Name ______________________________ Section ____________

Worksheet 7: Chemical Equilibrium and Acids/Bases

1. For each of the following reactions, write the expressions for K_c and K_p. What is the relationship between K_c and K_p? Does the reaction represent a homogeneous or heterogeneous equilibrium?
   a. H_2 (*g*) + I_2 (*g*) $\rightleftharpoons$ 2HI (*g*)

   $$K_c = \frac{[HI]^2}{[H_2][I_2]} \qquad K_p = \frac{(P_{HI})^2}{P_{H_2}P_{I_2}} \qquad K_c = K_p$$ **homogeneous**

   b. CH_3OH (*g*) $\rightleftharpoons$ CO (*g*) + H_2 (*g*)

   $$K_c = \frac{[H_2][CO]}{[CH_3OH]} \qquad K_p = \frac{P_{H_2}P_{CO}}{P_{CH_3OH}} \qquad K_c(RT) = K_p$$ **homogeneous**

   c. $2NH_3$ (*g*) + CO_2 (*g*) $\rightleftharpoons$ N_2CH_4O (*s*) + H_2O (*g*)

   $$K_c = \frac{[H_2O]}{[NH_3]^2[CO_2]} \qquad K_p = \frac{P_{H_2O}}{(P_{NH_3})^2 P_{CO_2}} \qquad K_c(RT)^{-2} = K_p$$ **heterogeneous**

   d. $2NBr_3$ (*s*) $\rightleftharpoons$ N_2 (*g*) + $3Br_2$ (*g*)

   $$K_c = [Br_2]^3[N_2] \qquad K_p = (P_{Br_2})^3 P_{N_2} \qquad K_c(RT)^4 = K_p$$ **heterogeneous**

   e. $2KClO_3$ (*s*) $\rightleftharpoons$ 2KCl (*s*) + $3O_2$ (*g*)

   $$K_c = [O_2]^3 \qquad K_p = (P_{O_2})^3 \qquad K_c(RT)^3 = K_p$$ **heterogeneous**

   f. CuO (*s*) + H_2 (*g*) $\rightleftharpoons$ Cu (*l*) + H_2O (*g*)

   $$K_c = \frac{[H_2O]}{[H_2]} \qquad K_p = \frac{P_{H_2O}}{P_{H_2}} \qquad K_c = K_p$$ **heterogeneous**

2. The equilibrium constant for the reaction A (*g*) + B (*g*) $\rightleftharpoons$ C (*g*) + D (*g*) is K. What is the equilibrium constant for each of the following reactions?
   a. C (*g*) + D (*g*) $\rightleftharpoons$ A (*g*) + B (*g*) **K^{-1}**
   b. 2A (*g*) + 2B (*g*) $\rightleftharpoons$ 2C (*g*) + 2D (*g*) **K^{2}**
   c. ½A (*g*) + ½B (*g*) $\rightleftharpoons$ ½C (*g*) + ½D (*g*) **$K^{1/2}$**
   d. 2C (*g*) + 2D (*g*) $\rightleftharpoons$ 2A (*g*) + 2B (*g*) **K^{-2}**
   e. ¼C (*g*) + ¼D (*g*) $\rightleftharpoons$ ¼A (*g*) + ¼B (*g*) **$K^{-1/4}$**

3. For the following reactions calculate K using the given equilibrium conditions. Do the second set of conditions represent a system at equilibrium? If not, which way will the reaction shift in order to reach equilibrium?
   a. $2N_2\ (g) + O_2\ (g) \rightleftharpoons 2N_2O\ (g)$
      i. 2.80×10^{-4} mol N_2, 2.50×10^{-5} mol O_2, 2.00×10^{-2} mol N_2O in a 2.00 L flask

$$[N_2O] = \frac{2.00\times10^{-2}\,mol}{2.00L} = 1.00\times10^{-2}\,M$$

$$[N_2] = \frac{2.80\times10^{-4}\,mol}{2.00L} = 1.40\times10^{-4}\,M$$

$$[O_2] = \frac{2.50\times10^{-5}\,mol}{2.00L} = 1.25\times10^{-5}\,M$$

$$K_c = \frac{[N_2O]^2}{[N_2]^2[O_2]} = \frac{(1.00\times10^{-2})^2}{(1.40\times10^{-4})^2(1.25\times10^{-5})} = 4.08\times10^8$$

