11.1 & 2 Intermolecular Forces and Physical States

- The force of attraction between two neighboring molecules or atoms.
- The magnitude of intermolecular forces determine whether a pure substance will be solid, liquid or gas meaning their mp, bp, surface tension, viscosity.
- Intramolecular attractions are covalent in nature involving overlapping of bonding electron clouds. Intermolecular forces are much weaker than intramolecular forces.

**TABLE 11.2** Properties of the Phases of Matter

<table>
<thead>
<tr>
<th>Phase</th>
<th>Density</th>
<th>Shape</th>
<th>Volume</th>
<th>Strength of Intermolecular Forces*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>Low</td>
<td>Indefinite</td>
<td>Indefinite</td>
<td>Weak</td>
</tr>
<tr>
<td>Liquid</td>
<td>High</td>
<td>Indefinite</td>
<td>Definite</td>
<td>Moderate</td>
</tr>
<tr>
<td>Solid</td>
<td>High</td>
<td>Definite</td>
<td>Definite</td>
<td>Strong</td>
</tr>
</tbody>
</table>

*Relative to thermal energy.

**TABLE 11.1** The Three Phases of Water

<table>
<thead>
<tr>
<th>Phase</th>
<th>Temperature (°C)</th>
<th>Density (g/cm³, at 1 atm)</th>
<th>Molar Volume</th>
<th>Molecular View</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas (steam)</td>
<td>100</td>
<td>$5.90 \times 10^{-4}$</td>
<td>30.5 L</td>
<td></td>
</tr>
<tr>
<td>Liquid (water)</td>
<td>20</td>
<td>0.998</td>
<td>18.0 mL</td>
<td></td>
</tr>
<tr>
<td>Solid (ice)</td>
<td>0</td>
<td>0.917</td>
<td>19.6 mL</td>
<td></td>
</tr>
</tbody>
</table>
11.3 IMF in the Condensed Phases

\[ E = \text{const} \times \frac{q_1 \times q_2}{r} \]

**Dispersion (London) Force**
- Present in all molecules and atoms due to their electron contents.
- At any given instant when electron(s) populate a spot of the cloud/orbital, it causes an instantaneous or temporary dipole which can affect the neighboring atom or molecule.
- Magnitude of dispersion force depends upon how easily the electrons can be moved or polarized, which depends on the size of the cloud.
- Higher molar mass causes increased dispersion force.

**Dipole-Dipole Force**
- This force exists in all polar molecules.
- Their permanent dipoles interact with the dipoles of the neighboring ones.
- This causes higher mp and bp to polar molecules.

**Table 11.3**: Boiling Points of the Noble Gases

<table>
<thead>
<tr>
<th>Noble Gas</th>
<th>Molar Mass (g/mol)</th>
<th>Boiling Point (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>4.00</td>
<td>4.2</td>
</tr>
<tr>
<td>Ne</td>
<td>20.18</td>
<td>27</td>
</tr>
<tr>
<td>Ar</td>
<td>39.95</td>
<td>87</td>
</tr>
<tr>
<td>Kr</td>
<td>83.80</td>
<td>120</td>
</tr>
<tr>
<td>Xe</td>
<td>131.30</td>
<td>165</td>
</tr>
</tbody>
</table>

(Refer to Example 11.1 and Practice 11.1 for more help and hint.)
Hydrogen Bonding

- Another stronger force of attraction.
- It requires polar molecule with H bonded to F, O, N, atoms of high electronegativity.
- A $\delta^+$ charge and its small size causes H to feel attracted to F, O, and N of the other molecule.

Ion-Dipole Force

- This force occurs when an ionic compound is mixed with a polar compound.
- Important in aqueous solutions of ionic compounds.
- Cations are surrounded by negative pole of polar solvent and anions are surrounded by positive poles causing what's called solvation.
- This enhances solubility.

<table>
<thead>
<tr>
<th>Name</th>
<th>Formula</th>
<th>Molar Mass (amu)</th>
<th>Structure</th>
<th>bp ($^\circ$C)</th>
<th>mp ($^\circ$C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol</td>
<td>C₂H₅O</td>
<td>46.07</td>
<td>CH₃CH₂OH</td>
<td>78.3</td>
<td>-114.1</td>
</tr>
<tr>
<td>Dimethyl Ether</td>
<td>C₂H₆O</td>
<td>46.07</td>
<td>CH₃OCH₃</td>
<td>-22.0</td>
<td>-138.5</td>
</tr>
</tbody>
</table>

