I have observed all the rules of academic integrity while taking this exam

(There are 7 problems on 10 pages. Please count them.)

Signature
EQUATIONS AND CONSTANTS YOU MAY NEED

\[
pH = -\log [H^+] \\
[H^+] = 10^{-pH} \\
pOH = -\log [OH^-] \\
[OH^-] = 10^{-pOH} \\
[H^+] [OH^-] = K_w = 1 \times 10^{-14} \\
pH + pOH = 14
\]

| \[
\frac{[H^+][A^-]}{[HA]} = \frac{[H_2O^+][A^-]}{[HA]} = K_a
\] | \[
\frac{[BH^+][OH^-]}{[B]} = K_b
\] |
|---|---|
| \[
\frac{[HA][OH^-]}{[A^-]} = \frac{K_w}{K_a}
\] | \[
\frac{[B][H^+]}{[BH^+]} = \frac{[B][H_2O^+]}{[BH^+]} = \frac{K_w}{K_b}
\] |

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**K_a values for Selected Weak Acids**

<table>
<thead>
<tr>
<th>Acid</th>
<th>K_a</th>
</tr>
</thead>
<tbody>
<tr>
<td>HClO₂</td>
<td>1.2 \times 10^{-2}</td>
</tr>
<tr>
<td>HNO₂</td>
<td>4.0 \times 10^{-4}</td>
</tr>
<tr>
<td>HC₂H₃O₂</td>
<td>1.8 \times 10^{-5}</td>
</tr>
<tr>
<td>HOCl</td>
<td>3.5 \times 10^{-8}</td>
</tr>
<tr>
<td>HCN</td>
<td>6.2 \times 10^{-10}</td>
</tr>
<tr>
<td>NH₄⁺</td>
<td>5.6 \times 10^{-10}</td>
</tr>
<tr>
<td>HO₆H₅</td>
<td>1.6 \times 10^{-10}</td>
</tr>
</tbody>
</table>

**K_b values for Selected Weak Bases**

<table>
<thead>
<tr>
<th>Base</th>
<th>K_b</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH₃</td>
<td>1.8 \times 10^{-5}</td>
</tr>
<tr>
<td>CH₃NH₂</td>
<td>4.4 \times 10^{-4}</td>
</tr>
<tr>
<td>C₂H₅NH₂</td>
<td>5.6 \times 10^{-4}</td>
</tr>
<tr>
<td>C₆H₅NH₂</td>
<td>3.8 \times 10^{-10}</td>
</tr>
<tr>
<td>C₅H₅N</td>
<td>1.7 \times 10^{-9}</td>
</tr>
</tbody>
</table>
**Question #1** (12 pts)

Hydrogen can be prepared from methane by the following endothermic reaction:

\[ \text{CH}_4 (g) + \text{H}_2\text{O} (g) \rightleftharpoons \text{CO} (g) + 3\text{H}_2 (g) \]

Predict the shift in equilibrium that would occur if the following were to take place (circle correct answers):

(a) Carbon monoxide is removed
(b) Pressure is increased by decreasing volume
(c) Pressure is increased by adding methane gas
(d) Pressure is increased by adding argon gas
(e) Heat is added
(f) A solid dehydrating agent is added (that reacts with \(\text{H}_2\text{O}\))

(shift left) (shift right) no effect
(shift left) shift right / no effect
(shift left) shift right / no effect
(shift left / shift right) no effect
(shift left / shift right) no effect
(shift left / shift right) no effect

**Question #2** (16 pts)

(a) (4 pts) For the following reaction, identify the acid, base, conjugate acid and conjugate base:

\[ \text{C}_2\text{H}_5\text{NH}^+ + \text{H}_2\text{O} \rightleftharpoons \text{C}_2\text{H}_5\text{N} + \text{H}_3\text{O}^+ \]

