- ***Candidates should be able to*** *:*

  - ***Describe*** *solids, liquids and gases in terms of the* ***spacing, ordering and motion of atoms or molecules.***

  - ***Describe*** *a* ***simple kinetic model*** *for solids, liquids and gases.*

  - ***Describe*** *an experiment that demonstrates* ***Brownian motion*** *and discuss the* ***evidence for the movement of molecules*** *provided by such an experiment.*

  - ***Define*** *the term* ***pressure*** *and use the kinetic model to explain the* ***pressure exerted by gases.***

  - ***Define internal energy*** *as the sum of the random distribution of kinetic and potential energies associated with the molecules of a system.*

  - ***Explain*** *that the rise in temperature of a body leads to an increase in its internal energy.*

  - ***Explain*** *that a* ***change of state*** *for a substance leads to changes in its internal energy but not its temperature.*

  - ***Describe*** *using a simple kinetic model for matter the terms* ***melting, boiling and evaporation.***

DESCRIPTION OF SOLIDS, LIQUIDS AND GASES

According to ***KINETIC THEORY,*** *all matter consists of tiny, identical particles called* ***MOLECULES*** *which in turn consist of* ***ATOMS.*** *The atoms themselves are made up of* ***PROTONS, NEUTRONS*** *and* ***ELECTRONS*** *and, as we shall see later, the protons and neutrons are themselves made up of still smaller particles called* ***QUARKS.***

A **MOLECULE** is the smallest particle of a **pure substance** that is characteristic of the **substance** (e.g. a molecule of **carbon dioxide (CO_2)** consists of **1 atom of carbon** chemically joined to **2 atoms of oxygen**).

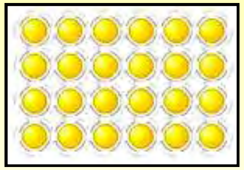
An **ATOM** is the smallest particle of an **element** that is characteristic of the **element** (e.g. an atom of helium consists of **2 protons, 2 neutrons** and **2 electrons**).

Matter can exist in one of three states, ***SOLID, LIQUID*** *or* ***GAS.***

THE SOLID STATE

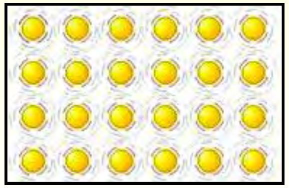
In a ***SOLID*** *:*

- *The molecules are arranged in a* ***regular, 3-dimensional*** *structure.*



LOW TEMPERATURE

- *The atoms and molecules are bonded to each other by* ***strong, attractive*** *forces due to the electrical charges of the electrons and protons in the atoms.*



HIGHER TEMPERATURE

- *The molecules are relatively* ***close to each other (~ 3.0×10^{-10} m)*** *and* ***vibrate randomly in SHM about fixed positions.*** *The* ***higher the temperature*** *of the solid, the* ***greater is the amplitude*** *of vibration of the molecules.*

- *Heating causes the molecules to gain **kinetic energy** resulting in increased amplitude of vibration. The temperature of the solid rises and if enough heat energy is supplied, the molecules vibrate so vigorously that they break free from each other. The **potential energy** of the molecules increases and at this stage the solid loses its shape and is said to **MELT** (i.e. the substance passes from the solid to the liquid state).*

THE LIQUID STATE

*In a **LIQUID** :*

- *The molecules are still in contact and vibrating, but they are **free to move around randomly** and this is why a liquid **flows** and has **no fixed shape.***

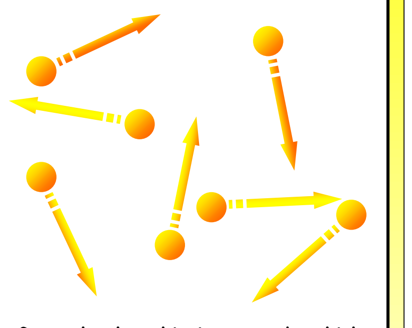
- *The attractive forces between the molecules are **weaker than in a solid** and not strong enough to hold them in fixed positions.*

- *The **separation of the molecules is about the same as it is in solids (~ 3.0 x 10^{-10} m).***

- *Heating causes the molecules to gain **kinetic energy** and so the **higher the temperature** of a liquid, the **greater the speed of the molecules.** Continued heating eventually gives the molecules enough **kinetic energy** to completely break free from each other. The liquid is then said to **VAPORISE** (i.e. the substance passes from the **liquid** to the **gaseous** state).*

THE GASEOUS (OR VAPOUR) STATE

*In a **GAS (or VAPOUR)** :*



Gas molecules whizzing around at high speed and in random directions.