      ii. $[N_2]=2.00 \times 10^{-4}$ M, $[O_2]=0.00245$ M, $[N_2O]=0.200$ M

$$Q_c = \frac{[N_2O]^2}{[N_2]^2[O_2]} = \frac{(0.200)^2}{(2.00\times10^{-4})^2(0.00245)} = 4.08\times10^8$$

at equilibrium

   b. $N_2\ (g) + 3H_2\ (g) \rightleftharpoons 2NH_3\ (g)$
      i. $P_{NH3}=3.1 \times 10^{-2}$ atm, $P_{N2}=8.5 \times 10^{-1}$ atm, $P_{H2}=3.1 \times 10^{-3}$ atm

$$K_p = \frac{(P_{NH_3})^2}{P_{N_2}(P_{H_2})^3} = \frac{(3.1\times10^{-2})^2}{(0.85)(3.1\times10^{-3})^3} = 3.8\times10^4$$

      ii. $P_{N2}=0.525$ atm, $P_{NH3}=0.0167$ atm, $P_{H2}=0.00761$ atm

$$Q_p = \frac{(P_{NH_3})^2}{P_{N_2}(P_{H_2})^3} = \frac{(0.0167)^2}{(0.525)(0.00761)^3} = 1.21\times10^3$$

shift to right (products)

c. $2NO\ (g) \rightleftharpoons N_2\ (g) + O_2\ (g)$

i. 0.032 mol NO, 0.62 mol N_2, and 4.0 mol O_2 in a 2.0 L flask

$$[NO] = \frac{0.032 mol}{2.0 L} = 0.016 M$$

$$[N_2] = \frac{0.62 mol}{2.0 L} = 0.31 M$$

$$[O_2] = \frac{4.0 mol}{2.0 L} = 2.0 M$$

$$K_c = \frac{[N_2][O_2]}{[NO]^2} = \frac{(0.31)(2.0)}{(0.016)^2} = 2.4 \times 10^3$$

ii. 0.024 mol NO, 2.0 mol N_2, and 2.6 mol O_2 in a 1.0 L flask

$$[NO] = \frac{0.024 mol}{1.0 L} = 0.024 M$$

$$[N_2] = \frac{2.0 mol}{1.0 L} = 2.0 M$$

$$[O_2] = \frac{2.6 mol}{1.0 L} = 2.6 M$$

$$Q_c = \frac{[N_2][O_2]}{[NO]^2} = \frac{(2.0)(2.6)}{(0.024)^2} = 9.0 \times 10^3$$

shift to left (reactants)

4. For the following reactions and with the information given, calculate K.

a. $2SO_3\ (g) \rightleftharpoons 2SO_2\ (g) + O_2\ (g)$

Initially 12.0 mol SO_3 is placed in a 3.0 L rigid container. At equilibrium, 3.0 mol SO_2 is present.

	$[SO_3]$	$[SO_2]$	$[O_2]$
Initial	4.0	0	0
Change	-2x	+2x	+x
Equilibrium	4.0-2x=3.0	2x=1.0	x=0.50

Only reactants are present, so reaction must proceed to form products.

$$K_c = \frac{[SO_2]^2[O_2]}{[SO_3]^2} = \frac{(1.0)^2(0.50)}{(3.0)^2} = 0.056$$

b. $S_8\ (g) \rightleftharpoons 4S_2\ (g)$
Initially, a sample of S_8 is placed in an empty rigid container at a pressure of 1.00 atm. At equilibrium, the partial pressure of S_8 is 0.25 atm.