<table>
<thead>
<tr>
<th>acid</th>
<th>(\text{C}_2\text{H}_5\text{NH}^+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>base</td>
<td>(\text{H}_2\text{O})</td>
</tr>
<tr>
<td>conjugate acid</td>
<td>(\text{H}_3\text{O}^+)</td>
</tr>
<tr>
<td>conjugate base</td>
<td>(\text{C}_2\text{H}_5\text{N})</td>
</tr>
</tbody>
</table>

(b) (2 pts) What is the pH of 0.001 M potassium hydroxide? (circle correct answer)

(i) \(\text{pH} = 10^{-3}\)
(ii) \(\text{pH} = 10^{-11}\)
(iii) \(\text{pH} = 2\)
(iv) \(\text{pH} = 3\)
(v) \(\text{pH} = 4\)
(vi) \(\text{pH} = 10\)
(vii) \(\text{pH} = 11\)
(viii) \(\text{pH} = 12\)
Question #2 (continued)

(c) (2 pts) When the pH is −1, what is the [OH−] concentration?

(i) 0.1 M  
(ii) 1 M  
(iii) 10 M  
(iv) 10−13 M  
(v) 10−14 M  
(vi) 10−15 M

(d) (2 pts) Which of the following is a superacid?

(i) HCl  
(ii) HNO3  
(iii) H2SO4  
(iv) HClO4  
(v) SbF5 + HF

(e) (2 pts) Which of the following ions is the strongest base?

\[
\begin{align*}
\text{BrO}^- & \quad \text{BrO}_2^- & \quad \text{BrO}_3^- & \quad \text{BrO}_4^- \\
\text{Answer: } & \quad \text{BrO}^- \\
\end{align*}
\]

(f) (4 pts) Which two of the following compounds are Lewis acids?

\[
\begin{align*}
\text{BF}_3 & \quad \text{NH}_3 & \quad \text{OH}^- & \quad \text{SO}_4^{2-} & \quad \text{AlCl}_3 & \quad \text{PO}_4^{3-} \\
\text{Answers: } & \quad \text{BF}_3 & \quad \text{and } & \quad \text{AlPO}_3
\end{align*}
\]
**Question #3** (15 pts)

(a) (6 pts) **Write equilibrium expressions** for the following reactions:

(e.g., for acetic acid and water, the equation is: \( \text{HC}_2\text{H}_3\text{O}_2 + \text{H}_2\text{O} \rightleftharpoons \text{C}_2\text{H}_3\text{O}_2^- + \text{H}_3\text{O}^+ \))

(i) pyridine + water  (Note: pyridine is \( \text{C}_5\text{H}_5\text{N} \), a weak base)

\[
\text{C}_5\text{H}_5\text{N} + \text{H}_2\text{O} \rightleftharpoons \text{C}_5\text{H}_5\text{NH}^+ + \text{OH}^- \\
K = \frac{[\text{C}_5\text{H}_5\text{NH}^+][\text{OH}^-]}{[\text{C}_5\text{H}_5\text{N}]} 
\]

(ii) ammonium ion + water

\[
\text{NH}_4^+ + \text{H}_2\text{O} \rightleftharpoons \text{NH}_3 + \text{H}_3\text{O}^+ \\
K = \frac{[\text{NH}_3][\text{H}_3\text{O}^+]}{[\text{NH}_4^+]} \\
\text{or} \quad K = \frac{[\text{NH}_3][\text{H}^+]}{[\text{NH}_4^+]} 
\]

(iii) cyanide ion + water

\[
\text{CN}^- + \text{H}_2\text{O} \rightleftharpoons \text{HCN} + \text{OH}^- \\
K = \frac{[\text{HCN}][\text{OH}^-]}{[\text{CN}^-]} 
\]

(b) (9 pts) **Predict the products** and **write balanced equations** for the following acid-base neutralization reactions: (Note: these are not equilibrium processes)

