Equilibrium Problems
Due: March 18, 2005.

1) Methanol (CH$_3$OH) is formed from carbon monoxide (CO) and hydrogen (H$_2$):

\[
\text{CO}(g) + 2 \text{H}_2(g) \rightleftharpoons \text{CH}_3\text{OH}(g)
\]

0.15 moles CO and 0.3 moles H$_2$ are put into a 1.5 L reactor. At equilibrium 0.12 moles of CO are found. What is $K_{eq}$?

\[
K_{eq} = \frac{[\text{CH}_3\text{OH}]}{[\text{CO}] [\text{H}_2]^2}
\]

\[
\begin{array}{c|c|c|c}
 & \text{I} & \text{C} & \text{E} \\
\hline
[\text{CO}] & 0.15/1.5 = 0.1 \text{ M} & 0.3/1.5 = 0.2 \text{ M} & 0.0 \\
[\text{H}_2] & -0.02 & -0.04 & +0.02 \\
\text{CH}_3\text{OH} & 0.12/1.5 = 0.08 \text{ M} & 0.16 & 0.02 \\
\end{array}
\]

\[
K_{eq} = \frac{[0.02]}{[0.08][16]^2} = 9.77
\]

Change occurs in stoichiometric ratios.
Law of Conservation of Mass:
Initial Concentration + Change = Equilibrium Concentration

2) Nitric oxide (NO) reacts with bromine (Br$_2$) to give nitrosyl bromide:

\[
2 \text{NO}(g) + \text{Br}_2(g) \rightleftharpoons 2 \text{NOBr}(g)
\]

0.0655 moles NO and 0.0328 moles Br$_2$ are put into a 1.0 L reactor. At equilibrium 0.0389 moles of NOBr are found. What is $K_{eq}$?

\[
K_{eq} = \frac{[\text{NOBr}]^2}{[\text{NO}]^2 [\text{Br}_2]}
\]

\[
\begin{array}{c|c|c|c}
 & \text{I} & \text{C} & \text{E} \\
\hline
[\text{NO}] & 0.0655 \text{ M} & 0.0328 \text{ M} & 0.0 \\
[\text{Br}_2] & -0.0389 & -0.01945 & +0.0389 \\
\text{NOBr} & 0.0266 \text{ M} & 0.0136 \text{ M} & 0.0389 \\
\end{array}
\]

\[
K_{eq} = \frac{[0.0389]^2}{[0.0266]^2[0.136]} = 157.3
\]

Change occurs in stoichiometric ratios.
Law of Conservation of Mass:
Initial Concentration + Change = Equilibrium Concentration

3) Nitrogen (N$_2$) reacts with hydrogen (H$_2$) to give ammonia:

\[
\text{N}_2(g) + 3 \text{H}_2(g) \rightleftharpoons 2 \text{NH}_3(g)
\]

0.75 moles N$_2$ and 2.25 moles H$_2$ are put into a 1.0 L reactor. At equilibrium 0.06 moles of NH$_3$ are found. What is $K_{eq}$?

\[
K_{eq} = \frac{[\text{NH}_3]^2}{[\text{N}_2][\text{H}_2]^3}
\]

\[
\begin{array}{c|c|c|c}
 & \text{I} & \text{C} & \text{E} \\
\hline
[\text{N}_2] & 0.75 \text{ M} & 2.25 \text{ M} & 0.0 \\
[\text{H}_2] & -0.03 & -0.09 & +0.06 \\
\text{NH}_3 & 0.72 \text{ M} & 2.26 \text{ M} & 0.06 \\
\end{array}
\]

\[
K_{eq} = \frac{[0.06]^2}{[0.72][2.26]^3} = 4.33 \times 10^{-4}
\]

Change occurs in stoichiometric ratios.
Law of Conservation of Mass:
Initial Concentration + Change = Equilibrium Concentration
4) The reaction $\text{CH}_4 + \text{H}_2\text{O} \rightleftharpoons \text{CO} + 3 \text{H}_2$ has $K = 5.67$ at 1300 K. If 3 moles $\text{CH}_4$ and 6 moles $\text{H}_2\text{O}$ are placed in a 1 L reactor what is the equilibrium concentration of $\text{H}_2$?

$$K = 5.67 = \frac{[\text{CO}][\text{H}_2]^3}{[\text{CH}_4][\text{H}_2\text{O}]}$$

<table>
<thead>
<tr>
<th>Initial</th>
<th>$[\text{CH}_4]$</th>
<th>$[\text{H}_2\text{O}]$</th>
<th>$[\text{CO}]$</th>
<th>$[\text{H}_2]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change</td>
<td>-x</td>
<td>-x</td>
<td>+x</td>
<td>+3x</td>
</tr>
<tr>
<td>Equilibrium</td>
<td>3 - x</td>
<td>6 - x</td>
<td>+x</td>
<td>+3x</td>
</tr>
</tbody>
</table>

Plug into Equilibrium Expression

$$K = 5.67 = \frac{[x][3x]^3}{[3-x][6-x]}$$

Lots of Algebra to do.

$$K = 5.67 = \frac{27x^4}{18-9x+x^2}$$

This equation can be solved graphically using EXCEL

Note that we want values of $x$ that fall into the range of 0 to 3 as otherwise we would have negative values of concentrations at equilibrium. Concentrations always have to be positive values.

