Chemical Reactions and Chemical Equations

A **chemical reaction** is a process in which one set of substances, called **reactants**, is converted to a new set of substances, called **products**.

$C(s) + O_2\,(g) \rightarrow CO_2\,(g)$

A C atom reacts with an O molecule, both disappear yielding a CO_2 molecule

Sometimes the reaction advances up to the limiting reactant is consumed: coal burns and disappears, in excess of air, yielding CO_2

In general, a mixture of reactants yield a mixture of reactants and products:

$NaCl\ (aq.) + AgNO_3\ (aq.) \rightarrow AgCl\ (s) + NaNO_3\ (aq.)$

$Cl^-\ (aq.) + Ag^+\ (aq.) \rightleftarrows AgCl\ (s)$

In the solution we still may find Cl^- (aq.) and Ag^+ (aq.) so that, independently of the amount of AgCl (s):

$[Cl^-]\ [Ag^+]=Kps$ (constant at a given T)

The equilibrium constant Kps changes with T:
→ we can dissolve $PbCl_2$ in water by just heating

The Equilibrium Constant Expression

For the hypothetical, generalized reaction

$$aA(aq) + bB(aq) \cdots \rightleftharpoons gG(aq) + hH(aq) \cdots$$

$$\boxed{K = \frac{(a_G)^g (a_H)^h \cdots}{(a_A)^a (a_B)^b \cdots}}$$

$a \longrightarrow$ activity

Equilibrium in the reaction

$$C(s) + H_2O(g) \rightleftharpoons CO(g) + H_2(g)$$

$$K = \frac{a_{CO}\, a_{H_2}}{a_{C(s)}\, a_{H_2O}} \approx \frac{P_{CO}\, P_{H_2}}{P_{H_2O}} = K_p\ ;\ [\quad] = \frac{P}{RT}\ ;\ K_p = K_c (RT)^{\Delta n_{gas}}$$

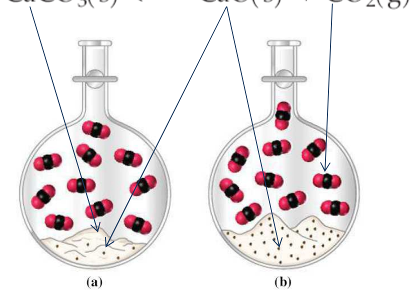
$$CaCO_3(s) \rightleftharpoons CaO(s) + CO_2(g)$$

$$K_c = [CO_2] \qquad K_p = P_{CO_2} \qquad K_p = K_c(RT)$$

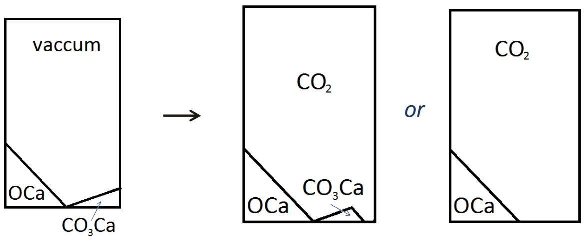
Why activity of solids is constant?

$$CaCO_3(s) \rightleftharpoons CaO(s) + CO_2(g)$$

(a) Equilibrium
(b) Introduction of additional $CaCO_3$ has no effects



Why heterogeneous reactions can be completed?



$P_{CO_2} \leq K_{P_s}$

Solubility

AgCl is poorly soluble in water: $K_{sp} = 1.8 \times 10^{-10}$. Low dissociation in water

$$AgCl\ (s) \rightleftharpoons Cl^-\ (aq.) + Ag^+\ (aq.)$$

Table salt (NaCl) has a high K_{sp} and is quite soluble. High dissociation in water

$$NaCl\ (s) \rightleftharpoons Cl^-\ (aq.) + Na^+\ (aq.)$$

Weak and Strong Acids

HCl is a strong acid, highly dissociated in in water

$$HCl + H_2O \rightleftharpoons Cl^-\ (aq.) + H^+\ (aq.)$$

Acetic adic AcH is a weak acid, poorly dissociated in in water

$$AcH + H_2O \rightleftharpoons Ac^-\ (aq.) + H^+\ (aq.)$$

Brønsted–Lowry Theory of Acids and Bases

Dissociation is a chemical reaction with water:

$HCl + H_2O \longrightarrow Cl^- (aq.) + H^+ (aq.)$

$HCl + H_2O \longrightarrow Cl^- + H_3O^+$

Acid base base acid

Acid: gives a proton
Base: accepts a proton

TABLE 16.1 Relative Strengths of Some Common Brønsted–Lowry Acids and Bases

Increasing acid strength ↑ / Increasing base strength ↓

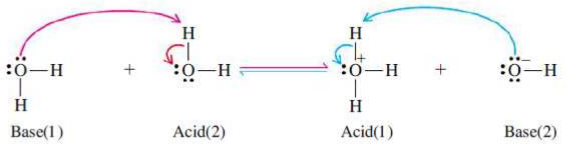
Acid		Conjugate Base	
Perchloric acid	$HClO_4$	Perchlorate ion	ClO_4^-
Hydroiodic acid	HI	Iodide ion	I^-
Hydrobromic acid	HBr	Bromide ion	Br^-
Hydrochloric acid	HCl	Chloride ion	Cl^-
Sulfuric acid	H_2SO_4	Hydrogen sulfate ion	HSO_4^-
Nitric acid	HNO_3	Nitrate ion	NO_3^-
Hydronium ion[a]	H_3O^+	Water[a]	H_2O
Hydrogen sulfate ion	HSO_4^-	Sulfate ion	SO_4^{2-}
Nitrous acid	HNO_2	Nitrite ion	NO_2^-
Acetic acid	CH_3COOH	Acetate ion	CH_3COO^-
Carbonic acid	H_2CO_3	Hydrogen carbonate ion	HCO_3^-
Ammonium ion	NH_4^+	Ammonia	NH_3
Hydrogen carbonate ion	HCO_3^-	Carbonate ion	CO_3^{2-}
Water	H_2O	Hydroxide ion	OH^-
Methanol	CH_3OH	Methoxide ion	CH_3O^-
Ammonia	NH_3	Amide ion	NH_2^-

TABLE 16.3 Ionization Constants of Some Weak Acids and Weak Bases in Water at 25 °C

	Ionization Equilibrium	Ionization Constant K	pK
Acid		K_a =	pK_a =
Iodic acid	$HIO_3 + H_2O \rightleftharpoons H_3O^+ + IO_3^-$	1.6×10^{-1}	0.80
Chlorous acid	$HClO_2 + H_2O \rightleftharpoons H_3O^+ + ClO_2^-$	1.1×10^{-2}	1.96
Chloroacetic acid	$ClCH_2COOH + H_2O \rightleftharpoons H_3O^+ + ClCH_2COO^-$	1.4×10^{-3}	2.85
Nitrous acid	$HNO_2 + H_2O \rightleftharpoons H_3O^+ + NO_2^-$	7.2×10^{-4}	3.14
Hydrofluoric acid	$HF + H_2O \rightleftharpoons H_3O^+ + F^-$	6.6×10^{-4}	3.18
Formic acid	$HCOOH + H_2O \rightleftharpoons H_3O^+ + HCOO^-$	1.8×10^{-4}	3.74
Benzoic acid	$C_6H_5COOH + H_2O \rightleftharpoons H_3O^+ + C_6H_5COO^-$	6.3×10^{-5}	4.20
Hydrazoic acid	$HN_3 + H_2O \rightleftharpoons H_3O^+ + N_3^-$	1.9×10^{-5}	4.72
Acetic acid	$CH_3COOH + H_2O \rightleftharpoons H_3O^+ + CH_3COO^-$	1.8×10^{-5}	4.74
Hypochlorous acid	$HOCl + H_2O \rightleftharpoons H_3O^+ + OCl^-$	2.9×10^{-8}	7.54
Hydrocyanic acid	$HCN + H_2O \rightleftharpoons H_3O^+ + CN^-$	6.2×10^{-10}	9.21
Phenol	$HOC_6H_5 + H_2O \rightleftharpoons H_3O^+ + C_6H_5O^-$	1.0×10^{-10}	10.00
Hydrogen peroxide	$H_2O_2 + H_2O \rightleftharpoons H_3O^+ + HO_2^-$	1.8×10^{-12}	11.74
Base		K_b =	pK_b =
Diethylamine	$(C_2H_5)_2NH + H_2O \rightleftharpoons (C_2H_5)_2NH_2^+ + OH^-$	6.9×10^{-4}	3.16
Ethylamine	$C_2H_5NH_2 + H_2O \rightleftharpoons C_2H_5NH_3^+ + OH^-$	4.3×10^{-4}	3.37
Ammonia	$NH_3 + H_2O \rightleftharpoons NH_4^+ + OH^-$	1.8×10^{-5}	4.74
Hydroxylamine	$HONH_2 + H_2O \rightleftharpoons HONH_3^+ + OH^-$	9.1×10^{-9}	8.04
Pyridine	$C_5H_5N + H_2O \rightleftharpoons C_5H_5NH^+ + OH^-$	1.5×10^{-9}	8.82
Aniline	$C_6H_5NH_2 + H_2O \rightleftharpoons C_6H_5NH_3^+ + OH^-$	7.4×10^{-10}	9.13