(Refer to Example 11.2 and Practice 11.2 for more help and hint.)
Q #49 & 50. Determine the kinds of intermolecular forces that are present in each of the following elements or compounds:

| a. | Kr     | b. | NCl₃  |
| c. | SiH₄    | d. | HF    |
| e. | N₂      | f. | NH₃   |
| g. | CO      | h. | CCl₄  |

Q54. Arrange the following in order of increasing boiling point. Explain your reasoning.

a. H₂S    b. H₂Se   c. H₂O

Q #55. For each pair of compounds, pick the one with the highest boiling point. Explain your reasoning.

a. CH₃OH or CH₃SH    b. CH₃OCH₃ or CH₃CH₂OH   c. CH₄ or CH₃CH₃

Q #59. Which of the following pairs of substances would you expect to form homogeneous solutions when combined? For those that form homogeneous solutions, indicate the type of forces that are involved.

a. CCl₄ and H₂O    b. KCl and H₂O    c. Br₂ and CCl₄    d. CH₃CH₂OH and H₂O
11.4 IMF in Surface Tension, Viscosity, Capillary Action

**Surface Tension**
- Molecules of pure liquids at the surface have higher potential energy than the interior ones.
- As a result, liquids tend to minimize the surface area making the surface to behave like a "skin".
- It is the energy required to increase the surface area by a unit amount.
- Water and benzene’s surface tension are 72.8 and 28 mJ/m².

**Viscosity**
- It is the resistance of a liquid to flow, i.e., preventing one to flow around another.
- This force depends on the IMF and the shape of the molecule.

**TABLE 11.5 Viscosity of Several Hydrocarbons at 20 °C**

<table>
<thead>
<tr>
<th>Hydrocarbon</th>
<th>Molar Mass (g/mol)</th>
<th>Formula</th>
<th>Viscosity (cP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-Pentane</td>
<td>72.15</td>
<td>CH₃CH₂CH₂CH₃</td>
<td>0.240</td>
</tr>
<tr>
<td>N-Hexane</td>
<td>86.17</td>
<td>CH₃CH₂CH₂CH₂CH₃</td>
<td>0.326</td>
</tr>
<tr>
<td>N-Heptane</td>
<td>100.2</td>
<td>CH₃CH₃CH₂CH₂CH₃</td>
<td>0.409</td>
</tr>
<tr>
<td>N-Octane</td>
<td>114.2</td>
<td>CH₃CH₃CH₂CH₂CH₂CH₃</td>
<td>0.542</td>
</tr>
<tr>
<td>N-Nonane</td>
<td>128.3</td>
<td>CH₃CH₃CH₂CH₂CH₂CH₂CH₃</td>
<td>0.711</td>
</tr>
</tbody>
</table>

**Capillary Action**
- It is the ability of a liquid to flow against gravity up a narrow tube.
- It is a combination of cohesive and adhesive forces.

**Q #63** The structures of two isomers of heptanes are shown below. Which of these two compounds would you expect to have the greater viscosity?

**Compound A**

**Compound B**
11.5 Vaporization and Vapor Pressure

**Vaporization Process**

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Chemical Formula</th>
<th>Normal Boiling Point (°C)</th>
<th>$\Delta H_{\text{vap}}$ (kJ/mol) at Boiling Point</th>
<th>$\Delta H_{\text{vap}}$ (kJ/mol) at 25 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>H$_2$O</td>
<td>100</td>
<td>40.7</td>
<td>44.0</td>
</tr>
<tr>
<td>Rubbing alcohol (isopropyl alcohol)</td>
<td>C$_3$H$_8$O</td>
<td>82.3</td>
<td>39.9</td>
<td>45.4</td>
</tr>
<tr>
<td>Acetone</td>
<td>C$_2$H$_4$O</td>
<td>56.1</td>
<td>29.1</td>
<td>31.0</td>
</tr>
<tr>
<td>Diethyl ether</td>
<td>C$_4$H$_9$O</td>
<td>34.6</td>
<td>26.5</td>
<td>27.1</td>
</tr>
</tbody>
</table>

**Energetics of Vaporization**

- When the high energy molecules are lost from the liquid, it lowers the average kinetic energy.
- If energy is not drawn back into the liquid, its temp. will decrease – therefore, vaporization is an endothermic process and condensation is an exothermic process.
- Vaporization requires input of energy to overcome the attractions between molecules.

(Refer to Example 11.3 and Practice 11.3 for more help and hint.)

**Vapor Pressure and Dynamic Equilibrium**
Vapor Pressure and BP

(Clausius-Clapeyron Eqn.)

\[
\ln \left( \frac{P_2}{P_1} \right) = -\frac{\Delta H_{\text{vap}}}{R} \left( \frac{1}{T_2} - \frac{1}{T_1} \right)
\]

(Refer to Example 11.4-5 and Practice 11.4-5 for more help and hint.)