I graphed $Q$ (Reaction Quotient) as a function of $x$. Equilibrium occurs when $Q = 5.67 = K$. From the graph the value of $x$ is 1.167.

$$[\text{CH}_4] \quad [\text{H}_2\text{O}] \quad [\text{CO}] \quad [\text{H}_2]$$

<table>
<thead>
<tr>
<th>Equilibrium</th>
<th>3 - x</th>
<th>6 - x</th>
<th>+x</th>
<th>+3x</th>
</tr>
</thead>
</table>

| Equilibrium | 1.833 | 4.833 | 1.167 | 3.501 |

I find $Q = \frac{(1.167 \times 3.501^3)/(1.833 \times 4.833)}{5.65}$ which is close to $K = 5.67$. The small error (0.3%) is due to round-off error and estimating from the graph.
5) At 700 K the equilibrium constant for the reaction $\text{CCl}_4 \rightleftharpoons \text{C} + 2 \text{Cl}_2$ is 60. If a 1 L reactor has two moles of CCl$_4$ placed in it, what fraction of CCl$_4$ is converted to chlorine gas?

$$K = 60 = \frac{[\text{Cl}]^2}{[\text{CCl}_4]}$$

<table>
<thead>
<tr>
<th>Initial</th>
<th>[CCl$_4$]</th>
<th>[C]</th>
<th>[Cl$_2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 M</td>
<td>0 M</td>
<td>0 M</td>
</tr>
<tr>
<td>Change</td>
<td>-x</td>
<td>+x</td>
<td>+2x</td>
</tr>
<tr>
<td>Equilibrium</td>
<td>2 – x</td>
<td>+x</td>
<td>+2x</td>
</tr>
</tbody>
</table>

Plug into Equilibrium Expression

$$K = 60 = \frac{[x][2x]^2}{2-x}$$

Lots of Algebra to do.

$$K = 60 = \frac{4x^3}{2-x}$$

This equation can be solved graphically using EXCEL

Note that we want values of x that fall into the range of 0 to 2 as otherwise we would have negative values of concentrations at equilibrium. Concentrations always have to be positive values.

![Problem 5](image)

I graphed Q (Reaction Quotient) as a function of x. Equilibrium occurs when $Q = 60 = K$. From the graph the value of x is 1.682.

<table>
<thead>
<tr>
<th>Equilibrium</th>
<th>[CCl$_4$]</th>
<th>[C]</th>
<th>[Cl$_2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 – x</td>
<td>+x</td>
<td>+2x</td>
</tr>
<tr>
<td>Equilibrium</td>
<td>0.318</td>
<td>1.682</td>
<td>3.364</td>
</tr>
</tbody>
</table>

I find $Q = \frac{(1.682^2)(3.364)^2}{0.318} = 59.9$ which is close to $K = 60$.

The small error (0.2%) is due to round-off error and estimating from the graph.

$0.318/2.0 = 0.16$ or 16% of the CCl$_4$ remains so 84% of the CCl$_4$ is converted to Cl$_2$. 
6) For the reaction \( N_2O_4 \rightleftharpoons 2NO_2 \) the equilibrium constant is equal to 4.5. If 0.3 moles of \( N_2O_4 \) are placed in a 1.5 L reactor how many grams of \( NO_2 \) will there be at equilibrium?

\[
K = 4.5 = \frac{[NO_2]^2}{[N_2O_4]}
\]

<table>
<thead>
<tr>
<th>Initial</th>
<th>0.2 M</th>
<th>0.0 M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change</td>
<td>-x</td>
<td>+2x</td>
</tr>
<tr>
<td>Equilibrium</td>
<td>0.2 - x</td>
<td>+2x</td>
</tr>
</tbody>
</table>

Plug into Equilibrium Expression

\[
K = 4.5 = \frac{[2x]^2}{0.2 - x}
\]

Lots of Algebra to do.

The quadratic equation can be used this time!

\[
[0.2 - x] * 4.5 = 4x^2
\]

\[
0 = 4x^2 + 4.5x - 0.9
\]

\[
a = 4, b = 4.5, c = -0.9
\]

\[
x = -1.298 & 0.173
\]

Only 0.173 gives a set of positive concentrations

\[
[N_2O_4] [NO_2]
\]

Equilibrium 0.2 - x +2x

Equilibrium 0.027 0.346

Double Check \( Q = (0.346)^2/0.027 = 4.43 = K \) with an error of 1.5% due to round-offs.