	P_{S8}	P_{S2}
Initial	1.00	0
Change	-x	+4x
Equilibrium	1.00-x	4x

Only reactants are present, so reaction must proceed to form products.

$$1.00atm - x = 0.25atm \rightarrow x = 0.75atm$$

$$P_{S_2} = 4(0.75atm) = 3.0atm$$

$$K_p = \frac{(P_{S_2})^4}{P_{S_8}} = \frac{(3.0)^4}{0.25} = 3.2 \times 10^2$$

c. $3Fe\ (s) + 4H_2O\ (g) \rightleftharpoons Fe_3O_4\ (s) + 4H_2\ (g)$
When the equilibrium partial pressure of water vapor is 15.0 torr, the total pressure at equilibrium is 36.3 torr.

$$P_{total} = P_{H_2O} + P_{H_2};\ \ 36.3\ torr = 15.0\ torr + P_{H_2};\ \ P_{H_2} = 21.3\ torr$$

$$K_p = \frac{(P_{H_2})^4}{(P_{H_2O})^4} = \frac{\left(21.3\ torr \times \frac{1atm}{760torr}\right)^4}{\left(15.0\ torr \times \frac{1atm}{760torr}\right)^4} = 4.07$$

d. $N_2\ (g) + 3H_2\ (g) \rightleftharpoons 2NH_3\ (g)$
In a closed container, 1.00 atm of N_2 is mixed with 2.00 atm of H_2. At equilibrium, the total pressure is 2.00 atm

	P_{N2}	P_{H2}	P_{NH3}
Initial	1.00	2.00	0
Change	-x	-3x	+2x
Equilibrium	1.00-x	2.00-3x	2x

Only reactants are present, so reaction must form products.

$$P_{total} = 2.00atm = P_{N_2} + P_{H_2} + P_{NH_3} = (1.00 - x) + (2.00 - 3x) + (2x) \rightarrow x = 0.500atm$$

$$P_{N_2} = 1.00atm - 0.500atm = 0.500atm$$

$$P_{H_2} = 2.00atm - 3(0.500atm) = 0.500atm$$

$$P_{NH_3} = 2(0.500atm) = 1.00atm$$

$$K_p = \frac{[NH_3]^2}{[N_2][H_2]^3} = \frac{(1.00)^2}{(0.500)(0.500)^3} = 16.0$$

5. For the following reactions and with the given initial conditions and K, calculate the equilibrium concentrations.
   a. $CaCO_3\ (s) \rightleftharpoons CaO\ (s) + CO_2\ (g)$ K_p=1.16
      An evacuated 10.0 L container.
      $K_p = 1.16 atm = P_{CO_2}$

   b. $NH_4OCONH_2\ (s) \rightleftharpoons 2NH_3\ (g) + CO_2\ (g)$ K_p=2.9 x 10^{-3}
      An evacuated rigid container.

	$[NH_3]$	$[CO_2]$
Initial	0	0
Change	+2x	+x
Equilibrium	2x	x

Only reactants are present, so reaction must proceed to form products.

$$K_p = 2.9\times10^{-3} = \left(P_{NH_3}\right)^2 P_{CO_2} = (2x)^2 x = 4x^3 \rightarrow x = 9.0\times10^{-2} atm$$

$$P_{NH_3} = 2\left(9.0\times10^{-2} atm\right) = 0.18 atm$$
$$P_{CO_2} = 9.0\times10^{-2} atm$$

   c. $SO_2\ (g) + NO_2\ (g) \rightleftharpoons SO_3\ (g) + NO\ (g)$ K_c=3.75
      All four gases have initial concentrations of 0.800 M

$$K_c = \frac{[SO_3][NO]}{[SO_2][NO_2]} \qquad Q_c = \frac{[0.800][0.800]}{[0.800][0.800]} = 1.00$$ **shift to right**

	$[SO_2]$	$[NO_2]$	$[SO_3]$	$[NO]$
Initial	0.800	0.800	0.800	0.800
Change	-x	-x	+x	+x
Equilibrium	0.800-x	0.800-x	0.800+x	0.800+x

$$K_c = \frac{[0.800+x][0.800+x]}{[0.800-x][0.800-x]} = \frac{[0.800+x]^2}{[0.800-x]^2} = 3.75$$

$$\frac{[0.800+x]}{[0.800-x]} = \sqrt{3.75} = 1.94 \rightarrow 0.800 + x = 1.55 - 1.94x \rightarrow x = 0.26M$$

$$[SO_3] = [NO] = 0.800 + 0.26 = 1.06M$$
$$[SO_2] = [NO_2] = 0.800 - 0.26 = 0.54M$$

d. $N_2\ (g) + O_2\ (g) \rightleftharpoons 2NO\ (g)$ K_c=0.050

Initially, P_{N2}=0.80 atm, P_{O2}=0.20 atm and P_{NO}= 0.

