + HC_2H_3O_2(aq) \rightarrow NaC_2H_3O_2(aq) + H_2O(l) + CO_2(g)$$

2. A student designs an experiment to study the reaction between $NaHCO_3$ and $HC_2H_3O_2$. The reaction is represented by the equation above. The student places 2.24 g of $NaHCO_3$ in a flask and adds 60.0 mL of 0.875 M $HC_2H_3O_2$. The student observes the formation of bubbles and that the flask gets cooler as the reaction proceeds.

(a) Identify the reaction represented above as an acid-base reaction, precipitation reaction, or redox reaction. Justify your answer.

(b) Based on the information above, identify the limiting reactant. Justify your answer with calculations.

(c) The student observes that the bubbling is rapid at the beginning of the reaction and gradually slows as the reaction continues. Explain this change in the reaction rate in terms of the collisions between reactant particles.

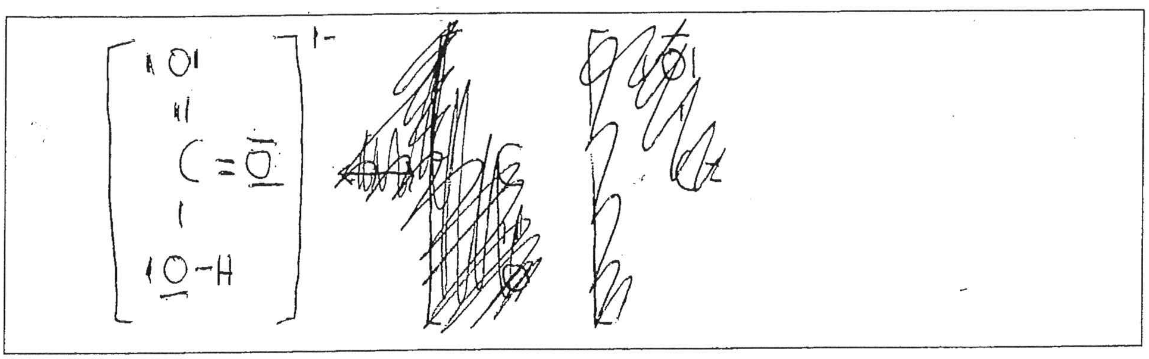
(d) In thermodynamic terms, a reaction can be driven by enthalpy, entropy, or both.

(i) Considering that the flask gets cooler as the reaction proceeds, what drives the chemical reaction between $NaHCO_3(s)$ and $HC_2H_3O_2(aq)$? Answer by drawing a circle around one of the choices below.

Enthalpy only Entropy only Both enthalpy and entropy

(ii) Justify your selection in part (d)(i) in terms of $\Delta G°$.

(e) The HCO_3^- ion has three carbon-to-oxygen bonds. Two of the carbon-to-oxygen bonds have the same length and the third carbon-to-oxygen bond is longer than the other two. The hydrogen atom is bonded to one of the oxygen atoms. In the box below, draw a Lewis electron-dot diagram (or diagrams) for the HCO_3^- ion that is (are) consistent with the given information.



(f) A student prepares a solution containing equimolar amounts of $HC_2H_3O_2$ and $NaC_2H_3O_2$. The pH of the solution is measured to be 4.7. The student adds two drops of 3.0 M $HNO_3(aq)$ and stirs the sample, observing that the pH remains at 4.7. Write a balanced, net-ionic equation for the reaction between $HNO_3(aq)$ and the chemical species in the sample that is responsible for the pH remaining at 4.7.

a) The reaction is an acid base reaction. It can't be a precipitation reaction because no solid is formed, and it isn't a redox reaction because oxidation states don't change. It is an acid reacting with a base to form water and a salt, which is what happens in an acid base reaction.

b) $60.0\ mL\ HC_2H_3O_2 \cdot \frac{1L}{1000mL} \cdot \frac{0.875\ mol}{L} \cdot \frac{1\ NaC_2H_3O_2}{1\ HC_2H_3O_2} = 0.0525\ mol\ NaC_2H_3O_2$

