WHY?
• Why is water usually a liquid and not a gas?
• Why does liquid water boil at such a high temperature for such a small molecule?
• Why does ice float on water?
• Why do snowflakes have 6 sides?
• Why is I₂ a solid whereas Cl₂ is a gas?
• Why are NaCl crystals little cubes?

Liquids, Solids & Intermolecular Forces
Unit #8 Chapter 10

Intermolecular Forces
Have studied INTRAmolecular forces—the forces holding atoms together to form molecules.
Now turn to forces between molecules — INTERmolecular forces.
Forces between molecules, between ions, or between molecules and ions.

Intermolecular Forces
Types of Intermolecular Forces are the following (in strength order)...
Ionic—those in a single ionic substance = strongest, the greater the charge (+2, -2 rather than +1, -1) the greater the effect
Dipole—those in molecular compounds that have a dipole moment
-Hydrogen-bonding = specific dipoles between H-F, H-O and H-N
All of these are strong for molecular compounds, with hydrogen-bonding being especially strong.
Induced dipole or London Dispersion Forces (LDF)—these are forces acting in every molecular compound or noble gas
These are the weakest of all forces caused by the motion of electrons (explain physical state of diatomic halogens)
Solids, Liquids and Gases

- Solids are tightly-packed and have strong intermolecular forces, whereas gases have virtually no forces acting within.
- We’d expect that liquids are somewhere in between and are but actually have more qualities of solids than gases.
- We will study the intermolecular forces that affect solids and liquids and the changes of state that occur.

Properties that result from strong intermolecular forces are a higher boiling point, higher freezing (melting) point and a lower vapor pressure.

When 2 molecular compounds meet

Dipole-Dipole Forces

Such forces bind molecules having permanent dipoles to one another.

<table>
<thead>
<tr>
<th>Compd</th>
<th>Mol. Wt.</th>
<th>Boil Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂</td>
<td>28</td>
<td>-196 °C</td>
</tr>
<tr>
<td>CO</td>
<td>28</td>
<td>-192 °C</td>
</tr>
<tr>
<td>Br₂</td>
<td>160</td>
<td>59 °C</td>
</tr>
<tr>
<td>ICl</td>
<td>162</td>
<td>97 °C</td>
</tr>
</tbody>
</table>

Dipole-Dipole Forces

Influence of dipole-dipole forces is seen in the boiling points of simple molecules.
Hydrogen Bonding

A special form of dipole-dipole attraction, which enhances dipole-dipole attractions.

H-bonding is strongest when X and Y are N, O, or F.

H-Bonding Between Methanol and Water

H-Bonding Between Two Methanol Molecules
H-Bonding Between Ammonia and Water

H-bond

This H-bond leads to the formation of NH₄⁺ and OH⁻

Hydrogen Bonding in H₂O

H-bonding is especially strong in water because
- the O—H bond is very polar (and there are 2 H-bonds in water)
- there are 2 lone pairs on the O atom

Accounts for many of water’s unique properties.

Hydrogen Bonding in H₂O

Ice has open lattice-like structure.

Ice density is < liquid.

And so solid floats on water.

Notice the negative slope of the ice-water equilibrium.
Hydrogen Bonding in $H_2O$

H bonds $\rightarrow$ abnormally high specific heat capacity of water (4.184 J/K•g).

This is the reason water is used to put out fires, it is the reason lakes/oceans control climate, and is the reason thunderstorms release huge energy.

Hydrogen Bonding

H bonds leads to abnormally high boiling point of water.

Because of the intermolecular forces, the change from liquid to gas needs extremely high energy for a molecule of this size.

Boiling Points of Simple Hydrocarbon Compounds
FORCES INVOLVING INDUCED DIPOLES

How can non-polar molecules such as O₂ and I₂ dissolve in water?

The water dipole INDUCES a dipole in the O₂ electron cloud.

This type of intermolecular force is called “Dipole-induced dipole”

FORCES INVOLVING INDUCED DIPOLES

Solubility increases with mass of the gas!

<table>
<thead>
<tr>
<th>Salt</th>
<th>Molar Mass (g/mol)</th>
<th>Solubility at 20 °C (g/L at 1 atm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>2.01</td>
<td>0.00190</td>
</tr>
<tr>
<td>I₂</td>
<td>253.8</td>
<td>0.00230</td>
</tr>
<tr>
<td>O₂</td>
<td>32.0</td>
<td>0.00080</td>
</tr>
</tbody>
</table>

This is a dipole-induced dipole force

FORCES INVOLVING INDUCED DIPOLES

Formation of a dipole in two nonpolar I₂ molecules.

Induced dipole-induced dipole
Induced Dipole-Induced Dipole Forces—also called LONDON DISPERSION FORCES (LDF)

A perfect example of this effect is found in the halogen family.

As mass increases the LDF also increases and this explains why F\textsubscript{2} and Cl\textsubscript{2} are gases (as you would expect) but Br\textsubscript{2} is a liquid and I\textsubscript{2} is a solid at room temperature.

The induced forces between I\textsubscript{2} molecules are very weak, so solid I\textsubscript{2} sublimes (goes from a solid to gaseous molecules).

Induced Dipole-Induced Dipoles

The magnitude of the induced dipole depends on the tendency to be distorted.

Higher molecular weight \(\rightarrow\) larger induced dipoles.

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Boiling Point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH\textsubscript{4} (methane)</td>
<td>-161.5</td>
</tr>
<tr>
<td>C\textsubscript{2}H\textsubscript{6} (ethane)</td>
<td>-88.6</td>
</tr>
<tr>
<td>C\textsubscript{3}H\textsubscript{8} (propane)</td>
<td>-42.1</td>
</tr>
<tr>
<td>C\textsubscript{4}H\textsubscript{10} (butane)</td>
<td>-0.5</td>
</tr>
</tbody>
</table>

Boiling Points of Hydrocarbons

Note linear relation between boiling point and molar mass. The larger the molecular mass the greater the effect.
**Intermolecular Forces Summary**

<table>
<thead>
<tr>
<th>Type of Interaction</th>
<th>Factor Responsible</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole - Dipole</td>
<td>Dipole moment (polar molecules)</td>
<td>$\text{H}_2\text{O}$, $\text{NH}_3$</td>
</tr>
<tr>
<td>Hydrogen bonding ($\text{H} \cdots \text{H}^+$)</td>
<td>Induced dipole (polar molecules)</td>
<td>$\text{H}_2\text{O} \cdots \text{H}_2\text{O}$</td>
</tr>
<tr>
<td>Hydrogen bonding ($\text{H} \cdots \text{H}^+$)</td>
<td>Dipole-induced dipole</td>
<td>$\text{H}_2\text{O} \cdots \text{H}_2\text{O}$</td>
</tr>
<tr>
<td>Van der Waals forces</td>
<td>Dipole-induced dipole</td>
<td>$\text{H}_2\text{O} \cdots \text{H}_2\text{O}$</td>
</tr>
</tbody>
</table>

Shown here in decreasing strength from top to bottom.

*Don’t forget that ionic forces are greater!*  
In molecular compounds, the intermolecular forces (dipole-dipole, hydrogen-bonds, dipole-induced dipole and LDF) are collectively called van der Waals forces.