At equilibrium: 1.5 L * 0.346 M = 0.519 moles \( NO_2 \) (46 g/mole) = 23.87 g

7) The reaction \( Br_2 + Cl_2 \rightleftharpoons 2 BrCl \) has \( K = 6.9 \). If the initial concentrations are \( [Br_2]=0.6 \text{ M} \) and \( [Cl_2]=0.4 \text{ M} \) what are the equilibrium concentrations of all three species?

\[
K = 6.9 = \frac{[BrCl]^2}{[Br_2][Cl_2]}
\]

<table>
<thead>
<tr>
<th>Initial</th>
<th>0.6 M</th>
<th>0.6 M</th>
<th>0.0 M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change</td>
<td>-x</td>
<td>-x</td>
<td>+2x</td>
</tr>
<tr>
<td>Equilibrium</td>
<td>0.6 - x</td>
<td>0.4 - x</td>
<td>+2x</td>
</tr>
</tbody>
</table>

Plug into Equilibrium Expression

\[
K = 6.9 = \frac{[2x]^2}{0.6-x}[0.4-x]
\]

Lots of Algebra to do.

The quadratic equation can be used this time!

\[
0 = 4x^2 + 6.9x - 1.656
\]

\[
a = -2.9, b = 6.9, c = -1.656
\]

\[
x = 2.108 & 0.271
\]

Only 0.271 gives a set of positive concentrations

\[
[Br_2] [Cl_2] [BrCl]
\]

Equilibrium 0.6 - x 0.4 - x +2x

Equilibrium 0.329 0.129 0.542

Double Check \( Q = (0.542)^2/(0.329*0.129) = 6.92 = K \) with an error of 0.5% due to round-offs.
8) The reaction $2 \text{BrCl} \rightleftharpoons \text{Br}_2 + \text{Cl}_2$ has $K = 0.145$. If the initial concentration of $[\text{BrCl}] = 0.056 \text{ M}$ what are the equilibrium concentrations of all three species?

$$K = 0.145 = \frac{[\text{Br}_2][\text{Cl}_2]}{[\text{BrCl}]^2}$$

<table>
<thead>
<tr>
<th>Initial</th>
<th>0.056 M</th>
<th>0.0 M</th>
<th>0.0 M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change</td>
<td>-2x</td>
<td>+x</td>
<td>+x</td>
</tr>
<tr>
<td>Equilibrium</td>
<td>0.056 – 2x</td>
<td>+x</td>
<td>+x</td>
</tr>
</tbody>
</table>

Plug into Equilibrium Expression

$$K = 0.145 = \frac{[x][x]}{[0.056-2x]^2}$$

Lots of Algebra to do.

The quadratic equation can be used this time!

$$0 = 0.42x^2 + 0.0325x - 4.52 \times 10^{-4}$$

$$x = 1.20 \times 10^{-2} \text{ and } -8.94 \times 10^{-2}$$

Only $1.20 \times 10^{-2}$ gives a set of positive concentrations

<table>
<thead>
<tr>
<th>[BrCl]</th>
<th>[Br$_2$]</th>
<th>[Cl$_2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equilibrium</td>
<td>0.056 – 2x</td>
<td>+x</td>
</tr>
<tr>
<td>Equilibrium</td>
<td>0.032</td>
<td>1.20 $\times 10^{-2}$</td>
</tr>
</tbody>
</table>

Double Check $Q = (0.012 \times 0.012)/(0.032)^2 = 0.141 = K$ with an error of 3.0% due to round-offs.

9) The reaction $2 \text{BrCl} \rightleftharpoons \text{Br}_2 + \text{Cl}_2$ has $K = 0.145$. If the initial concentrations of $[\text{BrCl}] = 0.056 \text{ M}$ and $[\text{Br}_2] = 0.036 \text{ M}$ what are the equilibrium concentrations of all three species?

$$K = 0.145 = \frac{[\text{Br}_2][\text{Cl}_2]}{[\text{BrCl}]^2}$$

<table>
<thead>
<tr>
<th>Initial</th>
<th>0.056 M</th>
<th>0.036 M</th>
<th>0.0 M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change</td>
<td>-2x</td>
<td>+x</td>
<td>+x</td>
</tr>
<tr>
<td>Equilibrium</td>
<td>0.056 – 2x</td>
<td>0.036+x</td>
<td>+x</td>
</tr>
</tbody>
</table>

Plug into Equilibrium Expression

$$K = 0.145 = \frac{x[x][0.036+x]}{[0.056-2x]^2}$$

Lots of Algebra to do.

The quadratic equation can be used this time!

$$0 = 0.42x^2 + 0.0685x - 4.52 \times 10^{-4}$$

$$x = 0.0063 \text{ and } -0.1694$$

Only $6.30 \times 10^{-3}$ gives a set of positive concentrations

<table>
<thead>
<tr>
<th>[BrCl]</th>
<th>[Br$_2$]</th>
<th>[Cl$_2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equilibrium</td>
<td>0.056 – 2x</td>
<td>0.036+x</td>
</tr>
<tr>
<td>Equilibrium</td>
<td>0.0434</td>
<td>0.0423</td>
</tr>
</tbody>
</table>

Double Check $Q = (0.0423 \times 0.0063)/(0.0434)^2 = 0.142 = K$ with an error of 2.5% due to round-offs.