Equilibrium

Unit: Kinetics & Equilibrium

MA Curriculum Frameworks (2016): HS-PS1-6

Mastery Objective(s): (Students will be able to…)

- List and explain factors that affect the equilibrium of a chemical reaction.
- Write equilibrium expressions from chemical equations and chemical equations from equilibrium expressions.

Success Criteria:

- Equilibrium expressions have products on top and reactants on the bottom.
- Equilibrium expressions have coëfficients shown as exponents.

Tier 2 Vocabulary: forward, backward, expression

Language Objectives:

- Explain how different factors affect the equilibrium of a chemical reaction.

Notes:

reversible reaction: a reaction that proceeds in both forward and backward directions. Usually written with double half-arrows:

$$N_{2\,(g)} + 3\,H_{2\,(g)} \rightleftharpoons 2\,NH_{3\,(g)}$$

dynamic chemical equilibrium: reaction is happening in both directions, but the changes balance each other, so the concentrations of reactants & products remain constant. At equilibrium:

$$\text{rate}_{\text{forward reaction}} = \text{rate}_{\text{reverse reaction}} \quad \text{or} \quad k_f = k_r$$

concentration: the amount of a compound dissolved in a given amount of solution, usually expressed in $\frac{\text{mol}}{\text{L}}$ (moles of the compound per liter of solution).

A shorthand way to write the concentration of a compound is to place the chemical formula in square brackets. For example, $[NH_3]$ means "the concentration of NH_3 in $\frac{\text{mol}}{\text{L}}$".

Use this space for summary and/or additional notes:

Arrows Used in Chemical Equations

Arrow	Meaning
$A + B \rightarrow C + D$	A + B react to produce C + D Either there is little or no reverse reaction, or no information is given about equilibrium.
$A + B \rightleftharpoons C + D$	A + B are in equilibrium with C + D No information is given about whether products or reactants are favored.
$A + B \overset{\longrightarrow}{\leftharpoondown} C + D$	A + B are in equilibrium with C + D Products are favored. (*I.e.,* the concentrations of products are higher than the concentrations of reactants.)
$A + B \underset{\longleftarrow}{\rightharpoonup} C + D$	A + B are in equilibrium with C + D Reactants are favored. (*I.e.,* the concentrations of reactants are higher than the concentrations of products.)
$A \leftrightarrow B$	A and B are different resonance structures of the same compound. This is different from a chemical reaction that is at equilibrium.

Use this space for summary and/or additional notes:

<u>equilibrium expression</u>: a mathematical expression relating the concentrations of the products and reactants at equilibrium. For the reaction:

$$N_2 + 3\,H_2 \rightleftharpoons 2\,NH_3$$

the equilibrium expression is:

$$K_{eq} = \frac{[NH_3]^2}{[N_2][H_2]^3}$$

where $[NH_3]$ means the molarity of NH_3 (the concentration in $\frac{mol}{L}$).

The equilibrium expression comes from collision theory. In order for N_2 and H_2 to react, one N_2 and 3 H_2 molecules need to find each other. The probability of this 4-way collision is related to the product of the concentrations of each of the molecules involved, *i.e.,* $[N_2][H_2][H_2][H_2]$ or $[N_2][H_2]^3$. Notice that the coëfficients in the equation became exponents in the equilibrium expression.

The reverse reaction requires 2 NH_3 molecules to collide; the probability of this collision is the product of the concentrations, $[NH_3][NH_3]$ or $[NH_3]^2$. Again, the coëfficient "2" became the exponent.

For the equilibrium expression, we write the concentrations of products on the top and reactants on the bottom. (The reason for this comes from the rate laws for the forward and reverse reactions. Rate laws are beyond the scope of this course, but are studied in AP Chemistry.) However, for our purposes, it also means that an equilibrium constant greater than 1 means we have more products, and an equilibrium constant less than 1 means we have more reactants.

<u>equilibrium constant</u> (K_{eq}): when we plug the concentrations (in $\frac{mol}{L}$) for each of the products and reactions into the equilibrium expression, we get a value for K_{eq}.

If $K_{eq} > 1$ then there are more products than reactants, and we say that the "equilibrium lies to the right".

If $K_{eq} < 1$ then there are more reactants than products, and we say that "equilibrium lies to the left".

If $K_{eq} = 1$ then there are equal amounts of reactants and products, and we say that the reactants and products are equally favored.

K_{eq} depends on temperature, but is constant for a given reaction at a given temperature.

