Worksheet 10 – Chapter 18 – Common Ion Effect and Buffers KEY

I. Common Ions

A. When a weak acid solution has common ions added by a salt, the equilibrium will shift by Le Chatelier's principle. The shift in equilibrium position that occurs because of the addition of an ion already involved in the equilibrium reaction is called the ***common ion effect***.

B. A ***buffered*** solution is one that resists a change in its pH when either hydroxide ions or protons are added. Buffered solutions are simply solutions of weak acids or bases containing a common ion. When hydroxide ions are added to a buffer solution they react with the acid and are replaced by the Anions.

C. If you know the ratio of acid to base and both amounts are large the proton concentration can easily be found using the equation:

$$[H^+] = K_a \frac{[HA]}{[A^-]}$$

To find the pH easily the Henderson-Hasselbalch equation can be used:

$$pH = pK_a + \log\frac{[A^-]}{[HA]}$$

D. ***Buffer capacity*** of a buffered solution represents the amount of protons or hydroxide ions the buffer can absorb without a significant change in pH. Most effective buffer solutions contain large amounts of acid and conjugate base.

E. ***Titrations*** are commonly used to determine the amount of acid or base in a solution. The progress of an acid-base titration is often monitored by plotting the pH of the solution being analyzed as a function of the amount of titrant added. This is called a pH curve. The optimum area for buffering in a pH curve is in the vicinity where pKa equals the pH (or where the ratio of A- to HA equals 1). The equivalence point is where the amount of protons is equal to the amount of hydroxide ions.

F. ***Indicators*** are actually weak acids themselves that change color when H^+ is added or taken away from the structure. The best indicator for a titration is given by a indicator with pK_a or endpoint closest to the pH of the equivalence point.

The following is an acid-base equlibrium problem that involves many of the topics we have discussed in chapters 17 and 18. For each of the following solutions:

a. Describe (in words) what happens.
b. Write a chemical equation that describes what happens.
c. What is the proton donor? Why?
d. What is the proton acceptor? Why
e. After this solution has reached equlibrium: What species are present? What is their concentration? What is the pH and pOH?

1. Benzoic Acid (C_6H_5COOH) is a solid. 15.000 grams is dissolved in distilled water and diluted to 200.00 mL.

Benzoic Acid (C6H5COOH) is a solid. 15.000 grams is dissolved in 200.00 mL of distilled water.

a) Benzioic acid is a weak acid that will dissociate to in water to form benzoate ions and hydronium ions.

b) $C_6H_5COOH \quad + \quad H_2O \quad \text{<-->} \quad C_6H_5COO^{1-} \quad + \quad H_3O^{1+}$

c) benzoic acid is the proton donor (It is an acid)

d) water is the proton acceptor (It is the only avaialble base)

e) After the reaction has reached equlibrium:

$$M := \frac{mole}{liter} \qquad K_a := 6.46 \cdot 10^{-5} \qquad K_w := 1.0 \cdot 10^{-14}$$

$$Mass_{benzoic} := 15.000 \cdot gm \qquad V_{benzoic} := 200 \cdot mL$$

$$MW_{benzoic} := ((7 \cdot 12.001) + (2 \cdot 15.9994) + (6 \cdot 1.00794)) \cdot \frac{gm}{mole}$$

$$MW_{benzoic} = 122.05344 \cdot gm$$

$$mole_{benzoic} := \frac{Mass_{benzoic}}{MW_{benzoic}}$$

$$mole_{benzoic} = 0.1229 \cdot mole$$

$$C_{benzoic} := \frac{mole_{benzoic}}{V_{benzoic}}$$

$$C_{benzoic} = 0.61448 \cdot M$$

	C_6H_5COOH	+	H_2O	<-->	$C_6H_5COO^{1-}$	+	H_3O^{1+}
Start	$C_{benzoic} = 0.61448 \cdot M$				0		0
Change	$-X$				X		X
Equlibrium	$C_{benzoic} - X$				X		X

Start with the Equlibrium Expression

$$K_a = \frac{X \cdot X}{C_{benzoic} - X}$$

Substitute in known values

$$6.46 \cdot 10^{-5} = \frac{X \cdot X}{0.614 - X}$$

Solve

Using the Quadratic $\quad X = \begin{pmatrix} 6.2657507532092816567 \cdot 10^{-3} \\ -6.3303507532092816567 \cdot 10^{-3} \end{pmatrix}$

Assuming X is small in the denominator $\quad X = 6.2979679262441468867 \cdot 10^{-3}$

These two answers are essentially identical.