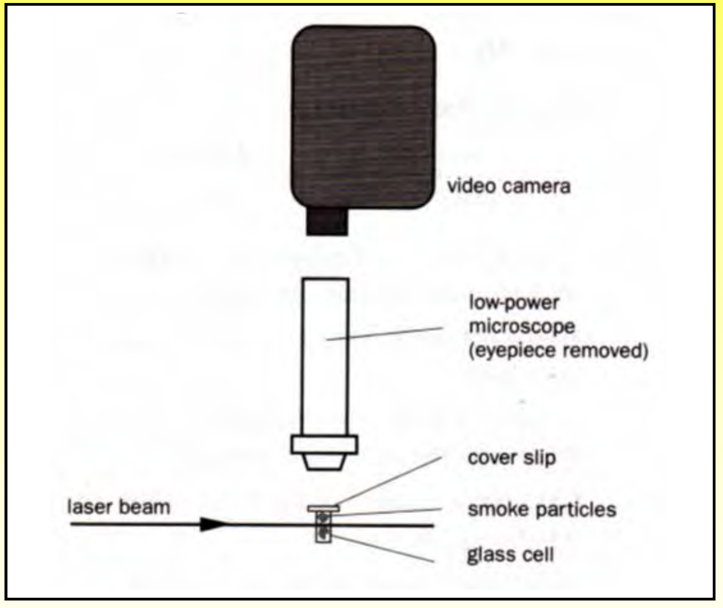
- *The **intermolecular forces are negligible** and so the molecules are completely free of each other. They **whiz around in rapid, random motion,** colliding with the walls of the containing vessel and with each other. It is this molecular bombardment of the container walls which gives rise to gas pressure.*

- *On average, the molecules are about **ten times** further apart **(~ 3.0 x 10^{-9} m)** than they are in solids and liquids. This is why a gas occupies a much larger volume than the same mass of liquid.*

- *Heating a gas or vapour causes the molecules to gain **kinetic energy** and so **speed up.***

BROWNIAN MOTION

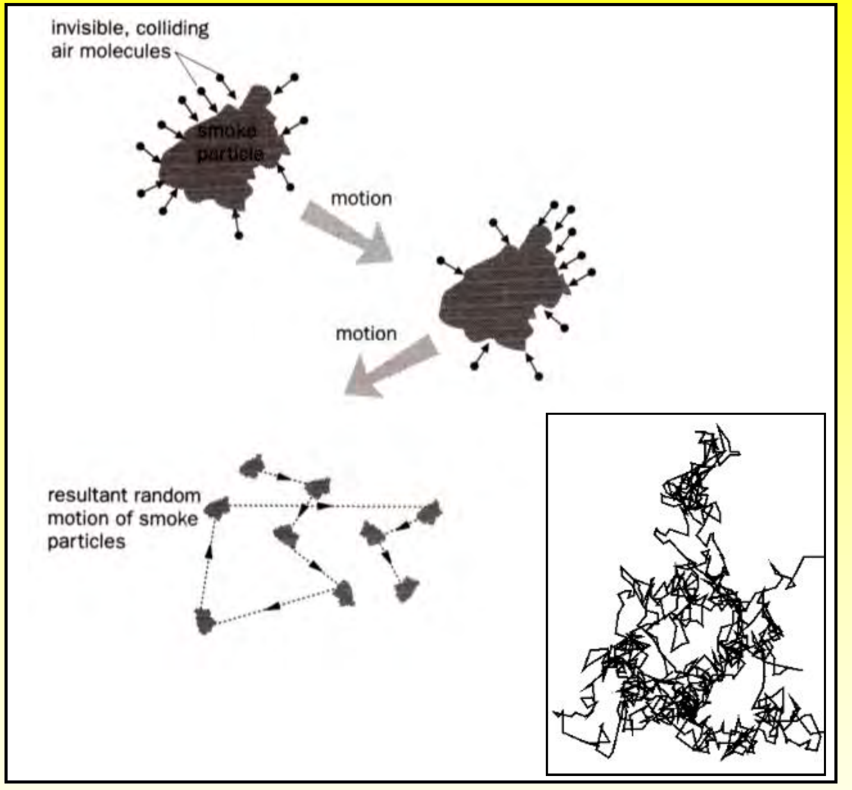
*This phenomenon was first observed in 1827 by a Scottish botanist called **Robert Brown** when he was examining tiny pollen grains suspended in water. He noticed that the grains seemed to be subject to continual, jerky movements, but he could not explain why. Almost eighty years later **Albert Einstein** solved the mystery and his explanation helped to convince many sceptics of the correctness of the **Kinetic Theory**.*