(i) aluminum hydroxide + sulfuric acid

\[
2\text{Al(OH)}_3 + 3\text{H}_2\text{SO}_4 \rightarrow \text{Al}_2(\text{SO}_4)_3 + 6\text{H}_2\text{O} 
\]

(ii) potassium oxide + nitric acid

\[
\text{K}_2\text{O} + 2\text{HNO}_3 \rightarrow 2\text{KNO}_3 + \text{H}_2\text{O} 
\]

(iii) calcium hydroxide + carbon dioxide

\[
\text{Ca(OH)}_2 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O} 
\]
**Question #4** (15 pts) (Circle correct answers)

(a) Explosives like dynamite and TNT are compounds that contain:

(i) OH groups
(ii) NH₂ groups
(iii) NO₂ groups
(iv) SO₄ groups
(v) PO₄ groups

(b) What is "nitrogen fixation"?

(i) the formation of ammonia from nitrogen and hydrogen
(ii) the decomposition of ammonium nitrate into N₂O and water
(iii) the oxidation of hydrazine to nitrogen and water
(iv) the oxidation of ammonia to nitric acid (the Ostwald process)
(v) none of the above

(c) Laughing gas, which used to be a common dental anesthetic agent, is:

(i) NO
(ii) NO₂
(iii) N₂O
(iv) N₂O₄
(v) N₂O₅

(d) The formula of ozone is:

(i) O⁺
(ii) O₂²⁻
(iii) O₃
(iv) O₂Cl
(v) OCl₂

(e) Which of the following is a stable form of elemental phosphorus?

(i) P₂
(ii) P₄
(iii) P₆
(iv) P₈
(v) none of the above
Question #4 (continued)

(f) What is the formula of the most stable and common form of sulfur?
   
   (i) $S_2$
   (ii) $S_4$
   (iii) $S_6$
   (iv) $S_8$
   (v) none of the above

(g) Which of the following elements can exist in oxidation states of $-1$, $+1$, $+3$, $+5$ & $+7$?

   (i) P
   (ii) S
   (iii) Cl
   (iv) Ar
   (v) none of the above

(h) Which of the following elements can exist in oxidation states of $-2$, $0$, $+2$, $+4$ & $+6$?

   (i) P
   (ii) S
   (iii) Cl
   (iv) Ar
   (v) none of the above

(i) Which noble gas element is known to form a large number of stable compounds?

   (i) He
   (ii) Ne
   (iii) Ar
   (iv) Kr
   (v) Xe

(j) Which of the elements discussed in Chapter 19 are two of the most important constituents of fertilizers?

   (i) N and P
   (ii) P and S
   (iii) N and S
   (iv) S and Cl
   (v) O and S
Question #5 (10 pts)

Calculate the pH of a 0.10 M solution of HCN (K_a = 6.2 \times 10^{-10}).

\[ HCN \rightleftharpoons H^+ + CN^- \]

Start:  
\[ \begin{array}{ccc} 0.1 & 0 & 0 \\ \end{array} \]

React:  
\[ \begin{array}{ccc} -x & x & x \\ \end{array} \]

At Equil:  
\[ \begin{array}{ccc} 0.1 - x & x & x \\ \end{array} \]

\[ \frac{[H^+][CN^-]}{[HCN]} = K_a \]

\[ \frac{(x)(x)}{0.1 - x} = 6.2 \times 10^{-10} \]

Assume 0.1 >> x

\[ \frac{x^2}{0.1} = 6.2 \times 10^{-10} \]

\[ x = \sqrt{(0.1)(6.2 \times 10^{-10})} \]

\[ = 7.8 \times 10^{-6} = [H^+] \]

\[ pH = -\log [H^+] = 5.1 \]
Question #6 (14 pts)

The pH of a $1.00 \times 10^{-3}$ M solution of pyrrolidine (the weak base $C_4H_9N$) is 10.82.