Select the appropriate root:

$$X := 6.2657507532092816567 \cdot 10^{-3} \cdot M$$

Concentrations of species present

Benzoic Acid	$C_{benzoic} := C_{benzoic} - X$	$C_{benzoic} = 0.60822 \cdot M$
Benzoate	$C_{benzoate} := X$	$C_{benzoate} = 0.00627 \cdot M$
Hydronium Ion	$C_{H3O} := X$	$C_{H3O} = 0.00627 \cdot M$
	$pH := -\log\left(X \cdot M^{-1}\right)$	$pH = 2.20303$
Hydroxide Ion	$C_{OH} := \frac{1 \cdot 10^{-14}}{X}$	$C_{OH} = 0 \cdot m^{6} \cdot M$
	$pOH := 14 - pH$	$pOH = 11.79697$

2. Sodium benzoate (NaC_6H_5COO) is a solid. Used as a preservative in most sodas. 10.000 grams is dissolved in distilled water and diluted to 100.00 mL.

2. Sodium benzoate (NaC_6H_5COO) is a solid. Used as a preservative in most pop (soda back east). 10.000 grams is dissolved in 100.00 mL of distilled water?

a) Sodium benzoate is a salt that will dissocaite completely in water. The benzoate ion will then act as a weak base and undergo hydrolysis with water to form benzioic acid and hydroxide ions.

b) NaC_6H_5COO ----> $C_6H_5COO^{1-}$ + Na^{1+}

$C_6H_5COO^{1-}$ + H_2O <--> C_6H_5COOH + OH^{1-}

c) water is the proton donor (It acts as an acid)

d) benzoate ion is the proton acceptor (It is the only avaialble base)

e) After the reaction has reached equlibrium:

$$Mass_{Na\_benzoate} := 10.00 \cdot gm \qquad V_{Na\_benzoate} := 100 \cdot mL$$

$$MW_{Na\_benzoate} := (22.989768 + (7 \cdot 12.001) + (2 \cdot 15.9994) + (5 \cdot 1.00794)) \cdot \frac{gm}{mole}$$

$$MW_{Na\_benzoate} = 144.03527 \cdot gm$$

$$mole_{Na\_benzoate} := \frac{Mass_{Na\_benzoate}}{MW_{Na\_benzoate}}$$

$$mole_{Na\_benzoate} = 0.06943 \cdot mole$$

$$C_{Na\_benzoate} := \frac{mole_{Na\_benzoate}}{V_{Na\_benzoate}}$$

$$C_{Na\_benzoate} = 0.69427 \cdot M$$

	C_6H_5COOH + H_2O <-->	$C_6H_5COO^{1-}$ +	H_3O^{1+}
Start	$C_{Na\_benzoate} = 0.69427 \cdot M$	0	0
Change	$-X$	X	X
Equlibrium	$C_{Na\_benzoate} - X$	X	X

Start with the Equlibrium Expression

$$K_b = \frac{X \cdot X}{C_{Na\_benzoate} - X} \qquad K_b := \frac{K_w}{K_a} \qquad K_b = 1.54799 \cdot 10^{-10}$$

Substitute in known values

$$1.548 \cdot 10^{-10} = \frac{X \cdot X}{0.694 - X}$$

Solve

Using the Quadratic $X = \begin{pmatrix} 1.036482491531348104\,3 \cdot 10^{-5} \\ -1.036497971531348104\,3 \cdot 10^{-5} \end{pmatrix}$

Assuming X is small in the denominator $X = 1.036490231502448845 \cdot 10^{-5}$

These two answers are essentially identical.

