

# SOLUTIONS

## I. INTRODUCTION

A. A solution is a mixture of a solvent and a dissolved material called the solute.

1. Characteristics of solute particles:

- Particles are single atoms, single ions or single small molecules.
- Particle size: less than 1 nanometer ( $\text{nm} = 1 \times 10^{-9}$  meters)
- Particles are evenly dispersed throughout the solvent.

2. A solution is a homogeneous mixture of two (or more) substances in (almost) any of the three states of matter.

SOLVENT	SOLUTE		
	SOLID	LIQUID	GAS
SOLID	<i>bronze (Sn in Cu) brass (Zn in Cu) steel (C in Fe)</i>	<i>Hg in Ag</i>	<i>H<sub>2</sub> in Pd</i>
LIQUID	<b>NaCl in H<sub>2</sub>O</b>	<b>C<sub>2</sub>H<sub>6</sub>O in H<sub>2</sub>O</b>	<b>CO<sub>2</sub> in H<sub>2</sub>O</b>
GAS			<i>O<sub>2</sub> in N<sub>2</sub></i>

3. Some Solution Vocabulary:

soluble          miscible          in solution  
insoluble      immiscible

## II. SOLUBILITY - how much will dissolve

SOLUBILITY is usually measured as the number of grams of solute that will dissolve in 100 grams of a solvent at a given temperature.

SATURATED SOLUTION: contains all the solute that will go into solution at a given temperature.

UNSATURATED SOLUTION: contains less solute than the amount of solute in a saturated solution at a given temperature.

SUPERSATURATED SOLUTION: contains more solute than the amount of solute in a saturated solution at a given temperature.

## III. CONCENTRATED & DILUTE SOLUTIONS

CONCENTRATED SOLUTION: contains a relatively large amount of solute in solution.

DILUTE SOLUTION: contains a relatively small amount of solute in solution

## V. FACTORS THAT AFFECT SOLUBILITY (in liquid solvents)

### A. NATURE OF SOLUTE AND SOLVENT

#### 1. SOLUBILITY of IONIC COMPOUNDS IN WATER

SOLUBILITY RULES	COMPOUND CONTAINS THIS ION		EXCEPT	WITH
S O L U B L E	CATION	Group IA		
		$\text{NH}_4^+$		
	ANION	$\text{NO}_3^-$		
		$\text{C}_2\text{H}_3\text{O}_2^-$		
		$\text{Cl}^-$ , $\text{Br}^-$ , $\text{I}^-$	$\text{Ag}^+$ , $\text{Hg}_2^{2+}$ , $\text{Pb}^{2+}$	
	$\text{SO}_4^{2-}$	$\text{Ca}^{2+}$ , $\text{Sr}^{2+}$ , $\text{Ba}^{2+}$ , $\text{Pb}^{2+}$		
I N S O L U B L E ★	ANION	$\text{S}^{2-}$	Group IA, IIA, $\text{NH}_4^+$	
		$\text{CO}_3^{2-}$	Group IA, $\text{NH}_4^+$	
		$\text{CrO}_4^{2-}$		
		$\text{PO}_4^{3-}$		
		$\text{OH}^-$	Group IA, $\text{Ca}^{2+}$ , $\text{Sr}^{2+}$ , $\text{Ba}^{2+}$	

★ VERY SLIGHTLY SOLUBLE

#### 2. SOLUBILITY OF MOLECULAR COMPOUNDS IN WATER

↳ Rule of thumb: "Like dissolves like"

a. SOLUBLE: Polar compounds are soluble in water.

Polar covalent compounds

All acids are polar, therefore all are soluble in water (except  $\text{H}_2\text{S}$ )

b. INSOLUBLE: Nonpolar compounds are insoluble (very slightly soluble) in water.

### B. TEMPERATURE

- In general, solubility of liquids and solids in liquid solvents increases with increase in solvent temperature. But it actually depends on whether the solution process is exothermic or endothermic.
- In general, the solubility of a gas in a liquid solvent decreases with increase in temperature.

### C. PRESSURE

- Solids & liquids: pressure has little effect on their solubility in liquid solvents.
- Gases: the greater the partial pressure of a gas above a liquid solvent, the greater the solubility of the gas in the liquid. (Henry's Law)

## V. ENTHALPY OF SOLUTION

### A. Enthalpy of Solution $\Delta H_{\text{soln}}$

1. Definition: the amount of energy absorbed or released when a substance enters solution.
2. The change in enthalpy depends on the amount of energy required to break bonds or attractions (solvent-solvent & solute-solute) and the energy released when new bonds are formed (solute-solvent)
  - a. If  $\Delta H_{\text{soln}}$  has a negative value:
  - b. If  $\Delta H_{\text{soln}}$  has a positive value:

### B. $\Delta H_{\text{soln}}$ for various solutions

1. Liquid dissolved in Liquid
2. Ionic Solid dissolved in Liquid
3. Molecular Solid dissolved in Liquid
4. Gas dissolved in Liquid
5. Ideal Solution

### C. Solubility and Temperature

1. Endothermic dissolving process ( $\Delta H_{\text{soln}}$  is positive)
2. Exothermic dissolving process ( $\Delta H_{\text{soln}}$  is negative)

## VI. SOLUTION CONCENTRATION

### A. MOLE FRACTION

$$X_A = \frac{n_A}{n_T}$$

$X_A$  = mole fraction of component A  
 $n_A$  = moles A in the solution  
 $n_T$  = total moles of all components in the solution

### B. PERCENT BY MASS(%) (parts per hundred)

1. Percent by Mass is calculated:

$$\% = \frac{\text{grams solute}}{\text{grams solution}} (100)$$

2. Percent by Mass is interpreted:

$$\% = \frac{\text{grams solute}}{100 \text{ grams solution}}$$

### C. MOLARITY (M)

$$M = \frac{\text{moles solute}}{\text{liter solution}}$$

### D. MOLALITY (m)

$$m = \frac{\text{moles solute}}{\text{kilogram solvent}}$$

### E. NORMALITY (N)

$$N = \frac{\text{equivalents solute}}{\text{liter solution}}$$

### F. CALCULATIONS

1. Molarity Calculations (review)

- What is the molarity of a solution that contains 2.00 g NaOH (molar mass = 40.0 g/mole) dissolved in enough water to give 200 mL of solution?
- How many mL of 0.250 M NaOH are required to provide 0.0200 mole NaOH?
- How many grams of AgNO<sub>3</sub> are needed to prepare 500 mL of a 0.300 M AgNO<sub>3</sub> solution? (molar mass AgNO<sub>3</sub> = 169.7 g/mole)
- Dilution problems:
  - To what total volume must you dilute 25.0 mL of 0.500 M KOH to produce a solution whose concentration is 0.350 M?
  - How many mL of concentrated H<sub>2</sub>SO<sub>4</sub> (18.0 M) are required to prepare 750 mL of 3.00 M H<sub>2</sub>SO<sub>4</sub>?
  - What is the concentration of the solution resulting from the dilution of 450 mL of 0.600 M HNO<sub>3</sub> to a total volume of 650 mL?

2. Molality and % Concentration Calculations (review Chem 110 notes and assigned homework and worksheet problems)



## VII. SOLUTIONS OF ELECTROLYTES

An ELECTROLYTE is a compound whose water solution conducts an electrical current (by virtue of the movement of ions in the solution).

- A. STRONG ELECTROLYTE: any compound whose water solution conducts strongly. Whether a compound is a strong electrolyte must be determined experimentally. Compounds whose solutions usually conduct strongly are soluble salts, strong acids, and strong bases.
- B. WEAK ELECTROLYTE: any compound whose water solution conducts weakly. Whether a compound is a weak electrolyte must be determined experimentally. Compounds whose solutions usually conduct weakly are weak acids and weak bases.
- C. NONELECTROLYTE: any compound whose water solution does not conduct. Experimentally determined.

## VIII. SOLUTIONS SUMMARY

COMPOUNDS		SOLUBLE OR INSOLUBLE IN WATER	MOST ABUNDANT PARTICLE(S) IN SOLUTION	ELECTROLYTE
MOLECULAR	COVALENT	POLAR		
		NONPOLAR		
	ACIDS	STRONG		
		WEAK		
	NITROGENOUS (WEAK) BASES	NH <sub>3</sub>		
IONIC	SALTS	SOLUBLE		
		INSOLUBLE		
	METAL HYDROXIDES	SOLUBLE (STRONG BASES)		
		INSOLUBLE		
	METAL OXIDES	—	—	—

## IX. NET IONIC EQUATIONS

### A. Writing Net Ionic Equations

1. "MOLECULAR" EQUATION (ME): Write and balance the equation, including state designations {(s), (l), (g), (aq)}.
2. TOTAL IONIC EQUATION (TIE): Rewrite the "molecular" equation:
  - a. Copy, without changing, formulas and symbols for all species in the molecular equation that have state designation (s), (l), or (g).
  - b. Find compounds which have state designation (aq) in the molecular equation:
    - (1) Copy, without changing, formulas for compounds that are weak or nonelectrolytes.
    - (2) Change formulas for strong electrolytes: write solution inventory (symbols for the ions present in aqueous solution) for these compounds.
3. NET IONIC EQUATION (NIE): Rewrite the total ionic equation, leaving out ONLY the IONS that occur on both sides of the total ionic equation.
4. Make sure the net ionic equation is balanced with respect to charge.

### B Examples:

1. Aqueous solutions of barium hydroxide and acetic acid are mixed.

ME \_\_\_\_\_

TIE \_\_\_\_\_

NIE \_\_\_\_\_

2. Zinc is placed in an aqueous solution of hydrochloric acid.

ME \_\_\_\_\_

TIE \_\_\_\_\_

NIE \_\_\_\_\_

3. Aqueous solutions of sodium chloride and potassium bromide are mixed.

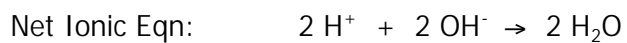
ME \_\_\_\_\_

TIE \_\_\_\_\_

NIE \_\_\_\_\_

### C. Stoichiometry of Ionic Reactions

1. 10.0 mL of a 0.125 M HCl solution was mixed with 50.0 mL of 0.150 M Ba(OH)<sub>2</sub> solution. Calculate the molar concentration of each species (except water) after the reaction.



2. 20.0 mL of a 0.150 M solution of  $\text{Al}_2(\text{SO}_4)_3$  are added to 30.0 mL of 0.200 M  $\text{CaBr}_2$  yielding a precipitate of  $\text{CaSO}_4$ . ( $\overline{\text{CaSO}_4} = 136.1 \text{ g/mole}$ )
- Assuming complete precipitation of  $\text{CaSO}_4$ , how many grams of  $\text{CaSO}_4$  are produced?
  - What is the molar concentration of each species after the reaction is complete?

## IX. COLLIGATIVE PROPERTIES OF SOLUTIONS

The formation of a solution has very little effect on the chemical properties of the components of the solution, but physical properties are altered. These colligative properties depend only on the number of solute particles dissolved in the solvent. The properties of the solvent that are affected are vapor pressure, boiling point, freezing point and osmotic pressure.

### A. VAPOR PRESSURES OF SOLUTIONS

Vapor pressure of any solution is the sum of the vapor pressures of the components of the solution. For a solution composed of two substances, A & B:

$$P_{\text{total}} = P_A + P_B$$

$P_{\text{total}}$  = pressure of the vapor above the solution  
 $P_A$  = partial vapor pressure of A  
 $P_B$  = partial vapor pressure of B

Partial pressures of the components of a solution are given by Raoult's Law:

$$P_A = X_A^{\text{soln}} P_A^\circ$$
$$P_B = X_B^{\text{soln}} P_B^\circ$$

$X_A^{\text{soln}}$  = mole fraction of A in the solution  
 $P_A^\circ$  = vapor pressure of pure A at given temperature  
 $X_B^{\text{soln}}$  = mole fraction of B in the solution  
 $P_B^\circ$  = vapor pressure of pure B at given temperature

Therefore:

$$P_{\text{total}} = X_A^{\text{soln}} \cdot P_A^\circ + X_B^{\text{soln}} \cdot P_B^\circ$$

#### 1. Vapor Pressure of a Solution of a Nonvolatile Nonelectrolyte in a Volatile Liquid.

Example: 35.0 g of glucose,  $C_6H_{12}O_6$ , (molar mass = 180.0 g/mole) is dissolved in 150.0 g  $H_2O$  at 25°C. The vapor pressure of pure water at 25°C is 23.8 torr.

- (a) Calculate the vapor pressure of the solution.
- (b) Calculate the change in vapor pressure of the solvent (vapor pressure lowering)

2. Vapor Pressure of a Solution Containing More than One Volatile Liquid.

- a. Example: A solution containing 75.0 g of benzene,  $C_6H_6(l)$  and 75.0 g of nitrobenzene,  $C_6H_5NO_2(l)$ , is prepared at  $25^\circ C$ . At that temperature, the vapor pressure of pure benzene is 93.4 torr and the vapor pressure of pure nitrobenzene is 26.9 torr.  
(molar masses: benzene = 78.1 g/mole nitrobenzene = 123.1 g/mole)

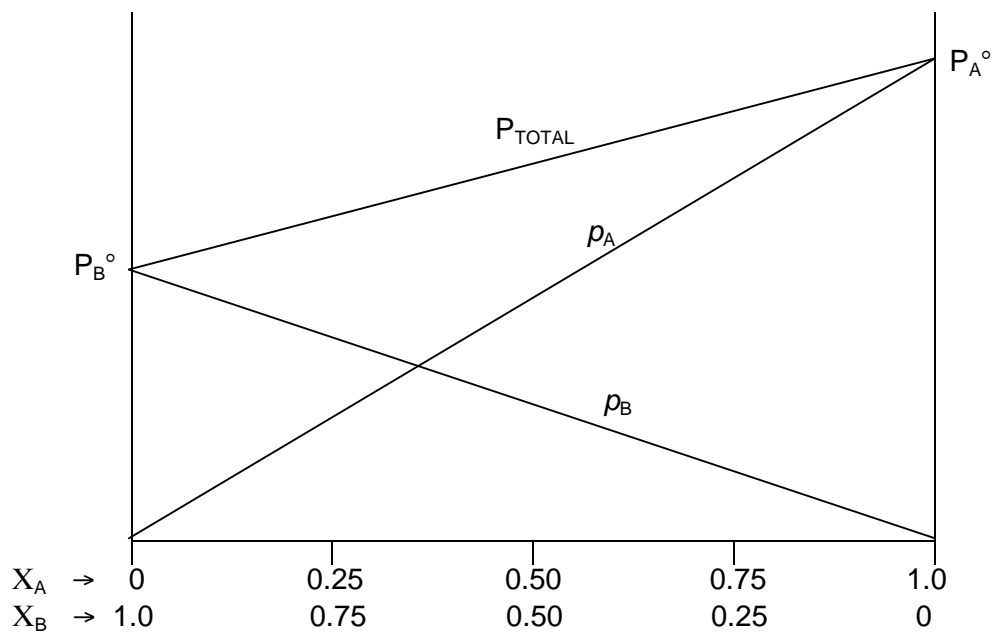
(1) What is the vapor pressure of the solution?

(2) What are the mole fractions of benzene and nitrobenzene in the vapor above the solution?

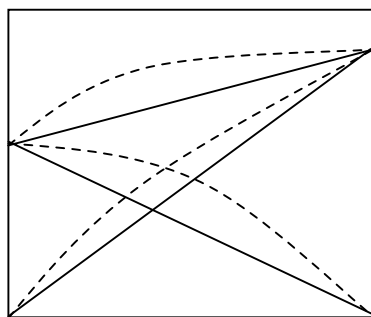
2. Solution of more than one volatile component, continued

b. Deviations from Raoult's Law

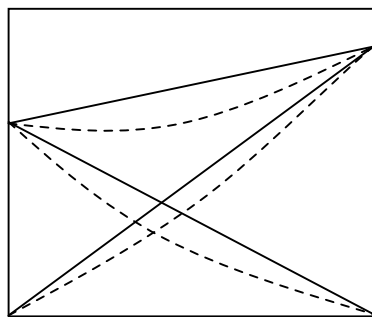
(1) IDEAL SOLUTION: No deviation from Raoult's Law.



(2) Positive Deviation from Raoult's Law: vapor pressure of solution is higher than predicted.



(3) Negative Deviation from Raoult's Law: vapor pressure of solution is lower than predicted.



3. Vapor Pressure of a Solution of Nonvolatile Electrolyte in a Volatile Liquid.

Example: Calculate the vapor pressure of a solution prepared by dissolving 35 g of solid  $\text{Na}_2\text{SO}_4$  (molar mass = 142 g/mole) in 175 g of water at 25°C. The vapor pressure of pure water at 25°C is 23.8 torr.

## B. BOILING POINTS OF SOLUTIONS

The boiling point of a solution is higher than the boiling point of the pure solvent.

### Calculation of Boiling Point Elevation

$$\Delta T_b = i \cdot K_b \cdot m$$

$\Delta T_b$  = difference in temperature between boiling point of the solution and the pure solvent.

$$= T_b^{\text{soln}} - T_b^{\text{solvent}}$$

$K_b$  = molal boiling point constant for the solvent.

Units of  $K_b$  are  $\frac{^\circ\text{C kg}}{\text{mole}}$

$m$  = molality of the solution =  $\frac{\text{mole solute}}{\text{kg solvent}}$  (text uses  $c_m$  for  $m$ )

$i$  = moles ions or molecules per mole compound in solution

#### 1. Boiling Point of a Solution of a Nonvolatile Nonelectrolyte in a Liquid.

Example: What is the boiling point of a solution of 45.0 g of glucose (molar mass: 180 g/mole) dissolved in 150 g of water. The molal boiling point constant for water is  $0.51 \text{ } ^\circ\text{C kg mole}^{-1}$ .

2. Boiling Point of a Solution of a Nonvolatile Electrolyte in a Liquid.

Example: What is the boiling point of a solution of 56.3 g of  $\text{Na}_2\text{SO}_4$  (molar mass = 142 g/mole) in 200 g of water? The molal boiling point constant for water is  $0.51\text{ }^\circ\text{C kg mole}^{-1}$ .

3. Additional Problem: A solution prepared by dissolving 0.300 g of an unknown nonvolatile solute in 30.0 g of carbon tetrachloride has a boiling point that is  $0.392^\circ\text{C}$  higher than that of pure  $\text{CCl}_4$ . What is the molar mass of the solute?  $K_b$  for  $\text{CCl}_4$  is  $5.02\text{ }^\circ\text{C kg mole}^{-1}$ .

### C. FREEZING POINTS OF SOLUTIONS

The freezing point of a solution is lower than the freezing point of the pure solvent.

Calculation of Freezing Point Lowering (or freezing point depression)

$$\Delta T_f = i \cdot K_f \cdot m$$

$\Delta T_f$  = difference in freezing point between the pure solvent and the solution.

$$T_f^{\text{solvent}} - T_f^{\text{soln}}$$

$K_f$  = molal freezing point constant for the solvent.

$$\text{Units of } K_f \text{ are } \frac{^\circ\text{C kg}}{\text{mole}}$$

$m$  = molality of the solution =  $\frac{\text{mole solute}}{\text{kg solvent}}$

$i$  = moles ions or molecules per mole compound in solution

#### 1. Freezing Point of a Solution of a Nonvolatile Nonelectrolyte in a Liquid Solvent.

Example: What is the freezing point of a solution of 36.0 g of glucose (molar mass = 180 g/mole) dissolved in 250 g of water. The molal freezing point constant for water is  $1.86 \text{ } ^\circ\text{C kg mole}^{-1}$ .

2. Freezing Point of a Solution of a Nonvolatile Electrolyte in a Liquid.

Example: What is the freezing point of a solution of 23.8 g of  $\text{Na}_2\text{SO}_4$  (molar mass = 142 g/mole) dissolved in 150 g of water.

The molal freezing point constant for water is  $1.86\text{ }^\circ\text{C kg mole}^{-1}$ .

3. Additional Problem: The antifreeze commonly used in car radiators is ethylene glycol,  $\text{C}_2\text{H}_4(\text{OH})_2$ . How many grams of ethylene glycol should be added to 1.00 kg of water to produce a solution that freezes at  $-15.0^\circ\text{C}$ ?

#### D. OSMOTIC PRESSURE OF SOLUTIONS

OSMOSIS: the movement of water through a semipermeable membrane from a dilute solution to a more concentrated one.

OSMOTIC PRESSURE: pressure difference between the two solutions.

Calculation of osmotic pressure:

$$\pi = M R T$$

$\pi$  = osmotic pressure

M = molarity of solution

R = Boltzman's constant (gas constant)

T = absolute temperature

$$\pi V = n R T$$

van't Hoff equation

Example: calculate the osmotic pressure of a sucrose solution prepared by dissolving 36.0 g of sucrose (molar mass = 342 g/mole) in enough water to make 275 mL of solution at 20.0°C.