Chapter 13: Properties of Mixtures: Solutions and Colloids
A *solution* is a homogenous mixture of a *solute(s)* and a *solvent* that has recognizable properties.

**Solute** = substance(s) present in the smaller amount(s)

**Solvent** = substance present in the largest amount in which the solute dissolves.

- homogeneous uniform composition
- Contain particles 0.1 – 2 nm: ions or small molecules
- Transparent, homogeneous and maybe colored
- Does not separate on standing
- Colloids and Suspensions contain large particles that can be separated physically
Connecting Dots: Example Using Data From Glucose

**Solubility of Glucose**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Solubility</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>91</td>
</tr>
<tr>
<td>30</td>
<td>125</td>
</tr>
<tr>
<td>50</td>
<td>244</td>
</tr>
<tr>
<td>70</td>
<td>357</td>
</tr>
<tr>
<td>90</td>
<td>556</td>
</tr>
</tbody>
</table>
Sodium acetate crystallizing from a supersaturated solution.

A small crystal of solid sodium acetate

Saturated Solution of sodium acetate

Spontaneous crystallization of the saturated solution.
The dissolution process in a solvent is an equilibrium process.

- Solute begins to dissolve in solvent.
- Rate of dissolution and precipitation begin to equalize.
- Solute is dissolving at the same rate that solute is precipitating. Concentrations no longer change = saturation.

At saturation:

\[
\text{Solute} + \text{Solvent} \rightleftharpoons \text{Solution}
\]

Dissolve \hspace{1cm} Crystallize
### Solvent Solubility Terms and Parts Required

<table>
<thead>
<tr>
<th>Term</th>
<th>Parts of Solvent Required for 1 part of Solute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very soluble</td>
<td>Less than 1 part</td>
</tr>
<tr>
<td>Freely soluble</td>
<td>1-10 parts</td>
</tr>
<tr>
<td>Soluble</td>
<td>10-30 parts</td>
</tr>
<tr>
<td>Sparingly Soluble</td>
<td>30-100 parts</td>
</tr>
<tr>
<td>Slightly soluble</td>
<td>100-1000 parts</td>
</tr>
<tr>
<td>Very slightly soluble</td>
<td>1000-10,000 parts</td>
</tr>
<tr>
<td>Insoluble</td>
<td>&gt; 10,000 parts</td>
</tr>
</tbody>
</table>

Science often uses confusing terminology that we sometimes just need to realize is part of life.
Science uses three different ways to help us understand how solutes dissolve in solvents.

1. **Practical Answer** (the one that comes in handy in real-life)

2. **Macroscopic Answer** (thermodynamic approach--cool if you like thermo---no need for molecules)

3. **Microscopic Answer** (molecular approach using IMF’s--helps one understand the practical)
Some Simplified Generalizations

✴ Substances dissolve when when IMF’s between a solute and solvent are of the same type--we call these types of solutions **IDEAL SOLUTIONS** (like the idea gas law)

✴ When IMF’s between solute or between solvent exceed those IMF’s between solute-solvent then properties are hard to predict. We call these solutions **NON-IDEAL solutions**.
Liquids are *miscible* if they mix to an appreciable extent. *Immiscible liquids* separate into different layers or phases.

Lowest density liquid rises to the top

Highest density liquid sinks to bottom

We can use miscibility as a means to separate substances that are soluble in polar and non-polar solvents.
1. Practical Answer: “Likes dissolve likes”. This means:

- Non-polar molecules are soluble in non-polar solvents.
  
  \[ \text{CCl}_4, \text{gasoline, kerosene, hexane, oils, are soluble (miscible) in non-polar solvent benzene C}_6\text{H}_6 \]

- Polar molecules and ionic compounds are soluble in polar solvents
  
  \[ \text{C}_2\text{H}_5\text{OH or NH}_3 \text{ or CH}_3\text{COOH are soluble in H}_2\text{O} \]
Pentane, $\text{C}_5\text{H}_{12}$ and 1-butanol, $\text{C}_4\text{H}_9\text{OH}$ have similar molecular masses. Which of the two would be more soluble in water and why?
Predict which solvent will dissolve more of the given solute:

(a) Sodium chloride in methanol (CH₃OH) or in propanol (CH₃CH₂CH₂OH)

(b) Ethylene glycol (HOCH₂CH₂OH) in hexane (CH₃CH₂CH₂CH₂CH₂CH₃) or in water.

