Section 11.4
Colligative Properties

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Learning Objectives

- Express concentrations of solution components using mole fraction and molality
- Describe the effect of solute concentration on various solution properties (vapor pressure, boiling point, freezing point, and osmotic pressure)
- Perform calculations using the mathematical equations that describe these various colligative effects
- Describe the process of distillation and its practical applications
- Explain the process of osmosis and describe how it is applied industrially and in nature

Concentration Units

Concentration Unit Review

- Molarity

$$M = \frac{\text{mol solute}}{\text{L solution}}$$

- Molality

$$m = \frac{\text{mol solute}}{\text{kg solvent}}$$

- Mol Fraction

$$X_{\text{A}} = \frac{\text{mol A}}{\text{total mol of all components}}$$

Converting from Molarity to Molality

$$\mathrm{M} = \frac{\mathrm{mols}_{\mathrm{solute}}}{\mathrm{V}_{\mathrm{soln}}} \quad \text{where} \quad \mathrm{V}_{\mathrm{soln}} = 1\,\mathrm{L}$$

$$\mathrm{V}_{\mathrm{soln}}\rho_{\mathrm{soln}} = \mathrm{m}_{\mathrm{soln}} = \mathrm{m}_{\mathrm{solute}} + \mathrm{m}_{\mathrm{solvent}}$$

$$\mathrm{m}_{\mathrm{soln}} - \mathrm{m}_{\mathrm{solute}} = \mathrm{m}_{\mathrm{soln}} - (\mathrm{mols}_{\mathrm{solute}})\mathrm{M}^{\mathrm{W}} = \mathrm{m}_{\mathrm{solvent}}$$

$$m = \frac{\mathrm{mols}_{\mathrm{solute}}}{\mathrm{m}_{\mathrm{solvent}}} \quad \text{where } \mathrm{m}_{\mathrm{solvent}} \text{ has units of kg}$$

Converting from Molality to Molarity

$$m = \frac{\mathrm{mols}_{\mathrm{solute}}}{\mathrm{m}_{\mathrm{solvent}}} \qquad \text{Where } \mathrm{m}_{\mathrm{solvent}} = 1\,\mathrm{kg}$$

$$\mathrm{m}_{\mathrm{soln}} = \mathrm{m}_{\mathrm{solvent}} + \mathrm{m}_{\mathrm{solute}} = \mathrm{m}_{\mathrm{solvent}} + \mathrm{mols}_{\mathrm{solute}}\mathrm{M}^{\mathrm{W}}$$

$$\mathrm{V}_{\mathrm{soln}} = \frac{\mathrm{m}_{\mathrm{soln}}}{\rho_{\mathrm{soln}}}$$

$$\mathrm{M} = \frac{\mathrm{mols}_{\mathrm{solute}}}{\mathrm{V}_{\mathrm{soln}}}$$

Molality to Mol Fraction

$$m_a = \frac{\text{mols A}}{\text{m}_{\text{solvent}}}$$

$$m_b = \frac{\text{mols B}}{\text{m}_{\text{solvent}}}$$

$$m_c = \frac{\text{mols C}}{\text{m}_{\text{solvent}}}$$

$$\text{m}_{\text{solvent}} = 1\,\text{kg}$$

$$\text{mols}_{\text{solvent}} = \text{m}_{\text{solvent}} \text{M}^{\text{W}}_{\text{solvent}}$$

$$\text{X}_a = \frac{\text{mols}_a}{\text{mols}_a + \text{mols}_b + \text{molsc} + \text{mols}_{\text{solvent}}}$$

Colligative Properties

Colligative Properties

- Solution properties differ from those of pure solutes and solvents.
- Most of the time, solution properties depend on the identity of the solutes and solvents.
- **Colligative Properties**, however, depend only of the concentration of the solute.
- They include: vapor pressure lowering, boiling point elevation, freezing point depression, and osmotic pressure.

Vapor Pressure Lowering

- Vapor pressure is the partial pressure of a liquid at equilibrium.

$$\text{Liquid} \rightleftharpoons \text{Gas}$$

- When a solute is dissolved in a liquid the vapor pressure will be lowered.
- Solute molecules occupy sites at the liquids surface blocking solvent molecules access to the gas phase.
- Solvent molecules can, however, recombine with the liquid phase on top of solute molecules.
- The result is fewer solvent molecules in the gas phase.

Raoult's Law

- The partial pressure exerted by any component of an ideal solution is equal to the vapor pressure of the pure component multiplied by its mole fraction in the solution.

$$P_{\mathrm{A}} = X_{\mathrm{A}} P_{\mathrm{A}}^{*}$$

- Raoult's Law can be combined with Dalton's Law to yield an expression of the total pressure exerted by the solution on the gas phase.

$$P_{\mathrm{solution}} = \sum_{i} P_i = \sum_{i} X_i P_i^{*}$$

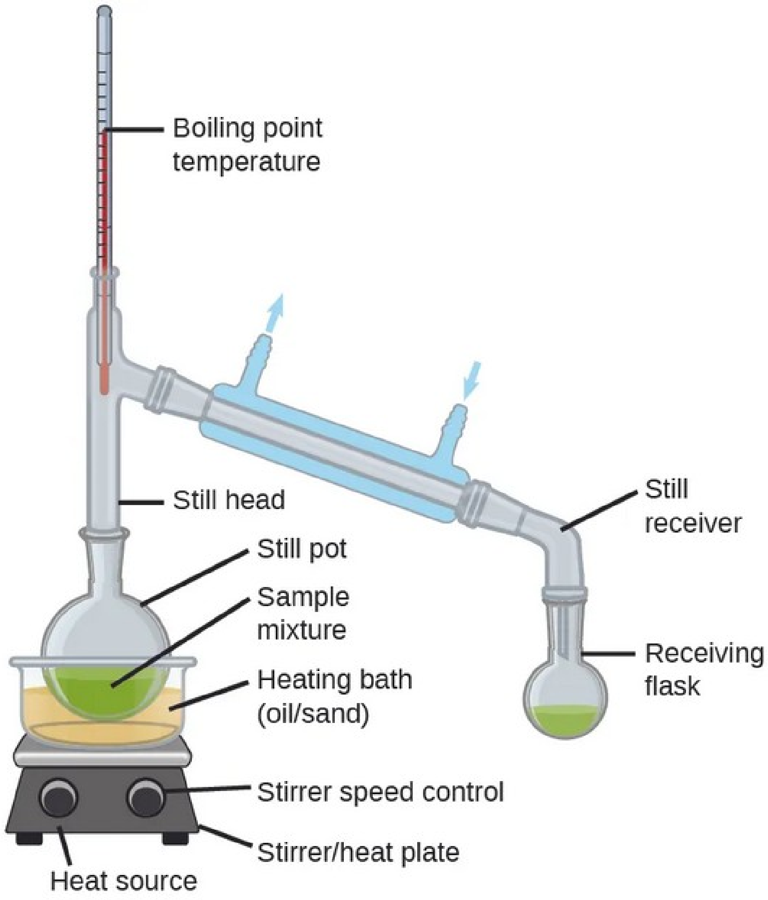
Nonvolatile Solutes

- When a solute's vapor pressure is essentially zero, it is said to be **nonvolatile**.
- When a solution contains only nonvolatile solutes, the solution's total pressure depends solely on the solvent.

$$P_{\text{solution}} = X_{\text{solvent}} P^*_{\text{solvent}}$$

Distillation

- Raoult's Law can be used to prove that the vapor released by a solution will be enriched in the less volatile component.
- This explains why distillation is an effective means of separating the components of a solution.



Boiling Point Elevation

- **Boiling Point Elevation** is the result of vapor pressure lowering.
- A higher temperature is required to reach a pressure equal to atmospheric pressure.
- The increase in temperature required is proportional to molality of the solution.

$$\Delta T_{\mathrm{b}} = K_{\mathrm{b}} m$$

- Where K_b is the **boiling point elevation constant.**
  - K_b is unique to each solvent.

Freezing Point Depression

- Solutions freeze at lower temperatures than pure liquids.
- Freezing Point Depression is directly proportional to the molality of the solution.

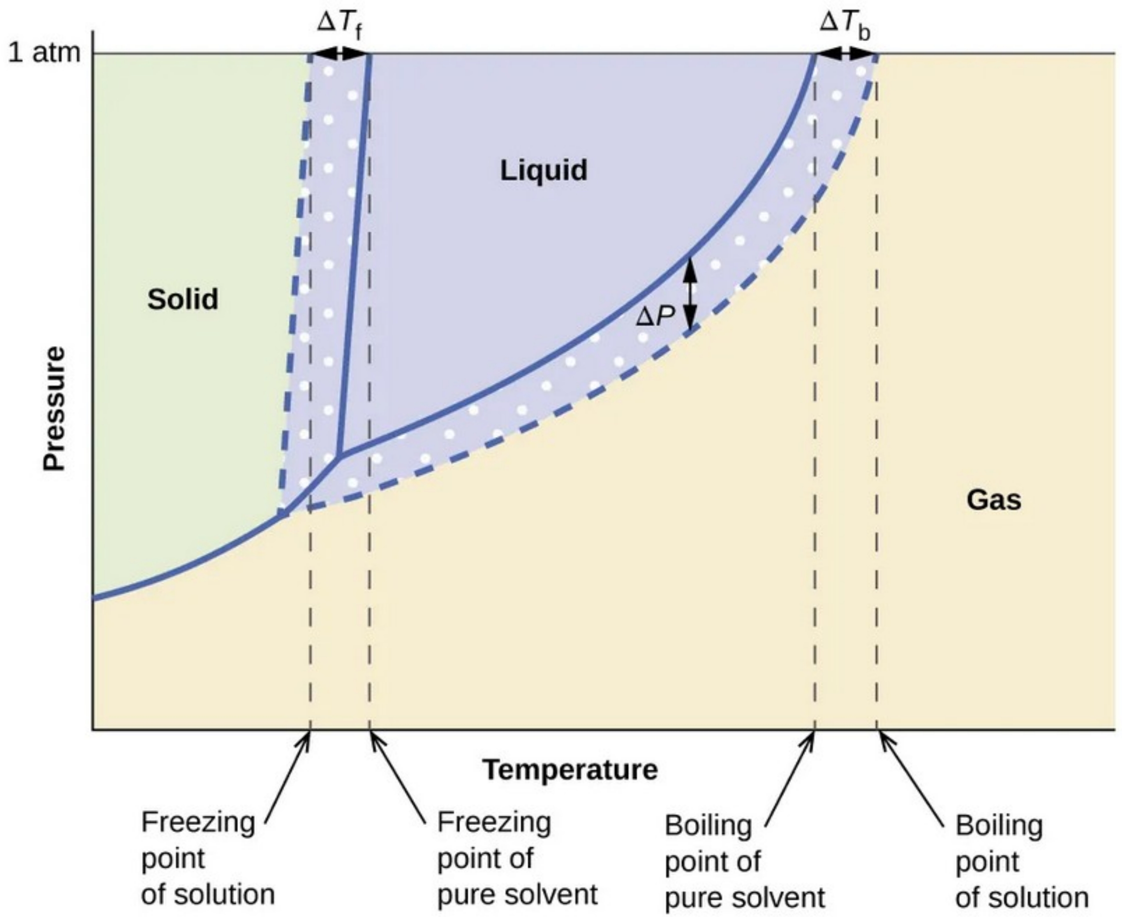
$$\Delta T_{\mathrm{f}} = K_{\mathrm{f}} m$$

- K_f is the **freezing point depression constant**.
  - K_f is unique to each solvent.

Common K_b and K_f Values

Solvent	Boiling Point (°C at 1 atm)	K_b (°Cm^{-1})	Freezing Point (°C at 1 atm)	K_f (°Cm^{-1})
water	100.0	0.512	0.0	1.86
hydrogen acetate	118.1	3.07	16.6	3.9
benzene	80.1	2.53	5.5	5.12
chloroform	61.26	3.63	–63.5	4.68
nitrobenzene	210.9	5.24	5.67	8.1

Solution Phase Diagram



Osmosis

- Some membranes only allow molecules or ions of a certain size, shape, polarity, etc. to pass through them.
- These membranes are called **semipermeable**.
- Osmosis occurs when
  - A semipermeable membrane separates two solutions
  - The same solvent exists on either side
  - Only the solvent molecules can permeate the membrane.
- Solvent molecules will diffuse across the membrane in both directions but at different rates. This is called **Osmosis**.

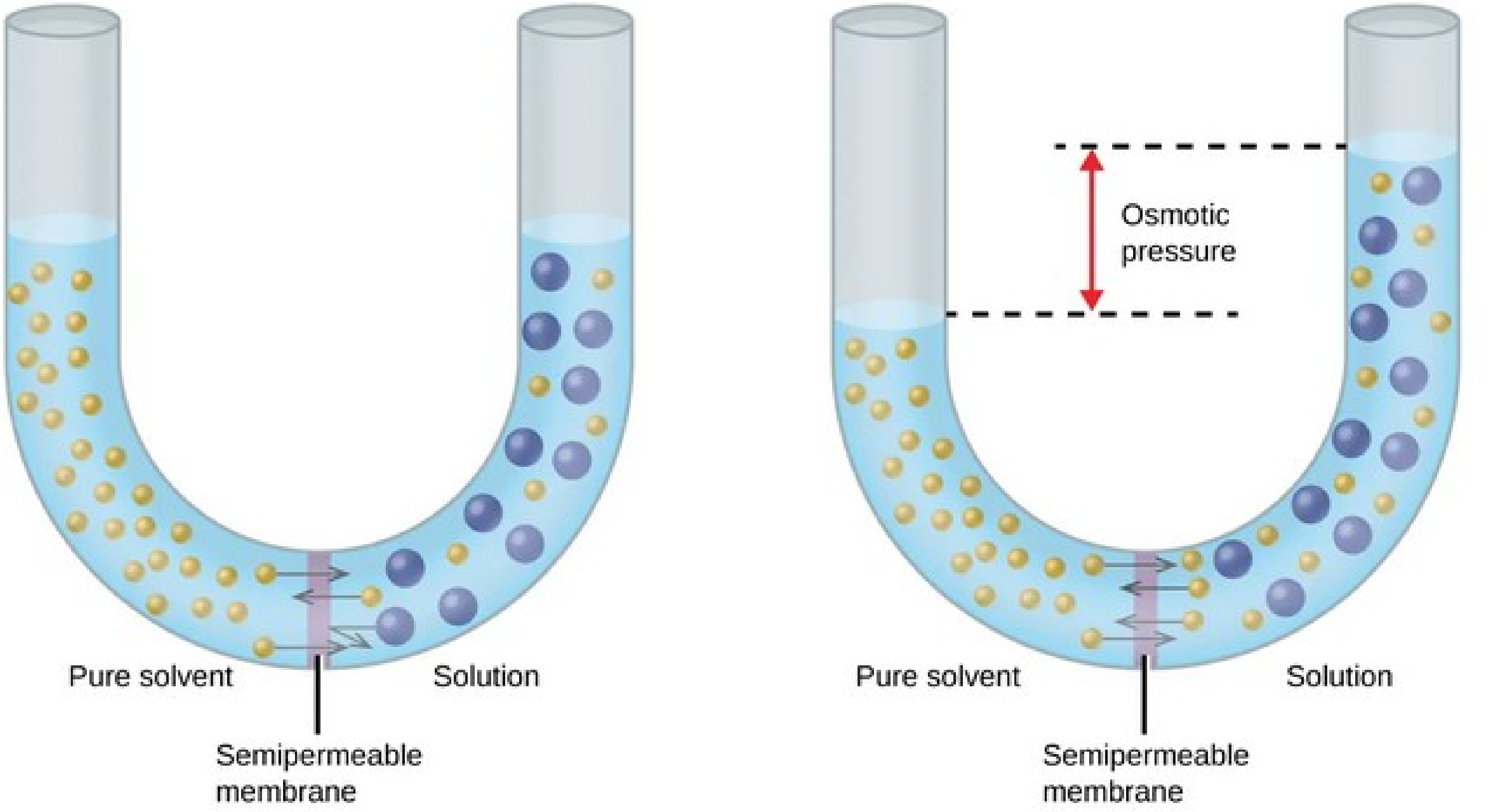
Osmotic Pressure

- The net effect of osmosis is solvent molecules accumulating on the side of the membrane with a more concentrated solution until one of two conditions is met.
  - The concentration of the two solutions is equal
  - The pressure differential across the membrane is equal to the osmotic pressure (Π).