***Brownian motion** can be clearly observed and studied using the arrangement shown in the diagram above.*

The glass cell is filled with smoke and quickly covered with a cover slip. It is then brightly illuminated with a laser beam and a low-power microscope in conjunction with a video camera and monitor is Used to view the motion of the smoke particles. These are seen on the screen as tiny light spots which are continually jiggling about.

EXPLAINING BROWNIAN MOTION



The observations can be explained by considering what happens to a single smoke particle.
The particle is quite large compared to the air molecules which, by virtue of their rapid, random motion, continually bombard it from all directions.

At any given moment, the particle is forced to move in a particular direction because the vector sum of molecular impacts is greater in that direction than in any other. A moment later, the particle may move in a new direction as the balance of air molecule impacts changes.

Thus the particle is pushed around haphazardly and this accounts for the observed 'jittery' motion.

PRESSURE EXERTED BY A GAS

PRESSURE exerted on a surface is defined as the perpendicular force per unit area of the surface.

The defining equation is :

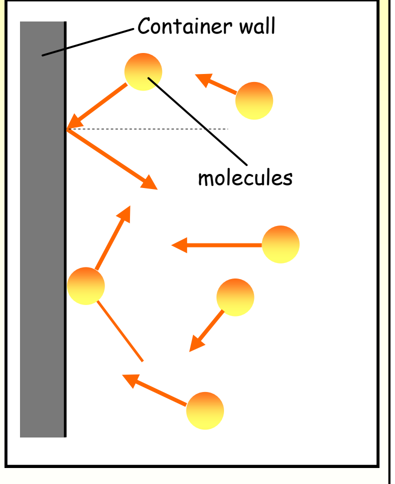
$$\text{PRESSURE } (p) = \frac{\text{FORCE } (F)}{\text{AREA } (A)}$$

Units: pressure (N m^{-2}) or (Pa); force (N); area (m^2)

GAS PRESSURE EXPLAINED IN TERMS OF MOLECULES

Consider a gas inside a container.

The gas molecules which are moving with different speeds in different directions, are continually colliding with each other and with the walls of the container. These collisions are assumed to be perfectly (i.e. There is no loss of kinetic energy and so no loss of speed on impact).



Each time a gas molecule collides with a wall its momentum changes and so it exerts a tiny force on the wall. Because there are a very large number of molecular impacts per second, the overall result is that in macroscopic terms the gas exerts a measurable pressure on the walls of the container.

INTERNAL ENERGY

- *As the name implies, the **INTERNAL** energy of an object is the **TOTAL** energy of all the molecules contained **within** the object.*

- *In the case of a **SOLID** object, the total molecular energy has two components :*

  - *A **KINETIC ENERGY (E_k)** component which is due to the vibration of the molecules about their fixed positions and depends on the temperature.*

  - *A **POTENTIAL ENERGY (E_p)** component which is due to the attraction forces which hold the molecules together and depends on the size of the bonding forces as well as the separation of the molecules.*

- *The kinetic and potential energy components are present in approximately equal proportions.*

*As the molecules vibrate in **simple harmonic motion** about their fixed positions, the size of the bonding forces, the molecular separation and the speed of the molecules is continually changing. As a result, there is a continuous interchange between the **Ek** and **Ep** components of the total internal energy. That is why the definition of internal energy which follows must contain the words '**random distribution**'.*

The **INTERNAL ENERGY** of an object is the sum of the **random distribution** of the **kinetic** and **potential** energies of all its molecules.