$2.24g\ NaHCO_3 \cdot \frac{1\ mol}{84.01g} \cdot \frac{1\ mol\ NaC_2H_3O}{1\ mol\ NaHCO_3} = 0.0267\ mol\ NaC_2H_3O_2$

$NaHCO_3$ is the limiting reactant

c) At the beginning, there is a relatively high concentration of reactants, which means it is more likely that a collision with the right amount of energy and correct orientation will occur, leading to a reaction. As the reaction progresses, and the concentration of reactants decreases, ~~less~~ a smaller fraction of the reactants will be colliding with enough energy to cause a reaction, thus leading to a slower reaction rate.

d)(ii) $\Delta G° = \Delta H - T\Delta S$. Since the flask gets cooler as the reaction progresses that means the reaction is endothermic, and ΔH is positive. For a reaction to be spontaneous, ΔG has to be negative, so if ΔH is positive, that means ΔS (entropy) must be large enough to overcome the positive ΔH and make ΔG negative. This means that entropy is the driving force in this reaction.

F) $C_2H_3O_2^- + H^+ \rightarrow HC_2H_3O_2$

$$NaHCO_3(s) + HC_2H_3O_2(aq) \rightarrow NaC_2H_3O_2(aq) + H_2O(l) + CO_2(g)$$

2. A student designs an experiment to study the reaction between $NaHCO_3$ and $HC_2H_3O_2$. The reaction is represented by the equation above. The student places 2.24 g of $NaHCO_3$ in a flask and adds 60.0 mL of 0.875 M $HC_2H_3O_2$. The student observes the formation of bubbles and that the flask gets cooler as the reaction proceeds.

   (a) Identify the reaction represented above as an acid-base reaction, precipitation reaction, or redox reaction. Justify your answer.

   (b) Based on the information above, identify the limiting reactant. Justify your answer with calculations.

   (c) The student observes that the bubbling is rapid at the beginning of the reaction and gradually slows as the reaction continues. Explain this change in the reaction rate in terms of the collisions between reactant particles.

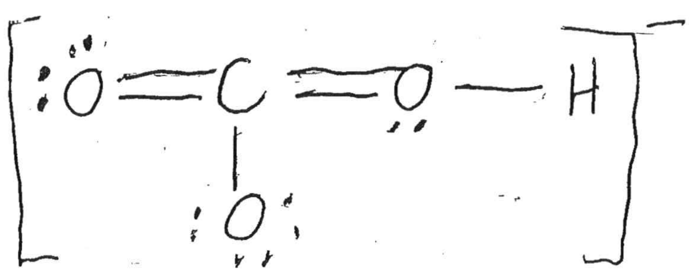
   (d) In thermodynamic terms, a reaction can be driven by enthalpy, entropy, or both.

      (i) Considering that the flask gets cooler as the reaction proceeds, what drives the chemical reaction between $NaHCO_3(s)$ and $HC_2H_3O_2(aq)$? Answer by drawing a circle around one of the choices below.

      Enthalpy only   Entropy only   Both enthalpy and entropy

      (ii) Justify your selection in part (d)(i) in terms of $\Delta G°$.

   (e) The HCO_3^- ion has three carbon-to-oxygen bonds. Two of the carbon-to-oxygen bonds have the same length and the third carbon-to-oxygen bond is longer than the other two. The hydrogen atom is bonded to one of the oxygen atoms. In the box below, draw a Lewis electron-dot diagram (or diagrams) for the HCO_3^- ion that is (are) consistent with the given information.



   (f) A student prepares a solution containing equimolar amounts of $HC_2H_3O_2$ and $NaC_2H_3O_2$. The pH of the solution is measured to be 4.7. The student adds two drops of 3.0 M $HNO_3(aq)$ and stirs the sample, observing that the pH remains at 4.7. Write a balanced, net-ionic equation for the reaction between $HNO_3(aq)$ and the chemical species in the sample that is responsible for the pH remaining at 4.7.

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2. ⓐ The ~~equation~~ reaction is an acid-base reaction due to the reactant being an acid, $HC_2H_3O_2(aq)$ and a base, $NaHCO_3(s)$.