(a) (4 pts) Write down the equation for $K_b$ (in terms of $C_4H_9N$ and other species that exist in solution)

$$C_4H_9N + H_2O \rightleftharpoons C_4H_9NH^+ + OH^-$$

$$K_b = \frac{[C_4H_9NH^+][OH^-]}{[C_4H_9N]}$$

(b) (10 pts) Calculate the value for $K_b$

$pH = 10.82$
$pOH = 14 - pH = 3.18$
$[OH^-] = 10^{-pOH} = 10^{-3.18} = 0.00066$

<table>
<thead>
<tr>
<th></th>
<th>$C_4H_9N$</th>
<th>$C_4H_9NH^+$</th>
<th>$OH^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
<td>0.001</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>React</td>
<td>-x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>At Equil</td>
<td>0.001-x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

$[C_4H_9NH^+] = [OH^-] = x = 0.00066 M$

$[C_4H_9N] = 0.001 - x = 0.001 - 0.00066 = 0.00034 M$

$$K_b = \frac{[C_4H_9NH^+][OH^-]}{[C_4H_9N]}$$

$$= \frac{(0.00066)^2}{0.00034} = 0.00132 \ (\approx 1.32 \times 10^{-3})$$
**Question #7 (18 pts)**

HA is an unknown weak acid, and NaA is its sodium salt. If a 0.147 M solution of NaA has a pH value of 9.63, calculate the pH of a 0.258 M solution of HA

**Step I: Calculate $K_a$**

Reaction is: $A^- + H_2O ⇌ HA + OH^-$

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

If $pH = 9.63$, $pOH = 14 - 9.63 = 4.37$

$[OH^-] = 10^{-4.37} = 4.26 \times 10^{-5}$

Initial

<table>
<thead>
<tr>
<th></th>
<th>$A^-$</th>
<th>HA</th>
<th>$OH^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.147</td>
<td>0</td>
<td>0</td>
<td></td>
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Change

<table>
<thead>
<tr>
<th></th>
<th>$A^-$</th>
<th>HA</th>
<th>$OH^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-x$</td>
<td>$x$</td>
<td>$x$</td>
<td></td>
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</table>

At Equilibrium

<table>
<thead>
<tr>
<th></th>
<th>$A^-$</th>
<th>HA</th>
<th>$OH^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.147 - x$</td>
<td>$x$</td>
<td>$x$</td>
<td></td>
</tr>
</tbody>
</table>

$$K_a = \frac{(4.26 \times 10^{-5})^2}{0.147 - 4.26 \times 10^{-5}} = \frac{(4.26 \times 10^{-5})^2}{0.147} = 1.24 \times 10^{-8}$$

**Step II:** Reaction is: $HA ⇌ H^+ + A^-$

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

Initial

<table>
<thead>
<tr>
<th></th>
<th>HA</th>
<th>$H^+$</th>
<th>$A^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.258</td>
<td>0</td>
<td>0</td>
<td></td>
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</tbody>
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Change

<table>
<thead>
<tr>
<th></th>
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<th>$H^+$</th>
<th>$A^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-x$</td>
<td>$x$</td>
<td>$x$</td>
<td></td>
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</table>

At Equilibrium

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<th></th>
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<tbody>
<tr>
<td>$0.258 - x$</td>
<td>$x$</td>
<td>$x$</td>
<td></td>
</tr>
</tbody>
</table>

$$K_a = \frac{Kw}{K_c} = \frac{10^{-14}}{1.24 \times 10^{-8}}$$

Assume $0.258 - x \approx 0.258$

$$\frac{x^2}{0.258} = \frac{10^{-14}}{1.24 \times 10^{-8}} = 8.0 \times 10^{-7}$$

$$x = \sqrt{(0.258)(8.0 \times 10^{-7})} = 4.56 \times 10^{-4} = [H^+]$$

$$pH = - \log (4.56 \times 10^{-4}) = 3.34$$