- *In the case of an* ***IDEAL GAS****, the intermolecular forces are assumed to be* ***negligible (zero)*** *and so the internal energy is entirely due to the* ***random kinetic energy of the molecules****.*

  It should be noted that for ***REAL*** *gases, there are small, but finite, forces of attraction between the molecules and so there is also a* ***potential energy*** *component to the internal energy.*

- *Although* ***HEAT (THERMAL) ENERGY*** *and* ***INTERNAL ENERGY*** *are closely linked, they do not have the same meaning.*

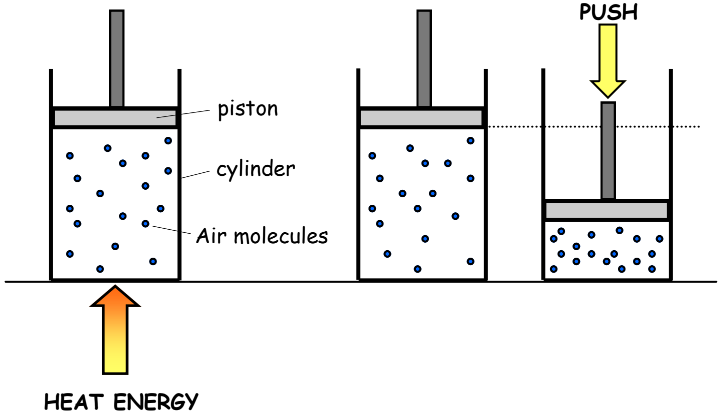
HEAT (THERMAL) ENERGY is the energy transferred between two points as a result of a temperature difference between them.

- *The* ***INTERNAL ENERGY*** *of a system is :*

INCREASED by - * ***Supplying heat energy to the system.***
And/or * ***Doing work on the system***

DECREASED by - * ***Transferring heat energy out of the system.***
And/or * ***Letting the system do work on the surroundings.***

To improve your understanding of how the internal energy of a system can be changed, consider the system to be the air enclosed by a piston and cylinder.



The **INTERNAL ENERGY** (and therefore the **TEMPERATURE**) of the air is increased by :

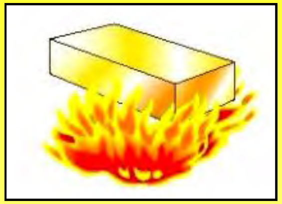
Supplying heat to it from Outside (with the piston held in position).

This causes an increase in the **KINETIC ENERGY** of the molecules.

Pushing the piston down into the cylinder (reducing the volume in which the air is contained).
This does work on the air and causes an increase in the **POTENTIAL ENERGY** of the molecules.

CHANGES OF STATE

MACROSCOPIC VIEW



- *When a solid is continuously heated, its temperature rises until it reaches a value, called the **MELTING POINT**, at which it starts to **MELT** (i.e. change from **solid to liquid**). Even though it is still being heated, **the temperature of the substance does not change while it is melting**.*

- *Once the melting process is complete, the temperature rises once again until it reaches another value, called the **BOILING POINT**, at which it starts to **BOIL**. Even though the substance continues to be supplied with heat, **its temperature will not change until all the liquid has changed into gas**, after which time the temperature will once again start to rise.*

MICROSCOPIC (MOLECULAR) VIEW

- *Heating a solid causes the molecules to gain **KINETIC ENERGY** and **vibrate more vigorously and with greater amplitude** about their fixed positions and this is seen as a **rise in temperature**.*

- *Eventually, at the **melting point**, the molecules have gained enough kinetic energy to break the bonds which hold them together. The molecules then take on a **more disordered arrangement** and their **POTENTIAL ENERGY** is increased by the fact that they are **slightly further apart**. This is seen as **melting**.*

- *Continued heating increases the **disorder, spacing and speed** of the molecules, which means that both their **KINETIC** and **POTENTIAL ENERGY** is increased. This is seen as a **rise in temperature**.*

- *Eventually, at the **boiling point**, the molecules have gained enough energy to **completely break free of each other**. The **spacing** and **speed** of the molecules increases dramatically and this is seen as the process of **boiling** in which **the liquid becomes a gas or vapour**.*

SUMMARY

- <u>DURING A CHANGE OF STATE</u> :
  - Energy must be **supplied or extracted**.
  - The **temperature stays the same**.
  - Molecules are **breaking free of each other (E_p increasing)** or **coming together (E_p decreasing)**

- <u>IN BETWEEN CHANGES OF STATE</u> :
  - **Energy supplied increases the temperature** of the substance and **energy extracted decreases the temperature** of the substance.
  - The molecules **move faster (or slower) (E_k increases or decreases)**.