	P_{N2}	P_{O2}	P_{NO}
Initial	0.80	0.20	0
Change	-x	-x	+2x
Equilibrium	0.80-x	0.20-x	2x

Only reactants are present, so reaction must proceed to form products.

$$K_c = K_p = \frac{(P_{NO})^2}{P_{N_2}P_{O_2}} = \frac{(2x)^2}{(0.80-x)(0.20-x)} = 0.050$$

$$3.95x^2 + 0.050x - 8.0\times10^{-3} = 0$$

solve with quadratic formula or graphing calculator

$x = 3.9\times10^{-2}\,atm$ **only positive root**

$$P_{N_2} = 0.80atm - \left(3.9\times10^{-2}\,atm\right) = 0.76atm$$

$$P_{H_2} = 0.20atm - \left(3.9\times10^{-2}\,atm\right) = 0.16atm$$

$$P_{NO} = 2\left(3.9\times10^{-2}\,atm\right) = 7.8\times10^{-2}\,atm$$

6. Complete the following table for the reaction:

$N_2\ (g) + 3H_2\ (g) \rightleftharpoons 2NH_3\ (g)$ + Energy

	$[N_2]$	$[H_2]$	$[NH_3]$
Remove N_2	-----------------	increases	decreases
Remove H_2	**increases**	**----------------**	**decreases**
Remove NH_3	**decreases**	**decreases**	**-----------------**
Add N_2	**------------------**	**decreases**	**increases**
Add H_2	**decreases**	**------------------**	**increases**
Add NH_3	**increases**	**increases**	------------------
Decrease temperature	**decreases**	**decreases**	**increases**
Increase temperature	**increases**	**increases**	**decreases**
Decrease pressure	**increases**	**increases**	**decreases**
Increase pressure	**decreases**	**decreases**	**increases**
Decrease volume	**decreases**	**decreases**	**increases**
Increase volume	increases	**increases**	**decreases**
Add catalyst	------------------	**------------------**	**------------------**
Add 1 mol Ar (g)	**------------------**	**------------------**	**------------------**

7. Classify each of the following substances as either a strong or weak base/acid. Identify its conjugate acid/base. For the strong acid/base solutions, calculate $[H^+]$, pH, $[OH^-]$, and pOH. $K_w=1.0 \times 10^{-14}$
   a. 0.250 M HNO_3 **strong acid** **conj. base = NO_3^-**
      $$\left[H^+\right]=0.250M$$
      $$pH=-\log(0.250)=0.602$$
      $$pOH=14-0.602=13.398$$
      $$\left[OH^-\right]=\frac{10^{-14}}{0.250}=4.00\times10^{-14}M$$
   b. 0.33 M NH_3 **weak base** **conj. acid = NH_4^+**
   c. 0.40 M HCOOH **weak acid** **conj. base = $HCOO^-$**
   d. 0.50 M $HClO_4$ **strong acid** **conj. base = ClO_4^-**
      $$\left[H^+\right]=0.50M$$
      $$pH=-\log(0.50)=0.30$$
      $$pOH=14-0.30=13.70$$
      $$\left[OH^-\right]=\frac{10^{-14}}{0.50}=2.0\times10^{-14}M$$
   e. 0.1 M HF **weak acid** **conj. base = F^-**
   f. 0.20 M HCl **strong acid** **conj. base = Cl^-**
      $$\left[H^+\right]=0.20M$$
      $$pH=-\log(0.20)=0.70$$
      $$pOH=14-0.70=13.30$$
      $$\left[OH^-\right]=\frac{10^{-14}}{0.20}=5.0\times10^{-14}M$$
   g. 2.2 M H_3PO_4 **weak acid** **conj. base = $H_2PO_4^-$**