Select the appropriate root:

$$X := 1.036490231502448845 \cdot 10^{-5} \cdot M$$

Concentrations of species present

Benzoic Acid	$C_{benzoate} := C_{Na\_benzoate} - X$	$C_{benzoate} = 0.69426 \cdot M$
Benzoate	$C_{benzoic} := X$	$C_{benzoic} = 1.03649 \cdot 10^{-5} \cdot M$
Hydroxide Ion	$C_{OH} := X$	$C_{OH} = 1.03649 \cdot 10^{-5} \cdot M$
	$pOH := -\log\left(C_{OH} \cdot M^{-1}\right)$	$pOH = 4.98443$
Hydronium Ion	$C_{H3O} := \frac{K_w \cdot M^2}{C_{OH}}$	$C_{H3O} = 9.64794 \cdot 10^{-10} \cdot M$
	$pH := -\log\left(C_{H3O} \cdot M^{-1}\right)$	$pH = 9.01557$

3. Sodium Hydroxide is a solid. 5.0000 grams is dissolved in 50.0 mL of distilled water.

3. Sodium Hydroxide (NaOH) is a solid. 5.000 grams is dissolved in 50.00 mL of distilled water?

a) Sodium hydroxide is a salt and a strong base. It will completely dissociate in water to form hydroxide ions and sodium ions

b) NaOH ----> OH^{1-} + Na^{1+}

c) NaOH is an Arrhenius base so it is not typically thought of in terms of proton donors and acceptors. One way to do this is that after the NaOH dissociates the hydroxide undergoes the following acid/base reaction.

OH^{1-} + H2O <--> H2O + OH^{1-}

Now the hydroxide can be considered the proton acceptor (base) and the water is considered the proton donor (acid)

e) After the reaction has reached equlibrium: (Note since NaOH is a strong base, it is not nessicary to work the equlibrium calcualtions. This reaction goes to completion.

$$\text{Mass}_{\text{NaOH}} := 5.00 \cdot \text{gm} \qquad V_{\text{NaOH}} := 50 \cdot \text{mL}$$

$$\text{MW}_{\text{NaOH}} := (22.989768 + 15.9994 + 1.00794) \cdot \frac{\text{gm}}{\text{mole}}$$

$$\text{MW}_{\text{NaOH}} = 39.99711 \cdot \text{gm}$$

$$\text{mole}_{\text{NaOH}} := \frac{\text{Mass}_{\text{NaOH}}}{\text{MW}_{\text{NaOH}}}$$

$$\text{mole}_{\text{NaOH}} = 0.12501 \cdot \text{mole}$$

$$C_{\text{NaOH}} := \frac{\text{mole}_{\text{NaOH}}}{V_{\text{NaOH}}}$$

$$C_{\text{NaOH}} = 2.50018 \cdot \text{M}$$

Concentrations of species present

Hydroxide Ion	$C_{OH} := C_{NaOH}$	$C_{OH} = 2.50018 \cdot M$
	$pOH := -\log\left(C_{OH} \cdot M^{-1}\right)$	$pOH = -0.39797$
Hydronium Ion	$C_{H3O} := \dfrac{K_w \cdot M^2}{C_{OH}}$	$C_{H3O} = 3.99971 \cdot 10^{-15} \cdot M$
	$pH := -\log\left(C_{H3O} \cdot M^{-1}\right)$	$pH = 14.39797$

4. The benzoic acid solution and the sodium benzoate solution are mixed together in a large flask.

4. The benzoic acid solution and the sodium benzoate solution are mixed together in a larg flask.

a) Benzioic acid is a weak acid and benzoate is the conjugate base so this system will form a buffer solution.

b) C_6H_5COOH + H_2O <--> $C_6H_5COO^{1-}$ + H_3O^{1+}

c) benzoic acid is the proton donor (It is an acid)

d) water is the proton acceptor (It is the only available base)

e) After the reaction has reached equilibrium:

First determine the concentration of the acid and the base after dilution:

$V_{total} := V_{benzoic} + V_{Na\_benzoate}$	$V_{total} = 300 \cdot mL$
$C_{acid} := \dfrac{mole_{benzoic}}{V_{total}}$	$C_{acid} = 0.40966 \cdot M$
$C_{base} := \dfrac{mole_{Na\_benzoate}}{V_{total}}$	$C_{base} = 0.23142 \cdot M$

Next look at the equilibrium

	C_6H_5COOH	+	H_2O	<-->	$C_6H_5COO^{1-}$	+	H_3O^{1+}
Start	$C_{acid} = 0.40966 \cdot M$				$C_{base} = 0.23142 \cdot M$		0
Change	$-X$				X		X
Equilibrium	$C_{acid} - X$				$C_{base} + X$		X

Start with the Equilibrium Expression

$$K_a = \frac{(C_{base} + X) \cdot X}{C_{acid} - X}$$

Substitute in known values

$$6.49 \cdot 10^{-5} = \frac{(0.23142 + X) \cdot X}{0.40966 - X}$$

Solve

Using the Quadratic

$$X = \begin{pmatrix} 1.147969291519977 \cdot 10^{-4} \\ -.2315996969291519977 \end{pmatrix}$$

Assuming X is small compared to the concentration of the acid or the base

$$X = 1.148860686198254 2563 \cdot 10^{-4}$$

These two answers are essentially identical.

Select the appropriate root:

$$X := 1.147969291519977 \cdot 10^{-4} \cdot M$$

Concentrations of species present

Benzoic Acid	$C_{benzoic} := C_{acid} - X$	$C_{benzoic} = 0.40954 \cdot M$
Benzoate	$C_{benzoate} := C_{base} + X$	$C_{benzoate} = 0.23154 \cdot M$
Hydronium Ion	$C_{H3O} := X$	$C_{H3O} = 1.14797 \cdot 10^{-4} \cdot M$
	$pH := -\log(X \cdot M^{-1})$	$pH = 3.94007$
Hydroxide Ion	$C_{OH} := \frac{1 \cdot 10^{-14} \cdot M^2}{X}$	$C_{OH} = 8.71103 \cdot 10^{-11} \cdot M$
	$pOH := 14 - pH$	$pOH = 10.05993$

5. 1.00 mL of the sodium hydroxide solution is added to the buffer.

5. 1.00 mL of the sodium hydroxide solution is added to the buffer.

Adding NaOH shifts the equilibrium from the above system. To solve for the new equilibrium conditions, two steps are required.

First since OH^- is a strong base, and benzoic acid is the strongest acid available,

$C_6H_5COOH + OH^- \leftrightarrow C_6H_5COO^{1-} + H_2O$

This reaction will go to completion so that for:

$C_{NaOH} = 2.50018 \cdot M$ $\qquad V_{NaOH} := 1 \cdot mL$

$mole_{NaOH} := C_{NaOH} \cdot V_{NaOH}$ $\qquad mole_{NaOH} = 0.0025 \cdot mole$

$V_{total} := V_{benzoic} + V_{Na\_benzoate} + V_{NaOH}$ $\qquad V_{total} = 0.301 \cdot liter$

The new initial, NON-EQULIBRIUM, conditions for benzoic acid and benzoate ion are:

Benzoic Acid

$mole_{acid} := mole_{benzoic}$

$mole_{acid} = 0.1229$

$mole_{benzoic} := mole_{acid} - mole_{NaOH}$

$C_{benzoic} := \frac{(mole_{benzoic})}{V_{total}}$

$C_{benzoic} = 0.4 \cdot M$

Benzoate

$mole_{base} := mole_{Na\_benzoate}$

$mole_{base} = 0.06943$

$mole_{benzoate} := mole_{base} + mole_{NaOH}$

$C_{benzoate} := \frac{(mole_{benzoate})}{V_{total}}$

$C_{benzoate} = 0.23896 \cdot M$

Based upon these initial concentrations, solve for the equilibrium values, assuming X reacts:

$$K_a = \frac{(C_{benzoate} + X) \cdot X}{C_{benzoic} - X}$$

Substitute in known values

$$6.49\cdot10^{-5}=\frac{(0.23896+X)\cdot X}{0.4-X}$$

Solve

Using the Quadratic $X=\begin{pmatrix}1.0855862725786263\cdot10^{-4}\\ -.2391334586272578 6263\end{pmatrix}$

Assuming X is small compared to the concentration of the acid or the base $X=1.0863742885838634081\cdot10^{-4}$

These two answers are essentially identical.

Select the appropriate root:

$$X := 1.0855862725786263\cdot10^{-4}\cdot M$$

Concentrations of species present

Benzoic Acid	$C_{benzoic} := C_{benzoic} - X$	$C_{benzoic} = 0.39988\cdot M$
Benzoate	$C_{benzoate} := C_{benzoate} + X$	$C_{benzoate} = 0.23907\cdot M$
Hydronium Ion	$C_{H3O} := X$	$C_{H3O} = 1.08559\cdot10^{-4}\cdot M$
	$pH := -\log(X\cdot M^{-1})$	$pH = 3.96434$
Hydroxide Ion	$C_{OH} := \frac{1\cdot10^{-14}\cdot M^2}{X}$	$C_{OH} = 9.21161\cdot10^{-11}\cdot M$
	$pOH := 14 - pH$	$pOH = 10.03566$

6. 10.00 mL of the sodium hydroxide solution is added to the buffer.

6. 10.00 mL of the sodium hydroxide solution is added to the buffer.

Adding NaOH shifts the equilibrium from the above system. To solve for the new equilibrium conditions, two steps are required.

First since OH^- is a strong base, and benzoic acid is the strongest acid available,

$$C_6H_5COOH + OH^- \text{<-->} C_6H_5COO^{1-} + H_2O$$

This reaction will go to completion so that for:

$C_{NaOH} = 2.50018 \cdot M$ $\quad$ $V_{NaOH} := 10 \cdot mL$

$mole_{NaOH} := C_{NaOH} \cdot V_{NaOH}$ $\quad$ $mole_{NaOH} = 0.025 \cdot mole$

$V_{total} := V_{benzoic} + V_{Na\_benzoate} + V_{NaOH}$ $\quad$ $V_{total} = 0.31 \cdot liter$

The new initial, NON-EQULIBRIUM, conditions for benzoic acid and benzoate ion are:

Benzoic Acid

$mole_{acid} = 0.1229$

$mole_{benzoic} := mole_{acid} - mole_{NaOH}$

$$C_{benzoic} := \frac{(mole_{benzoic})}{V_{total}}$$

$C_{benzoic} = 0.3158 \cdot M$

Benzoate

$mole_{base} = 0.06943$

$mole_{benzoate} := mole_{base} + mole_{NaOH}$

$$C_{benzoate} := \frac{(mole_{benzoate})}{V_{total}}$$

$C_{benzoate} = 0.30461 \cdot M$

Based upon these initial concentrations, solve for the equilibrium values, assuming X reacts:

$$K_a = \frac{(C_{benzoate} + X) \cdot X}{C_{benzoic} - X}$$

Substitute in known values

$$6.49 \cdot 10^{-5} = \frac{(0.30461 + X) \cdot X}{0.3158 - X}$$

Solve

Using the Quadratic $X = \begin{pmatrix} 6.72549552686874 \cdot 10^{-5} \\ -.304742154955268687\,4 \end{pmatrix}$

Assuming X is small compared to the concentration of the acid or the base $X = 6.728413381044614425 \cdot 10^{-5}$

These two answers are essentially identical.

