

**TABLE 11.4 Types of Intermolecular Forces**

Type	Present in	Molecular perspective	Strength
Dispersion	All molecules and atoms		
Dipole-dipole	Polar molecules		
Hydrogen bonding	Molecules containing H bonded to F, O, or N		
Ion-dipole	Mixtures of ionic compounds and polar compounds		

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## Surface Tension

- surface tension is a property of liquids that results from the tendency of liquids to minimize their surface area
- in order to minimize their surface area, liquids form drops that are spherical
  - ✓ as long as there is no gravity
- the layer of molecules on the surface behave differently than the interior
  - ✓ because the cohesive forces on the surface molecules have a net pull into the liquid interior
- the surface layer acts like an elastic skin

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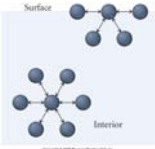
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## Surface Tension

- because they have fewer neighbors to attract them, the surface molecules are less stable than those in the interior
  - ✓ have a higher potential energy
- the surface tension of a liquid is the energy required to increase the surface area a given amount
  - ✓ at room temp, surface tension of H<sub>2</sub>O = 72.8 mJ/m<sup>2</sup>



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## Factors Affecting Surface Tension

- the stronger the intermolecular attractive forces, the higher the surface tension will be
- raising the temperature of a liquid reduces its surface tension
  - ✓ raising the temperature of the liquid increases the average kinetic energy of the molecules
  - ✓ the increased molecular motion makes it easier to stretch the surface

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4

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## Viscosity

- **viscosity** is the resistance of a liquid to flow
  - ✓ 1 poise = 1 P = 1 g/cm·s
  - ✓ often given in centipoise, cP
- larger intermolecular attractions = larger viscosity
- higher temperature = lower viscosity

TABLE 11.5 Viscosity of Several Hydrocarbons at 20 °C

Hydrocarbon	Molar Mass (g/mol)	Formula	Viscosity (cP)
N-Pentane	72.15	$\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3$	0.240
N-Hexane	86.17	$\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3$	0.326
N-Heptane	100.2	$\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3$	0.409
N-Octane	114.2	$\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3$	0.542
N-Nonane	128.3	$\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3$	0.711

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5

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## Capillary Action

- **capillary action** is the ability of a liquid to flow up a thin tube against the influence of gravity
  - ✓ the narrower the tube, the higher the liquid rises
- capillary action is the result of the two forces working in conjunction, the cohesive and adhesive forces
  - ✓ cohesive forces attract the molecules together
  - ✓ adhesive forces attract the molecules on the edge to the tube's surface

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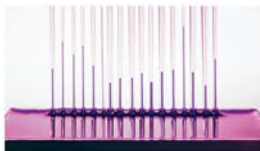
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## Capillary Action

- the adhesive forces pull the surface liquid up the side of the tube, while the cohesive forces pull the interior liquid with it
- the liquid rises up the tube until the force of gravity counteracts the capillary action forces



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7

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## Meniscus

- the curving of the liquid surface in a thin tube is due to the competition between adhesive and cohesive forces
- the meniscus of water is concave in a glass tube because its adhesion to the glass is stronger than its cohesion for itself
- the meniscus of mercury is convex in a glass tube because its cohesion for itself is stronger than its adhesion for the glass
  - ✓ metallic bonds stronger than intermolecular attractions



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8

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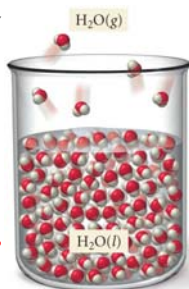
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## Vaporization

- molecules in the liquid are constantly in motion
- the average kinetic energy is proportional to the temperature
- however, some molecules have more kinetic energy than the average
- if these molecules are at the surface, they may have enough energy to overcome the attractive forces
  - ✓ therefore – **the larger the surface area, the faster the rate of evaporation**
- this will allow them to escape the liquid and become a **vapor**



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9

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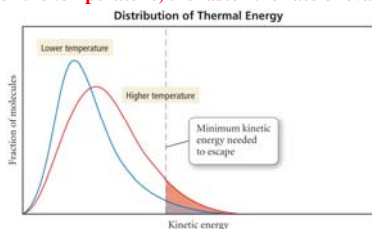
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## Distribution of Thermal Energy

- only a small fraction of the molecules in a liquid have enough energy to escape
- but, as the temperature increases, the fraction of the molecules with “escape energy” increases
- **the higher the temperature, the faster the rate of evaporation**



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10

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## Condensation

- some molecules of the vapor will lose energy through molecular collisions
- the result will be that some of the molecules will get captured back into the liquid when they collide with it
- also some may stick and gather together to form droplets of liquid
  - ✓ particularly on surrounding surfaces
- we call this process **condensation**

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11

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## Evaporation vs. Condensation

- vaporization and condensation are opposite processes
- in an open container, the vapor molecules generally spread out faster than they can condense
- the net result is that the rate of vaporization is greater than the rate of condensation, and there is a net loss of liquid
- however, in a closed container, the vapor is not allowed to spread out indefinitely
- the net result in a closed container is that at some time the rates of vaporization and condensation will be equal

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12

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## Effect of Intermolecular Attraction on Evaporation and Condensation

- the weaker the attractive forces between molecules, the less energy they will need to vaporize
- also, weaker attractive forces means that more energy will need to be removed from the vapor molecules before they can condense
- the net result will be more molecules in the vapor phase, and a liquid that evaporates faster – **the weaker the attractive forces, the faster the rate of evaporation**
- liquids that evaporate easily are said to be **volatile**
  - ✓ e.g., gasoline, fingernail polish remover
  - ✓ liquids that do not evaporate easily are called **nonvolatile**
    - e.g., motor oil

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13

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## 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 temperature 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