$$\Pi = MRT$$

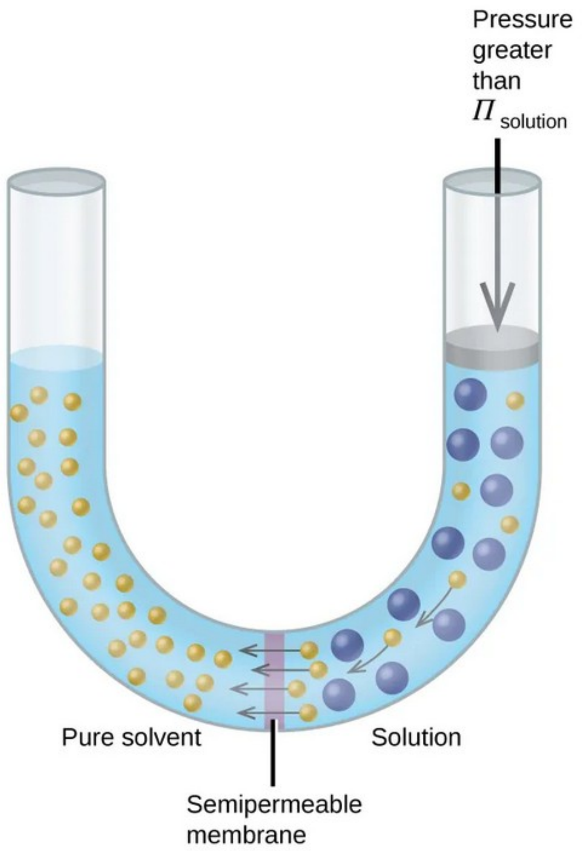
- Where *M* is the molarity, *T* is the temperature, and *R* is the gas law constant.

Osmosis and Osmotic Pressure



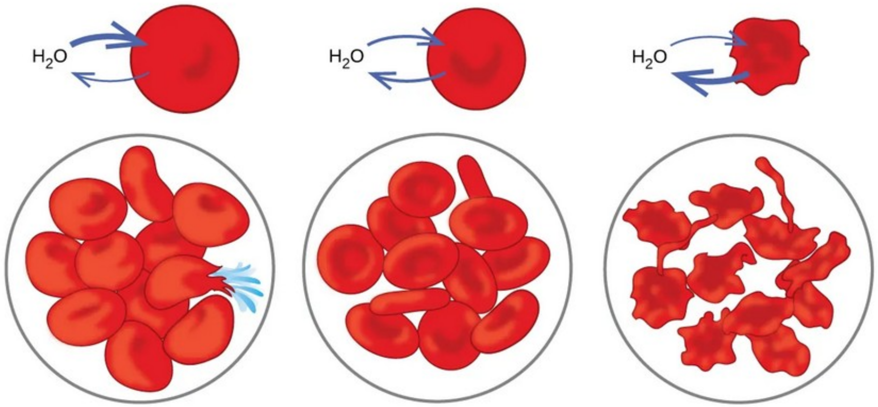
Reverse Osmosis

- When pressure greater than the osmotic pressure is applied to the more concentrated solution, the process can be reversed.



Isotonic, Hypotonic, and Hypertonic

- When the osmotic pressure between the two solutions is zero they are called **isotonic**.
- When a solution is less concentrated than another it is called **hypotonic**.
- When a solution is more concentrated than another it is called **hypertonic**.



Determination of Molar Mass

- Colligative Properties can be used to determine the molar mass of an unknown.
  1) Add a known mass of solute to a known amount of solvent.
  2) Measure the colligative property, ΔT_f, ΔT_b, or Π.
  3) Calculate the concentration (*m* or M) of the solute.

$$m = \frac{\Delta T_f}{K_f} \qquad m = \frac{\Delta T_b}{K_b} \qquad M = \frac{\Pi}{RT}$$

  4) Determine the number of mols present

$$\text{mols} = (m)(m_{\text{solvent}}) = (M)(V_{\text{soln}})$$

  5) Calculate the Molar Mass

$$M^W = \frac{m_{\text{solute}}}{\text{mols}}$$

Colligative Properties of Electrolytes

- When electrolytes dissolve they dissociate into ions.
- To account for this an factor called the **van't Hoff factor** is included in the colligative property equations.

$$i = \frac{\text{moles of particles in solution}}{\text{moles of formula units dissolved}}$$

$$\Delta \mathrm{T}_f = iK_f m \qquad \Delta \mathrm{T}_b = iK_b m$$