ⓑ $2.24g\ NaHCO_3 \times \frac{1\ mol}{84.008g} = .0267\ mol\ NaHCO_3$

$\frac{.875\ mol}{1\ L} \times .06\ L = .0525\ mol\ HC_2H_3O_2$

? mol needed $NaHCO_3 = .0525\ mol\ HC_2H_3O_2 \times \frac{1\ mol\ NaHCO_3}{1\ mol} = .0525\ mol\ NaHCO_3$ needed

$NaHCO_3$ is limiting

ⓒ When the reaction with an abundance of reactants, many reactants are available with enough energy and correct orientation to collide ~~react~~. As the reaction continues, less reactants are ~~in~~ available in the correct conditions to collide and react.

ⓓ i. on sheet

ii. As the flask gets cooler, enthalpy does not heat the reactants causing energy and faster particles so it doesn't help the reaction proceed. By keeping the particles busy and confusing entropy allows more reactants to spontaneously react in correct orientation.

ⓔ on sheet

ⓕ $HNO_3(aq) + HC_2H_3O_2(aq) \rightarrow C_2H_3O_2^-(aq) + H_2O(l) + NO_2(g)$

$H^+(aq) + NO_3^-(aq) + H^+(aq) + \cancel{C_2H_3O_2^-(aq)} \rightarrow \cancel{C_2H_3O_2^-(aq)} + H_2O(l) + NO_2(g)$

$H^+(aq) + NO_3^-(aq) + H^+(aq) \rightarrow H_2O(l) + NO_2(g)$

GO ON TO THE NEXT PAGE.

Question 2

Overview

Question 2 explored students' knowledge of reaction types, stoichiometry, kinetics, thermodynamics, molecular structure in the form of Lewis diagrams, and net-ionic equations. In part (a) students were to identify the type of reaction that occurs when $NaHCO_3$ reacts with $HC_2H_3O_2$. In part (b) students were to identify the limiting reactant in the reaction and provide a calculation to justify the identification. In part (c) students were asked to take a macroscopic observation and explain the change in reaction rate in terms of reactant particle collisions. In part (d) students were to determine whether the reaction between $NaHCO_3$ and $HC_2H_3O_2$ is driven by enthalpy, entropy, or both enthalpy and entropy, and justify their selection in terms of $\Delta G°$. Students were given information in part (e) on the HCO_3^- ion and asked to draw a Lewis electron-dot diagram(s) consistent with the given information. Students were then to write a net-ionic equation for what happens when $HNO_3(aq)$ is added to eqimolar amounts of $HC_2H_3O_2$ and $NaC_2H_3O_2$.

Sample: 2A
Score: 10

The student earned all points in parts (a), (b), (c), (d), (e), and (f). In part (a) the student identifies the reaction as an acid-base reaction for 1 point and then specifically identifies the acid reactant and the base reactant as the justification. In part (b) the student calculates the number of moles of each reactant, then selects $NaHCO_3$ as the limiting reactant. In part (c) the student links fewer reactant molecules to fewer collisions and a slower rate. In part (d) "Entropy only" is circled for 1 point and a discussion of the signs of various factors and their effects earned another point. In part (e) a correct Lewis diagram (including square brackets and the charge) earned 1 point, and another resonance form earned the other point. The student earned the point in part (f) for the correct equation.

Sample: 2B
Score: 8

The student earned all points in parts (a), (b), (c), (d), and (f). In part (e) the student did not earn either point because the Lewis diagram drawn includes a carbon atom with five bonds (one single bond and two double bonds), and resonance is not shown.

Sample: 2C
Score: 6

In part (a) the student earned 2 points. The student identifies the reaction as an acid-base reaction and correctly justifies the answer by identifying the acid and the base. In part (b) the student earned 2 points by calculating the number of moles of each reactant and comparing them stoichiometrically. In part (c) 1 point was earned for linking the number of particles to the number of collisions and then to reaction rate. One point was earned in part (d)(i) by circling "Entropy only." The point was not earned in part (d)(ii). In part (e) the student did not earn either point because the Lewis diagram drawn includes a carbon atom with five bonds (one single bond and two double bonds), and resonance is not shown. The student did not earn the point in part (f).