Select the appropriate root:

$$X := 6.728413381044614425 \cdot 10^{-5} \cdot M$$

Concentrations of species present

Benzoic Acid	$C_{benzoic} := C_{benzoic} - X$	$C_{benzoic} = 0.31572 \cdot M$
Benzoate	$C_{benzoate} := C_{benzoate} + X$	$C_{benzoate} = 0.30468 \cdot M$
Hydronium Ion	$C_{H3O} := X$	$C_{H3O} = 6.72841 \cdot 10^{-5} \cdot M$
	$pH := -\log\left(X \cdot M^{-1}\right)$	$pH = 4.17209$
Hydroxide Ion	$C_{OH} := \frac{1 \cdot 10^{-14} \cdot M^2}{X}$	$C_{OH} = 1.48623 \cdot 10^{-10} \cdot M$
	$pOH := 14 - pH$	$pOH = 9.82791$

7. 25.00 mL of the sodium hydroxide solution is added to the buffer.

7. 25.00 mL of the sodium hydroxide solution is added to the buffer.

Adding NaOH shifts the equilibrium from the above system. To solve for the new equilibrium conditions, two steps are required.

First since OH^- is a strong base, and benzoic acid is the strongest acid available,

$C_6H_5COOH \; + OH^- \; \text{<-->} \; C_6H_5COO^{1-} \; + \; H_2O$

This reaction will go to completion so that for:

$C_{NaOH} = 2.50018 \cdot M$ $\qquad V_{NaOH} := 25 \cdot mL$

$mole_{NaOH} := C_{NaOH} \cdot V_{NaOH}$ $\qquad mole_{NaOH} = 0.0625 \cdot mole$

$V_{total} := V_{benzoic} + V_{Na\_benzoate} + V_{NaOH}$ $\qquad V_{total} = 0.325 \cdot liter$

The new initial, NON-EQULIBRIUM, conditions for benzoic acid and benzoate ion are:

Benzoic Acid

$mole_{acid} = 0.1229$

$mole_{benzoic} := mole_{acid} - mole_{NaOH}$

$$C_{benzoic} := \frac{(mole_{benzoic})}{V_{total}}$$

$C_{benzoic} = 0.1858 \cdot M$

Benzoate

$mole_{base} = 0.06943$

$mole_{benzoate} := mole_{base} + mole_{NaOH}$

$$C_{benzoate} := \frac{(mole_{benzoate})}{V_{total}}$$

$C_{benzoate} = 0.40594 \cdot M$

Based upon these initial concentrations, solve for the equilibrium values, assuming X reacts:

$$K_a = \frac{(C_{benzoate} + X) \cdot X}{C_{benzoic} - X}$$

Substitute in known values

$$6.49\cdot10^{-5} = \frac{(0.40594+X)\cdot X}{0.1858-X} \qquad 6.49\cdot10^{-5} = \frac{(0.40594)\cdot X}{0.1858}$$

Solve

Using the Quadratic $\quad X = \begin{pmatrix} 2.969801110315791\cdot10^{-5} \\ -.40603459801110315791 \end{pmatrix}$

Assuming X is small compared to the concentration of the acid or the base $\quad X = 2.9704931763314775583\cdot10^{-5}$

These two answers are essentially identical.

Select the appropriate root:

$$X := 2.969801110315791\cdot10^{-5}\cdot M$$

Concentrations of species present

Benzoic Acid	$C_{benzoic} := C_{benzoic} - X$	$C_{benzoic} = 0.18579\cdot M$
Benzoate	$C_{benzoate} := C_{benzoate} + X$	$C_{benzoate} = 0.40597\cdot M$
Hydronium Ion	$C_{H3O} := X$	$C_{H3O} = 2.9698\cdot10^{-5}\cdot M$
	$pH := -\log\left(X\cdot M^{-1}\right)$	$pH = 4.52727$
Hydroxide Ion	$C_{OH} := \frac{1\cdot10^{-14}\cdot M^2}{X}$	$C_{OH} = 3.36723\cdot10^{-10}\cdot M$
	$pOH := 14 - pH$	$pOH = 9.47273$