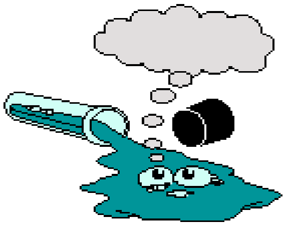
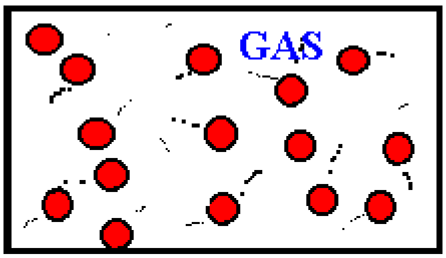


The Three States of Matter

KEYWORDS: ➡ Boiling ➡ Boiling point ➡ Brownian motion ➡ Condensing ➡ Cooling curve ➡ Diffusion ➡ Evaporation ➡ Freezing ➡ Freezing point ➡ Gas particle picture ➡ Heating curve ➡ Liquid particle picture ➡ Melting ➡ Melting point ➡ Properties of gases ➡ Properties of liquids ➡ Properties of solids ➡ sublimation ➡ Solid particle picture



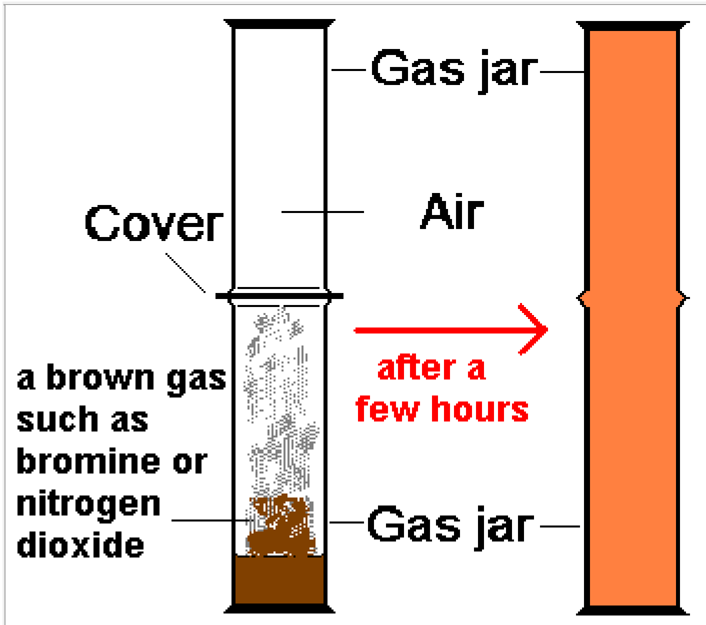
The particle model of a Gas

- Almost **no forces of attraction between the particles** so they are completely free of each other.
- Particles **widely spaced and scattered** at random throughout the container so there is no order in the system.
- Particles **move rapidly in all directions**, **frequently colliding** with each other and the side of the container.
- With **increase in temperature**, the **particles move faster as they gain kinetic energy**.

Using the particle model to explain the properties of a Gas

- **Gases have a very low density** ('light') because the particles are so spaced out in the container.
  - **Density order: solid > liquid >>> gases**
- Gases **flow freely** because there are no effective forces of attraction between the particles.
  - **Ease of flow order**: **gases > liquids >>> solids** (no real flow in solid unless you powder it!)
- Gases have **no surface**, and **no fixed shape or volume**, and because of lack of particle attraction, they always spread out and fill any container (so gas volume = container volume).
- Gases are **readily compressed** because of the 'empty' space between the particles.
  - **Ease of compression order**: **gases >>> liquids > solids** (almost impossible to compress a solid)
- If the 'container' volume can change, **gases readily expand* on heating** because of the lack of particle attraction, and **readily contract on cooling**.
  - On **heating, gas particles gain kinetic energy**, **move faster** and **hit the sides of the container more frequently**, and significantly, they **hit with a greater force**.
  - Depending on the container situation, either or both of the pressure or volume will increase (reverse on cooling).
  - **Note: *** It is the gas volume that expands NOT the molecules, they stay the same size!
- The natural **rapid and random movement** of the particles means that gases **readily 'spread' or diffuse**. **Diffusion** is fastest in gases where there is more space for them to move.
-

- The **rate of diffusion increases with increase in temperature as the particles gain kinetic energy and move faster**.
- Other **evidence for random particle movement**:
    - When smoke particles are viewed under a microscope they appear to 'dance around' when illuminated with a light beam at 90^{o} to the viewing direction. This is because the smoke particles show up by reflected light and 'dance' due to the millions of random hits from the fast moving air molecules. This is called '**Brownian motion**'. At any given instant of time, the hits will not be even, so the smoke particle get a greater bashing in a random direction.
    - If a long glass tube is filled at one with a plug of cotton wool soaked in conc. hydrochloric acid, and a similar plug of conc. ammonia solution at the other end. If left undisturbed and horizontal, despite the lack of tube movement (eg shake to mix), a white cloud forms about $^{1}/_{3}$rd along from the conc. acid tube end.
        - What happens is the colourless gases ammonia and hydrogen chloride diffuse down the tube and react to form fine white crystals of the salt ammonium chloride.
        - $NH_{3(g)} + HCl_{(g)} ==> NH_4Cl_{(s)}$
        - Note the rule: **The smaller the molecular mass, the faster the molecules move**.
            - Therefore the smaller the molecular mass, the faster the gas diffuses.
            - eg M_r(**NH_3**) = 14 + 1x3 = **17**, moves **faster** than M_r(**HCl**) = 1 + 35.5 = **36.5**
            - AND that's why they meet nearer the HCl end of the tube!
            - So the experiment is not only **evidence for molecule movement**, its also **evidence that different molecular masses move on at different speeds**.

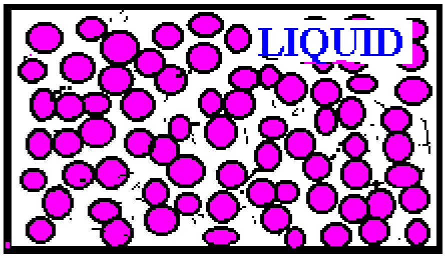


A coloured gas, that is heavier than air, is put into a gas jar and a second gas jar is placed over it separated with a cover.

If the cover is removed than coloured gas diffuses into the colourless air above. It can't be due to convection because the more dense gas starts at the bottom!

No 'shaking' or other means of mixing is required. The random movement of both lots of particles is enough to ensure that both gases are completely mixed eventually.

This is clear evidence for the process of diffusion due to particle movement.

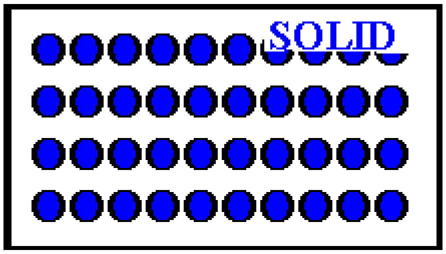


The particle model of a Liquid

- Much **greater forces of attraction between the particles in a liquid compared to gases**, but not quite as much as in solids.
- Particles **quite close together** but **still arranged at random** throughout the container, there is a little close range order as you can get clumps of particles clinging together temporarily.
- Particles **moving rapidly in all directions** but **more frequently collisions** with each other than in gases due to shorter distances between particles.
- With **increase in temperature**, the particles **move faster** as they **gain kinetic energy**, so increased collision rates, increased collision energy and increased rate of diffusion.

Using the particle model to explain the properties of a Liquid

- **Liquids have a much greater density than gases** ('heavier') because the particles are much closer together because of the attractive forces.
- **Liquids usually flow freely** despite the forces of attraction between the particles but liquids are not as 'fluid' as gases.
  - Note **'sticky' or viscous liquids have much stronger attractive forces** between the molecules BUT not strong enough to form a solid.
- **Liquids have a surface**, and a **fixed volume** (at a particular temperature) because of the increased particle attraction, but the shape is not fixed and is merely that of the container itself.
- Liquids are **not readily compressed** because of the lack of 'empty' space between the particles.
- Liquids **will expand on heating** but nothing like as much as gases because of the greater particle attraction restricting the expansion (will contract on cooling).
  - Note: When heated, the liquid particles gain kinetic energy and hit the sides of the container more frequently, and more significantly, they hit with a greater force, so in a sealed container the pressure produced can be considerable!
- The **natural rapid and random movement of the particles means that liquids 'spread' or diffuse**. Diffusion is much slower in liquids compared to gases because there is less space for the particles to move in and more 'blocking' collisions happen.
- **Evidence for random particle movement in liquids**:
  - If coloured crystals of eg the highly coloured salt crystals of potassium manganate(VII) are dropped into a beaker of water and covered at room temperature. Despite the lack of mixing, convection etc. the bright purple colour of the dissolving salt slowly spreads throughout all of the liquid but it is much slower than the gas experiment described above.
  - When pollen grains are viewed under a microscope they appear to 'dance around' when illuminated with a light beam at 90^{o} to the viewing direction. This is because the pollen grains show up by reflected light and 'dance' due to the millions of random hits from the fast moving water molecules. This is called '**Brownian motion**' after a botanist called Brown first described the effect. At any given instant of time, the hits will not be even all round the pollen grain, so they get a greater number of hits in a random direction.



The particle model of a Solid

- The **greatest forces of attraction are between the particles** in a solid and they pack together as tightly as possible in a neat and ordered arrangement.
- The particles are **too strongly held together to allow movement** from place to place but the particles vibrate about there position in the structure.
- With **increase in temperature, the particles vibrate faster** and more strongly as they gain kinetic energy.

Using the particle model to explain the properties of a Solid

- **Solids have the greatest density** ('heaviest') because the particles are closest together.
- **Solids cannot flow freely** like gases or liquids because the particles are strongly held in fixed positions.
- Solids have a **fixed surface and volume** (at a particular temperature) because of the strong particle attraction.
- Solids are **extremely difficult to compress** because there is no real 'empty' space between the particles.
- Solids will **expand a little on heating** but nothing like as much as liquids because of the greater particle attraction restricting the expansion (contract on cooling).
  - The expansion is caused by the increased energy of particle vibration, forcing them further apart.
- **Diffusion is almost impossible in solids** because the particles are too strongly held and there are no 'empty spaces' for particles to move into.

• Changes of State

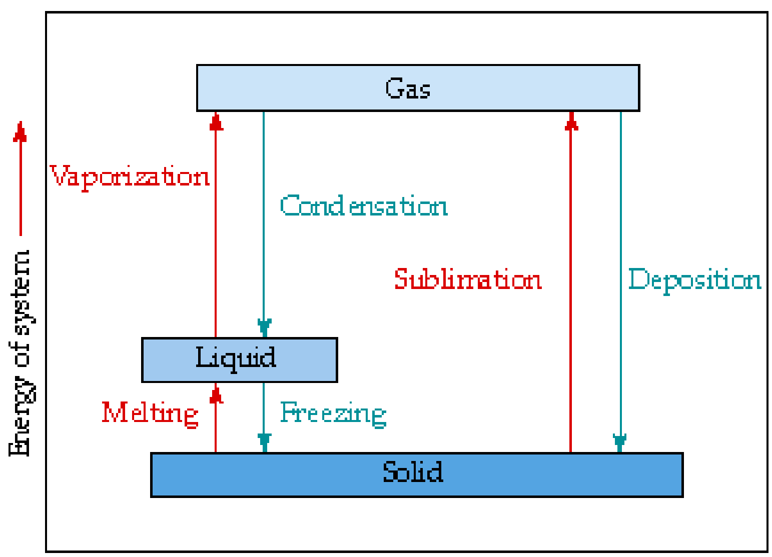
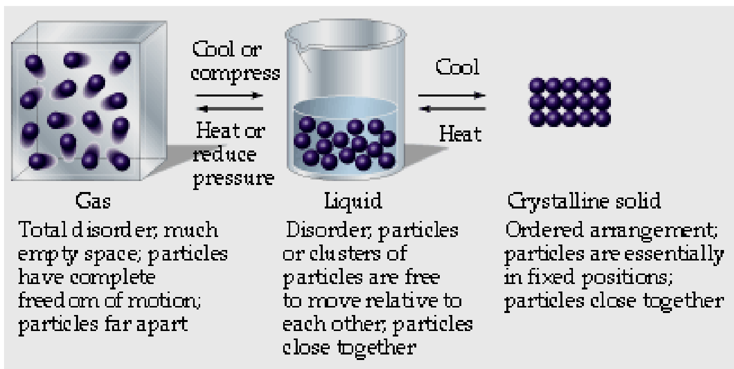
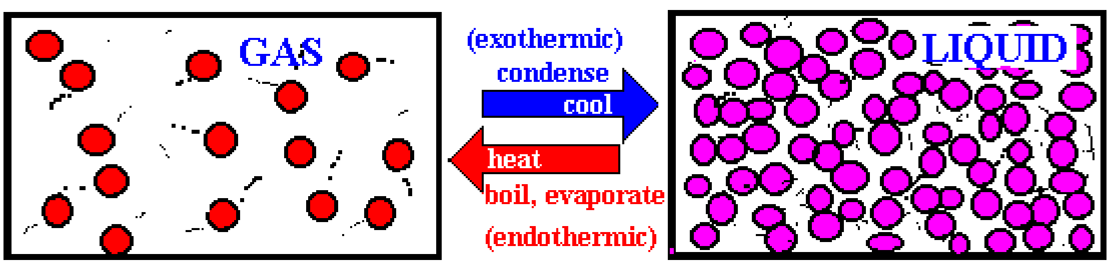


TABLE 11.1 Some Characteristic Properties of the States of Matter

Gas	Assumes both the volume and shape of container Is compressible Diffusion within a gas occurs rapidly Flows readily
Liquid	Assumes the shape of the portion of the container it occupies Does not expand to fill container Is virtually incompressible Diffusion within a liquid occurs slowly Flows readily
Solid	Retains its own shape and volume Is virtually incompressible Diffusion within a solid occurs extremely slowly Does not flow



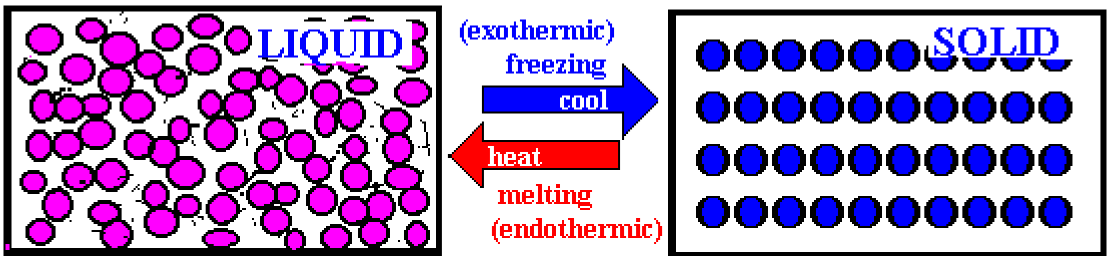


Evaporation and Boiling (liquid to gas)

- On **heating particles gain kinetic energy** and **move faster**.
- In **evaporation*** and boiling the **highest kinetic energy molecules can 'escape'** from the attractive forces of the other liquid particles.
- The particles lose any order and **become completely free to form a gas or vapour**.
- **Energy is needed to overcome the attractive forces** in the liquid and is taken in from the surroundings.
- This means heat is taken in, so **evaporation or boiling are endothermic** processes.
- If the **temperature is high enough boiling takes place**.
- **Boiling is rapid evaporation anywhere in the bulk liquid** and at a fixed temperature called the **boiling point** and requires continuous addition of heat.
- The rate of boiling is limited by the rate of heat transfer into the liquid.
- *** Evaporation** takes place more slowly **at any temperature between the melting point and boiling point**, and **only from the surface**, and results in the liquid becoming cooler due to loss of higher kinetic energy particles.

Condensing (gas to liquid)

- On **cooling, gas particles lose kinetic energy** and eventually become attracted together to form a liquid.
- There is an **increase in order as the particles are much closer together** and can form clumps of molecules.
- The process requires heat to be lost to the surroundings ie heat given out, so **condensation is exothermic**.
  - This is why steam has such a scalding effect, its not just hot, but you get extra heat transfer to your skin due to the exothermic condensation on your surface!



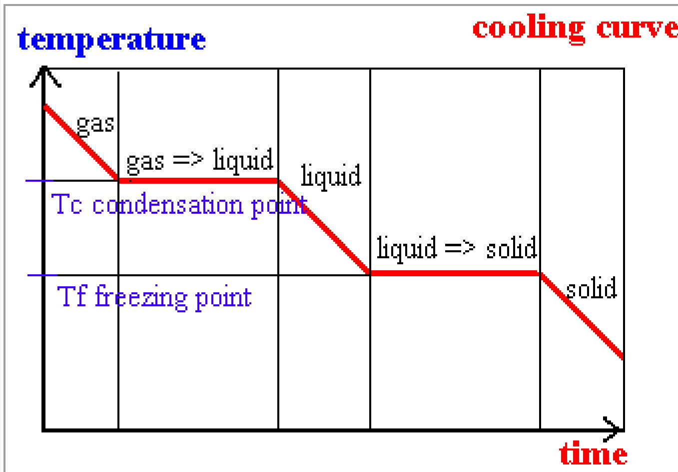
Melting (solid to liquid)

- When a **solid is heated the particles vibrate more strongly** as they gain kinetic energy and the particle attractive forces are weakened.
- Eventually, at the **melting point**, the attractive forces are too weak to hold the particles in the structure together in an ordered way and so the solid melts.
- The particles **become free to move around** and lose their ordered arrangement.
- **Energy is needed to overcome the attractive forces** and give the particles increased kinetic energy of vibration.
- So heat is taken in from the surroundings and **melting is an endothermic process**.

Freezing (liquid to solid)

- On **cooling, liquid particles lose kinetic energy** and so can become more strongly attracted to each other.
- Eventually at the **freezing point** the forces of attraction are sufficient to remove any remaining freedom and the particles come together to form the ordered solid arrangement.
- Since heat must be removed to the surroundings **freezing is an exothermic process**!!!

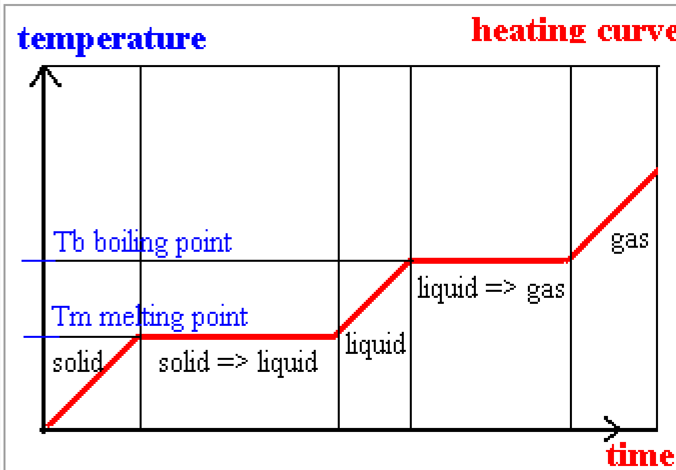
Cooling and Heating Curves



Note the temperature stays constant during the state changes of condensing Tc and freezing Tf. This is because all the energy removed on cooling at these temperatures weakens the inter-particle forces without temperature fall.

A cooling curve summarises the changes:

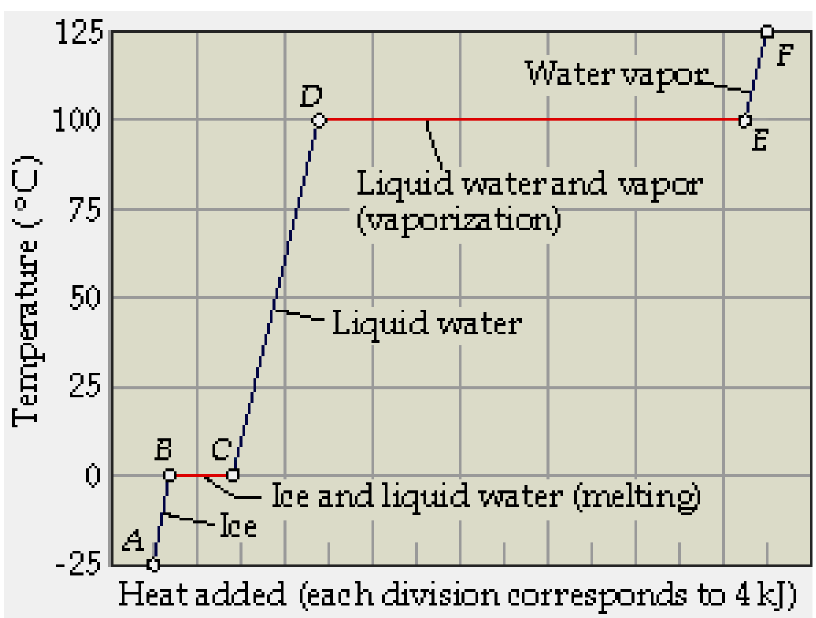
gas ➔ liquid ➔ solid



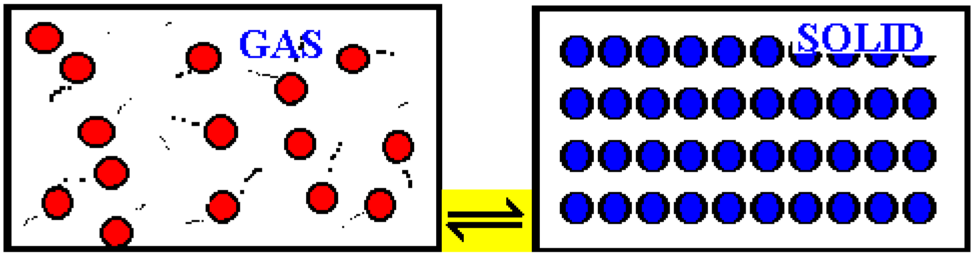
Note the temperature stays constant during the state changes of melting at Tm and boiling at Tb. This is because all the energy absorbed in heating at these temperatures goes into weakening the inter-particle forces without temperature rise.

A heating curve summarises the changes:

Solid ➔ liquid ➔ gas



Sublimation



- **Sublimation:**
  - **This** is when **a solid, on heating, directly changes into a gas**, AND **the gas on cooling re-forms a solid directly**. They **usually involve just a physical change** BUT its not always that simple!
- **Theory in terms of particles**:
  - When the solid is heated the particles vibrate with increasing force from the added thermal energy.
    - If the particles have enough kinetic energy of vibration to partially overcome the particle-particle attractive forces you would expect the solid to melt.
    - HOWEVER, if the particles at this point have enough energy at this point that would have led to boiling, the liquid will NOT form and the solid turns directly into a gas.
      - Overall **endothermic change**, energy absorbed and 'taken in' to the system.
  - On cooling, the particles move slower and have less kinetic energy.
    - Eventually, when the particle kinetic energy is low enough, it will allow the particle-particle attractive forces to produce a liquid.
    - BUT the energy may be low enough to permit direct formation of the solid, ie the particles do NOT have enough kinetic energy to maintain a liquid state!
      - Overall **exothermic change**, energy released and 'given out' to the surroundings.
- **Examples**:
  1. Even at room temperature bottles of solid **iodine** show crystals forming at the top of the bottle above the solid. The warmer the laboratory, the more crystals form when it cools down at night!
     - $I_{2\,(s)} \rightleftharpoons I_{2\,(g)}$ (physical change only)
  2. The formation of a **particular form of frost** involves the direct freezing of water vapour (gas). Frost can also evaporate directly back to water vapour (gas) and this happens in the 'dry' extremely cold winters of the Gobi Desert.
     - $H_2O_{(s)} \rightleftharpoons H_2O_{(g)}$ (physical change only)
  3. **Solid carbon dioxide (dry ice)** is formed on cooling the gas down to less than -78°C. On warming it changes directly to a very cold gas!, condensing any water vapour in the air to a 'mist', hence its use in stage effects.
     - $CO_{2\,(s)} \rightleftharpoons CO_{2\,(g)}$ (physical change only)
  4. On heating strongly in a test tube, **the white solid ammonium chloride**, decomposes into a mixture of two colourless gases ammonia and hydrogen chloride. On cooling the reaction is reversed and solid ammonium chloride reforms at the cooler top of the test tube.
     - **Ammonium chloride** + heat $\rightleftharpoons$ **ammonia + hydrogen chloride**
     - $NH_4Cl_{(s)} \rightleftharpoons NH_{3(g)} + HCl_{(g)}$ (this involves both chemical and physical changes)