Acid strength ↑ / Base strength ↑

Self-Ionization of Water and the pH Scale



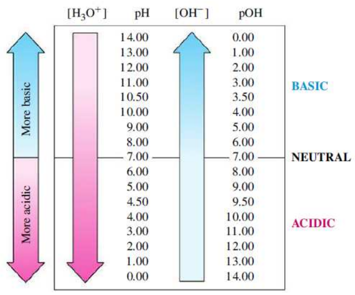
$$K_w = [H_3O^+][OH^-] = 1.0 \times 10^{-14}$$

At 25 °C in pure water: $[H_3O^+] = [OH^-] = 1.0 \times 10^{-7}\ M$

$$pH = -\log[H_3O^+] \qquad pOH = -\log[OH^-]$$

$$\longrightarrow \quad pK_w = pH + pOH = 14.00$$

$\longrightarrow$



Acids and Bases and Their Conjugates

$$\left.\begin{array}{ll} AH + H_2O \leftrightarrows A^- + H_3O^+ & K_a = \dfrac{[A^-][H_3O^+]}{[AH]} \\ A^- + H_2O \leftrightarrows AH + OH^- & K_b = \dfrac{[AH][OH^-]}{[A^-]} \end{array}\right\} \Rightarrow K_a\,K_b = \frac{[A^-][H_3O^+]}{[AH]}\frac{[AH][OH^-]}{[A^-]} \Rightarrow$$

$$K_a\,K_b = [H_3O^+][OH^-] \longrightarrow \boxed{K_a\,K_b = K_w = 10^{-14}}$$

Calculating the pH of an Acid Solution

$$AH + H_2O \leftrightarrows A^- + H_3O^+ \qquad K_a = \frac{[A^-][H_3O^+]}{[AH]}$$

$$H_2O + H_2O \leftrightarrows OH^- + H_3O^+ \qquad K_w = [OH^-][H_3O^+]$$

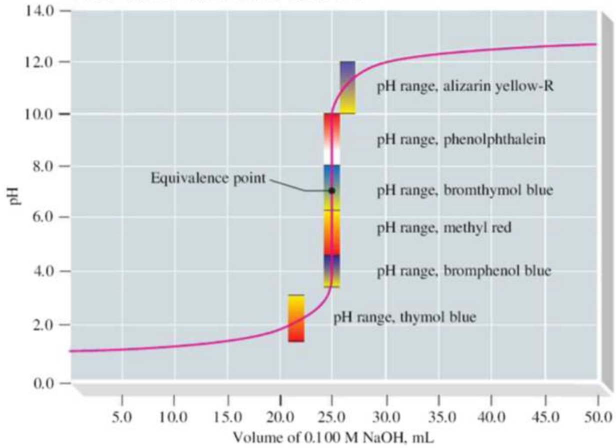
$$[AH]_0 = C_a = [AH] + [A^-]$$

$$[A^-] + [OH^-] = [H_3O^+]$$

Titration Curves

Titration Data	
mL NaOH(aq)	pH
0.00	1.00
10.00	1.37
20.00	1.95
22.00	2.19
24.00	2.70
25.00	7.00
26.00	11.30
28.00	11.75
30.00	11.96
40.00	12.36
50.00	12.52

Titration curve for the titration of a strong acid with a strong base—25.00 mL of 0.100 M HCl with 0.100 M NaOH



acid–base indicator

$$\underset{\text{Acid color}}{HIn} + H_2O \rightleftharpoons H_3O^+ + \underset{\text{Base color}}{In^-}$$

Titration curve for the titration of a weak acid with a strong base 25.00 mL of 0.100 M CH_3COOH with 0.100 M NaOH