(c) Diethyl ether (CH₃CH₂OCH₂CH₃) in water or in ethanol (CH₃CH₂OH)
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PLAN: Consider the intermolecular forces which can exist between solute molecules and consider whether the solvent can provide such interactions and thereby substitute.

SOLUTION:

(a) Methanol - NaCl is ionic and will form ion-dipoles with the -OH groups of both methanol and propanol. However, propanol is subject to the dispersion forces to a greater extent.

(b) Water - Hexane has no dipoles to interact with the -OH groups in ethylene glycol. Water can H bond to the ethylene glycol.

(c) Ethanol - Diethyl ether can interact through a dipole and dispersion forces. Ethanol can provide both while water would like to H bond.
Predict whether each of the following substances is more likely to dissolve in carbon tetrachloride or in water.

(a) heptane $\text{C}_7\text{H}_{16}$
(b) sodium sulfate
(c) $\text{HCl} (\text{g})$
(d) $\text{I}_2$
Arrange the following substances in order of increasing solubility in water.

(a) $\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3$
(b) $\text{OH-CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{OH}$
(c) $\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{OH}$
(d) $\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{Cl}$
Arrange the following substances in order of increasing solubility in water.

(a) CH₃CH₂CH₂CH₂CH₂CH₃
(b) OH-CH₂CH₂CH₂CH₂CH₂OH
(c) CH₃CH₂CH₂CH₂CH₂CH₂OH
(d) CH₃CH₂CH₂CH₂CH₂CH₂Cl

a < d < c < b
Colligative properties are physical properties of solutions that arise because of the *number of solute molecules* dissolved in solution and not on the kind of solute particles dissolved in solution.
Colligative properties of solutions is used in many applications.

- adding antifreeze to a car’s radiator
- spreading salt on ice
- de-icing airplanes
Colligative properties are properties that depend only on the number of solute particles in solution and not on the nature of the solute particles.

The Four-Colligative Properties

- Vapor-Pressure Lowering: \[ P_{\text{solution}} = X_{\text{solute}} P^\circ_{\text{solvent}} \]
- Boiling-Point Elevation: \[ \Delta T_b = K_b m \]
- Freezing-Point Depression: \[ \Delta T_f = -K_f m \]
- Osmotic Pressure (\( \pi \)): \[ \pi = MRT \]
**Vapor-Pressure Lowering:** A non-volatile, non-ionic solute added to a pure solvent will lower the vapor pressure of the pure solvent according to Raoult’s Law.

\[ p_A = X_A \cdot p_A^\circ \]

Nonvolatile solute molecules reduce the number of volatile solvent molecules at the surface of the liquid and as a result reduce solvent molecules escaping to the vapor phase.

\[ P_{solution} = X_{solvent} \cdot P_{solvent}^\circ \]

Vapor pressure of solution  | Mole Fraction of Solvent  | Vapor Pressure of Pure Solvent
What is the vapor pressure, at 100ºC, of a 50/50 % (v/v) solution of ethylene glycol, \( \text{C}_2\text{H}_6\text{O}_2 \), in water at 1 atm?  

\( \text{MM C}_2\text{H}_6\text{O}_2 = 62.06 \text{ g/mol} \) 
\( d(\text{C}_2\text{H}_6\text{O}_2) = 1.1155 \text{ g/mL} \) 
\( d(\text{H}_2\text{O}) = 1.0000 \text{ g/mL} \) 
\( d(50/50) = 1.069 \text{ g/mL} \)