PRACTICAL - COOLING CURVE FOR OCTODECANOIC ACID

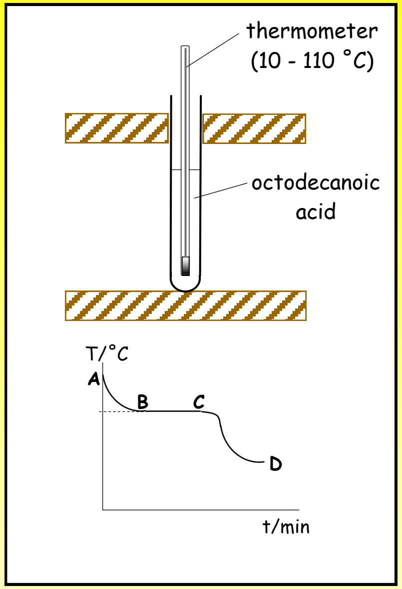
The octodecanoic acid is warmed in a water bath until it melts to become a clear liquid.

The test tube containing the liquid acid us then placed on a rack and allowed to cool. The temperature registered by the thermometer is read at 1 minute intervals and recorded in the table below.

The results are used to plot a graph of :

Temperature/°C *versus* **Time/min.**

The shape of your graph should be similar to that shown opposite.



t/min	1	2	3	4	5	6	7	8	9	10	11	12
T/°C												
t/min	13	14	15	16	17	18	19	20	21	22	23	24
T/°C												
t/min	25	26	27	28	29	30	31	32	33	34	35	36
T/°C												

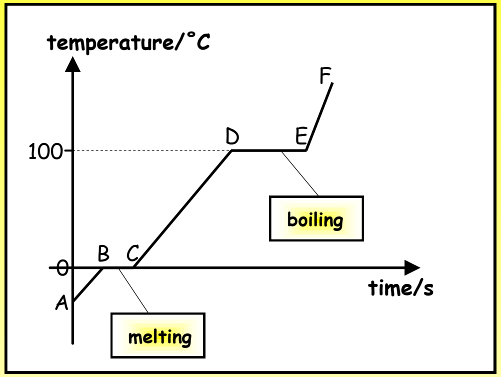
- **Explain (macroscopically and microscopically)** what is happening during each of the sections **AB, BC and CD** marked on the graph.

- What is the **melting point** of octodecanoic acid ?

ICE TO STEAM

Consider heating some ice until it melts and then to carry on heating until the water boils and turns to steam.

*If a graph of **temperature against time** is plotted for the whole process, it would look like the graph shown opposite.*



INTERPRETATION OF THE GRAPH

section	***macroscopic & microscopic view of what is happening***	***E_k or E_p increasing***
AB	*The ice starts at **T < 0°C** and heats up to **0°C** . The molecules **gain energy** and **vibrate more strongly**.*	*E_k*
BC	*The ice **MELTS**. **T remains constant at 0°C** until **ALL** the ice has melted, even though heat energy continues to be supplied. The molecules become **more disordered** and their **separation increases slightly**.*	*E_p*
CD	*Water **T rises towards 100°C**. The molecules **move about more and more rapidly**.*	*E_k*
DE	*The water **BOILS**. **T remains constant at 100°C** until **ALL** the water has changed into steam, even though heat energy continues to be supplied. The **separation of the molecules increases dramatically** and they are **moving rapidly in all directions**.*	*E_p*
EF	*Steam **T rises beyond 100°C**. The molecules are now **very far apart** and in a state of **rapid, random motion**.*	*E_k*

- *It should be noted that* ***melting the ice requires much less Energy than boiling the same amount of water.***

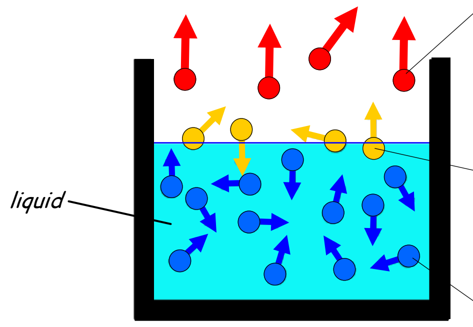
This is because when a solid ***MELTS*** *the molecules are* ***still bonded*** *to most of the neighbouring molecules, whereas when a liquid* ***BOILS*** *enough energy has to be supplied to make each molecule* ***break completely free*** *of all its neighbours.*

EVAPORATION

We are very familiar with the process of evaporation in our everyday life. People have used it since time immemorial to dry clothes after washing and the rain that is so vital to the growth of crops is, after all, only water that has previously evaporated from seas, rivers and lakes.

A heavy downpour is sometimes followed by bright sunshine and in these conditions, rapid evaporation becomes quite clearly visible.

MOLECULAR EXPLANATION OF EVAPORATION



The molecules in a liquid have a ***range of kinetic energies.*** *Those with* ***low energy*** *are bound within the liquid, whereas those having* ***high energy*** *can overcome the attraction forces of surface molecules and thereby escape to become vapour molecules. Some, having a* ***medium amount of energy,*** *escape momentarily, but are then pulled back by the attraction forces of surface molecules.*

The ***RATE OF EVAPORATION*** *is be increased by increasing :*

- *The* ***TEMPERATURE*** *of the liquid.*
  (That's why we hang out the washing on a hot, sunny day).
- *The* ***SURFACE AREA*** *of the liquid.*
  (That's why the clothes need to be spread out on the line).
- *The* ***AIRFLOW RATE*** *over the surface.*
  (That's why the clothes dry faster if its windy).

MOLECULAR EXPLANATION OF THE FACTORS WHICH AFFECT THE RATE OF EVAPORATION

THE HIGHER THE TEMPERATURE OF THE LIQUID THE FASTER IT EVAPORATES.

This is because the number of high energy molecules in a liquid increases with temperature and so the number of molecules capable of escaping (i.e. evaporating) will be greater.

THE LARGER THE SURFACE AREA OF THE LIQUID THE FASTER IT EVAPORATES.

This is because there is now a larger escape surface and so a greater number of high energy molecules per second can leave the liquid.

THE GREATER THE AIRFLOW RATE OVER THE LIQUID SURFACE THE FASTER IT EVAPORATES.

This is because the fast-moving air molecules will collide with medium energy molecules which may have had just enough energy to pop out of the surface and thus help them to escape completely. Without the air flow, these medium energy vapour molecules might otherwise have been pulled back into the liquid by attraction forces from the surface molecules.

- HOMEWORK QUESTIONS

1 **Describe,** using diagrams to illustrate your answers, the main differences between **solids, liquids and gases** in terms of :

1. The **ordering** of the molecules.
2. The **spacing** of the molecules.
3. The **motion** of the molecules.

2 **Describe** an experiment that demonstrates **Brownian motion** and **explain** the observations from such an experiment in **terms of molecules.** What **evidence for the movement of molecules** is provided by the experiment ?

3 (a) In **terms of molecules,** explain why :

(i) **A solid has a fixed shape.**
(ii) **Liquids and gases can flow.**
(iii) **A gas is much less dense than a solid or a liquid.**

(b) **Describe** the effect on the molecules of a solid of :

(i) Supplying energy **to raise its temperature.**
(ii) Supplying energy to it **to cause it to melt.**

(c) Using the **kinetic model,** explain why a gas exerts a pressure.

4 When a solid is heated, its **internal energy** increases. **Explain**, in molecular terms :

(a) What is meant by **internal energy**.

(b) Why increasing the **internal energy** of the object differs from increasing its **kinetic energy**.

5 A lock of **ice at –5°C** is continually heated at a constant rate until it has changed into **super-heated steam at 180°C.**

(a) Draw a graph of **temperature against time** for the whole process and **label each section** of your graph to show what is happening at that point.

(b) **Explain, in terms of molecules,** what is happening to the internal energy during each of the sections you have labelled on your graph.

6 (a) Using a **labelled diagram** to illustrate your answer, **explain evaporation in molecular terms.**

(b) **Explain,** in terms of molecules, why the **rate of evaporation** from a liquid is increased if :

(i) The **temperature** is increased.

(ii) The **surface area** of the liquid is increased.

(iii) The **air flow rate** over the liquid surface is increased.