Q #67. Which will evaporate more quickly: 55 mL of water in a beaker with a diameter of 4.5 cm, or 55 mL of water in a dish with a diameter of 12 cm? Will the vapor pressure of the water be different in the two containers? Explain.

Q #69. Spilling room-temperature water over your skin on a hot day will cool you down. Spilling vegetable oil (of the same temperature) over your skin on a hot day will not. Explain the difference.

Q #77. Ethanol has a heat of vaporization of 38.56 kJ/mol and a normal boiling point of 78.4 °C. What is the vapor pressure of ethanol at 15°C?
Critical Point – Unusual Phase

11.6 Sublimation and Fusion

Sublimation

Fusion

11.7 Heating Curve for Water

Q #81. An 8.5-g ice cube is placed into 255 g of water. Calculate the temperature change in the water upon the complete melting of the ice. Assume that all of the energy required to melt the ice comes from the water.

Q #83. How much heat (in kJ) is required to warm 10.0 g of ice, initially at –10.0°C, to steam at 110.0°C? The heat capacity of ice is 2.09 J/g · °C and that of steam is 2.01 J/g · °C.
11.8 Phase Diagram – major features

Regions

Lines

Triple Point

Critical Point

Q #85. Consider the phase diagram on the right. Identify the phases present at points a through g.
Q #89. The phase diagram for sulfur is shown on the right. The rhombic and monoclinic phases are two solid phases with different structures.
   a. Below what pressure will solid sulfur sublime?
   b. Which of the two solid phases of sulfur is most dense?

11.9 Extraordinary Properties of Water

Q #91. Water has a high boiling point for its relatively low molar mass. Why?

11.10 Crystalline Solids – X-Ray Crystallography (skip)
11.11 Crystalline Solids – Basic Unit Cells
Q #97. Determine the number of atoms per unit cell for each of the following metals.

(Refer to Example 11.7 and Practice 11.7 for more help and hint.)

<table>
<thead>
<tr>
<th>Cubic Cell Name</th>
<th>Atoms per Unit Cell</th>
<th>Structure</th>
<th>Coordination Number</th>
<th>Edge Length in terms of $r$</th>
<th>Packing Efficiency</th>
<th>Fraction of volume occupied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple Cubic</td>
<td>1</td>
<td><img src="image" alt="Simple Cubic Structure" /></td>
<td>6</td>
<td>$2r$</td>
<td>52%</td>
<td><img src="image" alt="Simple Cubic Packing Efficiency" /></td>
</tr>
<tr>
<td>Body-centered Cubic</td>
<td>2</td>
<td><img src="image" alt="Body-centered Cubic Structure" /></td>
<td>8</td>
<td>$\frac{4r}{\sqrt{3}}$</td>
<td>68%</td>
<td><img src="image" alt="Body-centered Cubic Packing Efficiency" /></td>
</tr>
<tr>
<td>Face-centered Cubic</td>
<td>4</td>
<td><img src="image" alt="Face-centered Cubic Structure" /></td>
<td>12</td>
<td>$2\sqrt{2}r$</td>
<td>74%</td>
<td><img src="image" alt="Face-centered Cubic Packing Efficiency" /></td>
</tr>
</tbody>
</table>

(a) Polonium
(b) Tungsten
(c) Nickel
#99. Platinum crystallizes with the face-centered cubic unit cell. The radius of a platinum atom is 139 pm. Calculate the edge length of the unit cell and the density of platinum in g/cm³.

11.12 Crystalline Solids – Fundamental Types

### Molecular Solids

### Ionic Solids
Atomic Solids

Metallic solids

Q #105. Identify each of the following solids as molecular, ionic, or atomic.

a. Ar(s)  b. H₂O(s)  c. K₂O(s)  d. Fe(s)

Q #107. Which of the following solids has the highest melting point? Why?

Ar(s), CCl₄(s), LiCl (s), CH₃OH (s)

Q #107. Of each pair of solids, which one has the higher melting point and why?

a. TiO₂(s) or HOOH(s)

b. CCl₄(s) or SiCl₄(s)

c. Kr(s) or Xe(s)

d. NaCl(s) or CaO(s)

11.13 Crystalline Solids – Band Theory (skip)

Cumulative problem

Q #128. A sealed flask contains 0.55 g of water at 28 °C. The vapor pressure of water at this temperature is 28.36 mmHg. What is the minimum volume of the flask in order that no liquid water be present in the flask?