\[
\begin{align*}
\text{Moles C}_2\text{H}_6\text{O}_2 &= 500. \text{ mL} \times 1.1155 \text{ g C}_2\text{H}_6\text{O}_2 \times \frac{1 \text{ mol}}{62.06 \text{ g}} = 8.99 \text{ mol} \\
\text{Moles H}_2\text{O} &= 500. \text{ mL} \times 1.000 \text{ g H}_2\text{O} \times \frac{1 \text{ mol}}{18.02 \text{ g}} = 27.8 \text{ mol} \\
\text{Mole Fraction H}_2\text{O} &= 27.8 \text{ mol}/ (27.8 \text{ mol} + 8.99 \text{ mol}) = 0.7556 \\
\end{align*}
\]

\[
\begin{align*}
\text{P}_{\text{H}_2\text{O}} &= \chi_{\text{H}_2\text{O}} \text{ P}^o_{\text{H}_2\text{O}} \\
\text{P}_{\text{H}_2\text{O}} &= 0.7556 \times 760. \text{ torr} = 574. \text{ torr}
\end{align*}
\]
Vapor-Pressure Lowering

\[ P_{\text{Solvent}} = \chi_{\text{solvent}} P^\circ_{\text{solvent}} \quad (1) \]

\[ \chi_{\text{Solute}} + \chi_{\text{Solvent}} = 1 \quad (2) \]

\[ \chi_{\text{Solvent}} = 1 - \chi_{\text{Solute}} \quad (3) \]

substituting 3 into 1

\[ P_{\text{Solvent}} = (1 - \chi_{\text{Solute}}) P^\circ_{\text{solvent}} \quad (4) \]

expanding 4

\[ P_{\text{Solvent}} = P^\circ_{\text{solvent}} - P^\circ_{\text{solvent}} (\chi_{\text{Solute}}) \quad (5) \]

\[ \Delta P = (P^\circ_{\text{solvent}} - P_{\text{solv/sol}}) = P^\circ_{\text{solvent}} (\chi_{\text{Solute}}) \]
Calculate the vapor pressure lowering, $\Delta P$, when 10.0 mL of glycerol ($C_3H_8O_3$) is added to 500.0 mL of water at 50. °C. At this temperature, the vapor pressure of pure water is 92.5 torr and its density is 0.988 g/mL. The density of glycerol is 1.26 g/mL.

**PLAN:** Find the mol fraction, $\chi$, of glycerol in solution and multiply by the vapor pressure of water. 

$\Delta P = (P^\circ_{\text{solvent}} - P_{\text{solvent}}) = P^\circ_{\text{solvent}} (\chi_{\text{Solute}})$

**SOLUTION:**

$10.0 \text{ mL } C_3H_8O_3 \times \frac{1.26 \text{ g } C_3H_8O_3}{\text{mL } C_3H_8O_3} \times \frac{\text{mol } C_3H_8O_3}{92.09 \text{ g } C_3H_8O_3} = 0.137 \text{ mol } C_3H_8O_3$

$500.0 \text{ mL } H_2O \times \frac{0.988 \text{ g } H_2O}{\text{mL } H_2O} \times \frac{\text{mol } H_2O}{18.02 \text{ g } H_2O} = 27.4 \text{ mol } H_2O$

$\Delta P = \frac{0.137 \text{ mol } C_3H_8O_3}{0.137 \text{ mol } C_3H_8O_3 + 27.4 \text{ mol } H_2O} \times 92.5 \text{ torr} = 0.461 \text{ torr}$

$\chi = 0.00498$
2. Boiling Point Elevation

- The addition of a nonvolatile non-ionic solute dissolved in a pure solvent increases the boiling point of a solution.

\[ \Delta T_b = T_{bp} - T_{bp}^\circ = K_b \cdot m \]

- Boiling point elevation (+)
- Pure solvent boiling point
- Solution boiling point
- Molal boiling point elevation constant (°C/m)
- Molality (mol/kg)
3. Freezing Point Depression

- The addition of a non-volatile non-ionic solute dissolved in a pure solvent decreases the freezing point of the solution.

\[ \Delta T_f = T_f - T_{fp} = -K_f m \]

- **Freezing point depression** (°C)
- **Molal freezing point depression** constant (°C/m)
- **Solution Molality** (mol/kg)
- **Pure solvent freezing point**