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14

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## Heat of Vaporization

- the amount of heat energy required to vaporize one mole of the liquid is called the **Heat of Vaporization,  $\Delta H_{\text{vap}}$** 
  - ✓ sometimes called the enthalpy of vaporization
- always endothermic, therefore  $\Delta H_{\text{vap}}$  is +
- somewhat temperature dependent
- $\Delta H_{\text{condensation}} = -\Delta H_{\text{vaporization}}$

TABLE 11.7 Heats of Vaporization of Several Liquids at Their Boiling Points and at 25 °C

Liquid	Chemical Formula	Normal Boiling Point (°C)	$\Delta H_{\text{vap}}$ (kJ/mol) at Boiling Point	$\Delta H_{\text{vap}}$ (kJ/mol) at 25 °C
Water	H <sub>2</sub> O	100	40.7	44.0
Rubbing alcohol (isopropyl alcohol)	C <sub>3</sub> H <sub>8</sub> O	82.3	39.9	45.4
Acetone	C <sub>3</sub> H <sub>6</sub> O	56.1	29.1	31.0
Diethyl ether	C <sub>4</sub> H <sub>10</sub> O	34.6	26.5	27.1

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15

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## Dynamic Equilibrium

- in a closed container, once the rates of vaporization and condensation are equal, the total amount of vapor and liquid will not change
- evaporation and condensation are still occurring, but because they are opposite processes, there is no net gain or loss of either vapor or liquid
- when two opposite processes reach the same rate so that there is no gain or loss of material, we call it a **dynamic equilibrium**
  - ✓ this does **not** mean there are equal amounts of vapor and liquid – it means that they are **changing** by equal amounts

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16

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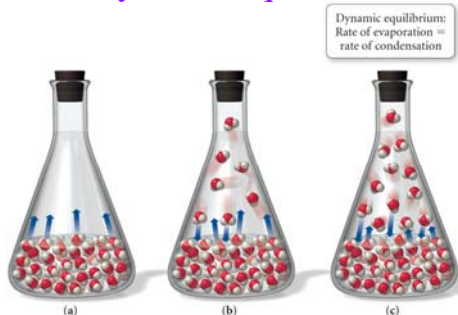
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## Dynamic Equilibrium



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## Vapor Pressure

- the pressure exerted by the vapor when it is in dynamic equilibrium with its liquid is called the **vapor pressure**
  - ✓ remember using Dalton's Law of Partial Pressures to account for the pressure of the water vapor when collecting gases by water displacement?
- the weaker the attractive forces between the molecules, the more molecules will be in the vapor
- therefore, **the weaker the attractive forces, the higher the vapor pressure**
  - ✓ the higher the vapor pressure, the more volatile the liquid

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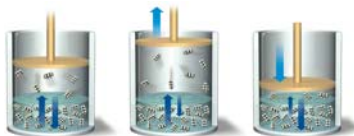
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### Vapor-Liquid Dynamic Equilibrium

- if the volume of the chamber is increased, that will decrease the pressure of the vapor inside
  - ✓ at that point, there are fewer vapor molecules in a given volume, causing the rate of condensation to slow
- eventually enough liquid evaporates so that the rates of the condensation increases to the point where it is once again as fast as evaporation
  - ✓ equilibrium is reestablished
- at this point, the vapor pressure will be the same as it was before



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19

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### Dynamic Equilibrium

- a system in dynamic equilibrium can respond to changes in the conditions
- **when conditions change, the system shifts its position to relieve or reduce the effects of the change**

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20

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### Vapor Pressure vs. Temperature

- increasing the temperature increases the number of molecules able to escape the liquid
- the net result is that **as the temperature increases, the vapor pressure increases**
- small changes in temperature can make big changes in vapor pressure
- the rate of growth depends on strength of the intermolecular forces

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21

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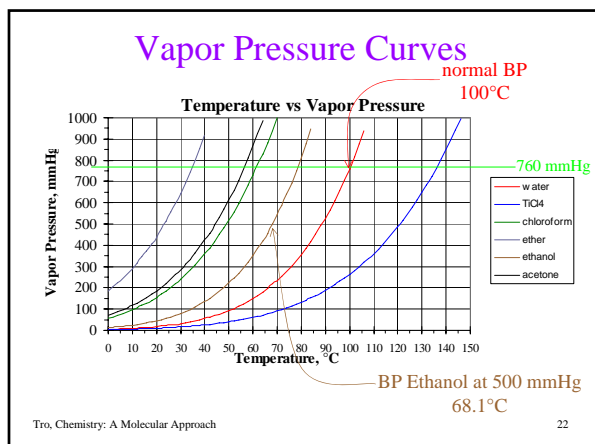
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### Boiling Point

- when the temperature of a liquid reaches a point where its vapor pressure is the same as the external pressure, vapor bubbles can form anywhere in the liquid
  - ✓ not just on the surface
- this phenomenon is what is called **boiling** and the temperature required to have the vapor pressure = external pressure is the **boiling point**

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### Boiling Point

- the normal boiling point is the temperature at which the vapor pressure of the liquid = 1 atm**
- the lower the external pressure, the lower the boiling point of the liquid

**TABLE 11.8** Boiling Points of Water at Several Locations of Varied Altitudes

Location	Elevation (ft)	Approximate Pressure (atm) <sup>a</sup>	Approximate Boiling Point of Water (°C)
Mt. Everest, Tibet (highest mountain peak on Earth)	29,035	0.32	78
Mt. McKinley (Denali), Alaska (highest mountain peak in North America)	20,320	0.46	83
Mt. Whitney, California (highest mountain peak in 48 contiguous U.S. states)	14,495	0.60	87
Denver, Colorado (mile high city)	5,286	0.83	94
Boston, Massachusetts (sea level)	20	1.0	100

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