Use this space for summary and/or additional notes:

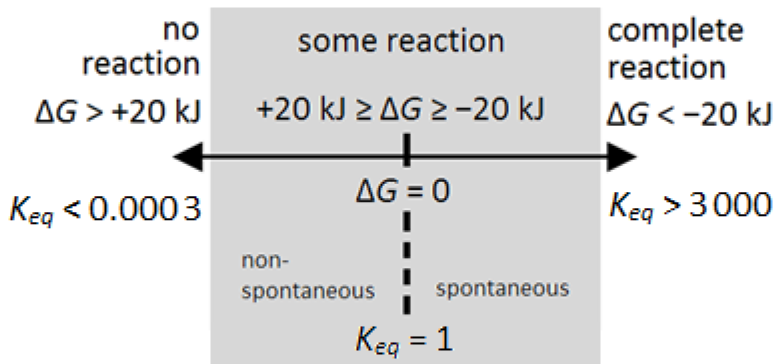
Equilibrium Constant *vs.* Free Energy

In the section on Thermodynamics, starting on page 452, we saw that the extent of the reaction (how much reaction occurs) depends on the change in Gibbs free energy of the reaction.

The equilibrium constant is related to the Gibbs free energy by the equation:

$$\Delta G = -RT\ln(K_{eq}) \quad \text{or} \quad K_{eq} = e^{-\Delta G/RT}$$

While the calculations are beyond the scope of this course, you should understand that a higher value of ΔG corresponds with a higher value of the equilibrium constant K_{eq}:



Sample Problems:

Q: Write the equilibrium expression for the chemical reaction $2\,H_2 + Cl_2 \rightleftharpoons 2\,HCl$

A: Products go on the top and reactants go on the bottom.
Coëfficients become exponents.

$$K_{eq} = \frac{[HCl]^2}{[H_2]^2[Cl_2]}$$

Q: Write the chemical equation for the equilibrium expression: $K_{eq} = \frac{[CO_2]^4[H_2O]^2}{[C_2H_2]^2[O_2]^5}$

A: The denominator becomes the reactants (on the left), and the numerator becomes the products (on the right). Exponents become coëfficients:

$$2\,C_2H_2 + 5\,O_2 \rightleftharpoons 4\,CO_2 + 2\,H_2O$$

Use this space for summary and/or additional notes:

Q: Calculate the value of the equilibrium constant for the reaction $2\,NOBr \rightleftharpoons 2\,NO + Br_2$ if the concentration of NOBr is 3.00 M, the concentration of NO is 0.750 M, and the concentration of Br_2 is 0.200 M

A: The equilibrium expression is:

$$K_{eq} = \frac{[NO]^2[Br_2]}{[NOBr]^2}$$

Plugging in the concentrations, we get:

$$K_{eq} = \frac{(0.750)^2(0.200)}{3.00^2} = 0.0125$$

Note that the units for equilibrium constants are tricky, because each concentration is in $\frac{mol}{L}$. This means that if a concentration is squared, the units become $(\frac{mol}{L})^2 = \frac{mol^2}{L^2}$. This means that every equilibrium constant has its own units, depending on the number of molecules that take part in the forward and reverse reactions.

From the equilibrium expression, the units of the equilibrium constant for this expression happens to be:

$$\frac{(\frac{mol}{L})^2(\frac{mol}{L})}{(\frac{mol}{L})^2} = \frac{mol}{L}$$

Working with the units for the equilibrium constant is beyond the scope of this course.

Use this space for summary and/or additional notes:

Homework Problems

Write the expression for the equilibrium constants for each of the following reactions.

1. $Xe + 3\,F_2 \rightleftharpoons 2\,XeF_6$

2. $CH_4 + 2\,H_2S \rightleftharpoons CS_2 + 4\,H_2$

3. $3\,CO_2 + 4\,H_2O \rightleftharpoons C_3H_8 + 5\,O_2$

4. Write the chemical equation for the equilibrium system given by the expression:

$$K_{eq} = \frac{[H_2O]^2[O_2]}{[H_2O_2]^2}$$

5. Write the chemical equation for the equilibrium system given by the expression:

$$K_{eq} = \frac{[NH_3]^2}{[N_2][H_2]^3}$$

6. Write the chemical equation for the equilibrium system given by the expression:

$$K_{eq} = \frac{[HCl]^4[O_2]}{[H_2O]^2[Cl_2]^2}$$

Use this space for summary and/or additional notes:

7. A reaction vessel contains 0.150 M CH_4, 0.233 M H_2O, 0.259 M H_2, and 0.513 M CO. If the equilibrium reaction is $CH_4 + H_2O \rightleftharpoons CO + 3\,H_2$, write the equilibrium expression and calculate the value of K_{eq}.

Answer: K_{eq} = 0.255

8. A 10 L flask contains 0.128 mol of CO, 0.155 mol of H_2 and 0.0244 mol of CH_3OH. If the equilibrium reaction is $CH_3OH \rightleftharpoons CO + 2\,H_2$, write the equilibrium expression and calculate the value of K_{eq}.
(*Note: you will need to divide each number of moles by 10 L to get the concentrations in* $\frac{\text{mol}}{\text{L}}$.)

Answer: K_{eq} = 0.001 26

Use this space for summary and/or additional notes: