States of Matter

CHEMISTRY • ATOMS AND BONDING • STATES OF MATTER

Section 1: The States of Matter

• What are the states of matter and how do they differ? How can we explain their properties in terms of particles?

Since Sir Isaac Newton's time, matter has traditionally been divided into three states: solids, liquids and gases, with each state having its own characteristics.

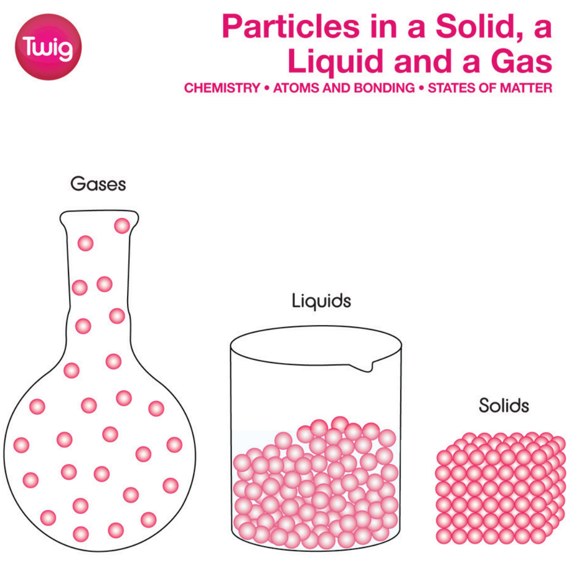
Solids have a fixed shape and a fixed volume. They are very difficult to compress. The particles in a solid are:
• Very close together, so they cannot easily be squashed any more tightly
• Strongly attracted (bonded) to one another, so they cannot move about freely
• Vibrating around fixed points, but not moving from place to place

Liquids have no fixed shape, but they do have a fixed volume. They take up the shape of the container you put them in, except that there is a horizontal, but slightly curved, surface (called the meniscus) at the top of the liquid. Liquids are difficult to compress. The particles in a liquid are:
• Close together
• Quite strongly attracted to one another
• Moving randomly and freely, constantly sliding past one another

Gases have no fixed shape or fixed volume. They take up the shape of the container you put them in and fill it completely. They can diffuse (spread out) easily from a region of high concentration to a region of low concentration. For example, if you spray some air freshener at one end of a room, the smell will soon spread throughout the room. Gases are easy to compress. The particles in gases are:
• Far apart, and are more than 99.99% empty space
• Only very weakly attracted to one another
• Moving randomly and freely

The state of a substance depends on three main factors: the types of particle it is made from; how strongly they ttract one another; the temperature.

DIAGRAM 01:



The particles within diamond are very strongly attracted, it is therefore a solid at room temperature

If the particles attract one another very strongly, as in diamond or metals such as iron, melting the substance will require vast amounts of energy to pull the particles apart. Substances like diamond and iron are therefore solids at room temperature. If the particles only attract one another very weakly, for example, the molecules of oxygen or the atoms of helium, the substance will be a gas at room temperature, because not much energy is needed to pull the particles apart. If the strength of the attraction is neither very strong nor very weak, the substance may be a liquid at room temperature, such as water, mercury or bromine.

• Suggested Film
- Solids, Liquids and Gases

• Worksheet Question
- Question 1

• How can we change the state of a substance from one state to another?

DIAGRAM 02:

To change the state of a substance from solid to liquid, from liquid to gas, or from solid directly to gas requires energy, usually in the form of heat. Energy is needed to pull the particles apart, and so we need to heat a solid to change it into a liquid. This is called melting, and (for pure solids) takes place at a specific temperature, the melting point.

The particles on the surface of a liquid are moving, and some of them move with enough energy to break free from the other particles and escape from the surface. This is called evaporation and can take place over a range of temperatures.

If we keep heating the liquid, more and more particles have sufficient energy to break free and start to form bubbles of vapour inside the body of the liquid. This is called boiling and (for a pure liquid) takes place at a specific temperature, the boiling point.

All the changes mentioned above are known as physical changes, because no new substance is being made. There are also reversible changes. If we cool a liquid we can make a solid. This process is called freezing, and is familiar in cold weather when liquid water turns to ice. If we cool a gas it will turn to a liquid: we call this process condensing. On cold days the water in our breath will condense on the inside of car windows.

Extension Questions

Q1. What is sublimation?

A few substances can change directly from a solid to a gas because the forces between their particles are so weak. This is called sublimation. Iodine sublimes from a black solid to a purple gas. Another example is solid carbon dioxide, known as dry ice, which changes directly from the solid ‘ice’ into carbon dioxide gas.

Q2. What is dry ice used for?

Dry ice is solid carbon dioxide and is much colder than ice made from water. It is used to preserve perishable items, such as food, as well as creating some of the special effects seen in music videos and films. The white patches above the poles on the planet mars are believed to be solid carbon dioxide. During the Martian winter solid carbon dioxide forms at the pole, and during the Martian summer the carbon dioxide sublimes, and the ice cap retreats.

• Suggested Films

- Changing States of Matter
- Water Forces
- How Do Snowflakes Form?
- How to Make Fake Snow

• Worksheet Questions

- Questions 2 and 3

• Can all substances be classified simply as solids, liquids or gases?

Newton's classification is useful, but not all substances fit neatly into his three states of matter. Some 'liquid' substances behave differently when shaken or when poured slowly. We call these non-Newtonian liquids and they are all around us. For example, tomato sauce becomes runny when it is shaken, but is quite thick if you try to pour it from the bottle. Toothpaste, salad cream and paint behave in a similar way. Custard and cream become more like solids when they are stirred or whipped, which is also an example of non-Newtonian behaviour.

Tomato sauce is a non-Newtonian liquid

• Suggested Film

- Non-Newtonian Liquids

Extension Question

Q3. What is Oobleck?

Oobleck is a mixture of cornflour and water. It is a typical non-Newtonian liquid, as it is a solid when you apply pressure, such as throwing it or running on it, but turns back into a liquid when the pressure is removed. Its funny name comes from a book by Dr. Seuss!

Section 2: Intermolecular Forces

• What are intermolecular forces?

Many (but not all) substances are made of particles called molecules. Molecules are particles made of groups of atoms that are bonded together by strong covalent bonds. For example, oxygen is made of oxygen molecules [O_2] made up of two oxygen atoms bonded together. Although the forces bonding the two oxygen atoms into a molecule are strong, the forces of attraction between the molecules are quite weak. In other words, oxygen molecules do not attract other oxygen molecules very strongly, which is why oxygen is a gas at room temperature.

The intermolecular forces are electrical in origin, and their strength depends partly on the types of atoms and the number of electrons in the molecule. Generally, large molecules attract one another more strongly than small molecules, because large molecules have more electrons per molecule. For example, iodine molecules [I_2] are made of iodine [I] atoms, and each iodine atom has 53 electrons, so the [I_2] molecules have 2 x 53 = 106 electrons per molecule. Fluorine atoms [F] have 9 electrons per atom, so fluorine molecules [F_2] have 2 x 9 = 18 electrons per molecule. With so many electrons, it takes much more energy to pull iodine molecules apart than to pull fluorine molecules away from one another. So at room temperature, iodine is a solid whereas fluorine is a gas.

Extension Question

Q4. How do electrons attract each other if they are all negatively charged?

The electrons in a molecule are constantly moving about, and, at a given instant, there will be slightly more electrons at one end of a molecule than the other. This makes the end of the molecule with more electrons slightly negative, and the other end of the molecule slightly positive. The positive end of one molecule attracts the negative end of another molecule, hence the Intermolecular attraction.

• Suggested Film

- Intermolecular Forces

• Worksheet Question

- Question 4

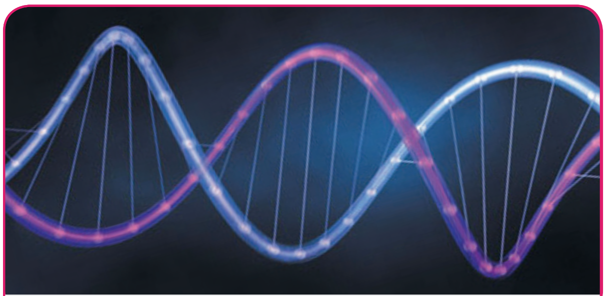
• Why are intermolecular forces important even though they are weak?

Although intermolecular forces are weak, compared to the strong forces of attraction involved in covalent bonds, metallic bonds and ionic bonds, they are responsible for holding together the molecules in a wide range of elements and compounds. These include the halogen elements, the noble gases, the hydrocarbons found in crude oil, fats, proteins and carbohydrates. In fact, most of the important compounds in our bodies are made of molecules, which are held together by intermolecular forces.

• Suggested Film

- Intermolecular Forces

• Why are intermolecular forces important for life on Earth?



Intermolecular forces affect the shape of DNA molecules

• Suggested Film

- Intermolecular Forces

Many of the most important biological substances, such as DNA, RNA, proteins (including enzymes, myoglobin and haemoglobin), starch and cellulose are made of molecules. The shapes of these molecules are determined partly by the intermolecular forces between their molecules.

The ability of DNA's double helix to replicate itself, for example, depends on the intermolecular forces, known as hydrogen bonds, between the two strands of the DNA molecule. There is a delicate balance between the forces of attraction being too strong (so the strands would not be able to separate) or too weak (so the molecule would fall apart). In either case, the DNA could not replicate itself and life, as we know it, would be impossible.

Section 3: Solutions, Separating Mixtures and Chromatography

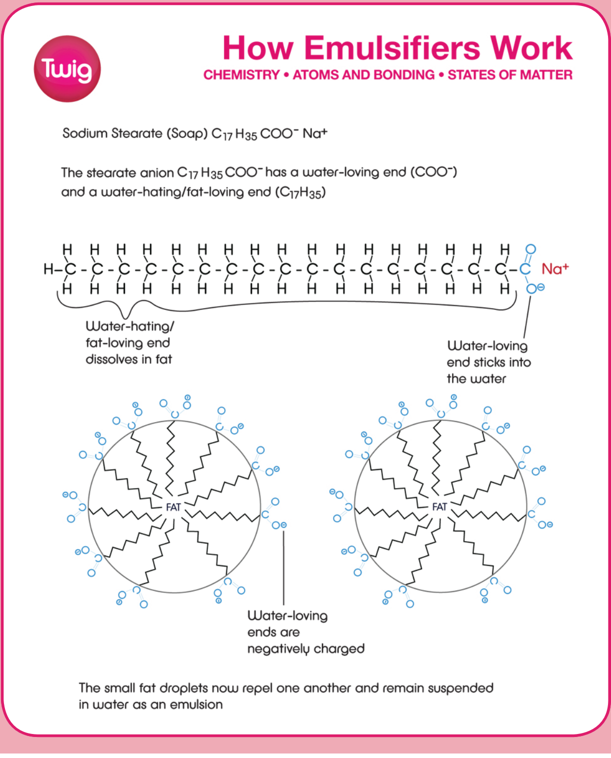
• What is a solution?

A solution is a special type of mixture in which one substance, the solvent, (for example, water) dissolves another substance, the solute, (for example, table salt). If a substance dissolves we say it is soluble, for example sugar is soluble in water. If a substance does not dissolve we say it is insoluble, for example sand is insoluble in water. Once in solution the solid will have completely broken up into tiny particles, which are then distributed evenly throughout the liquid. There are no more lumps of solid and the solution is completely clear, in the sense of being transparent, with no cloudiness at all.

If small particles of an insoluble solid are suspended in a liquid, such as mud in river water, we call this mixture a suspension. Suspensions are very common in everyday life: fruit squash, beer and hot chocolate drinks are all suspensions. In our bodies blood is an important suspension, with red and white blood cells suspended in blood plasma.

Liquids which do not mix together, such as oil and water, are called immiscible. Immiscible liquids can still form mixtures in which droplets of one liquid are suspended in the other, these are known as emulsions. Many common foodstuffs, such as milk, butter, salad cream and hot chocolate are emulsions. In order to stabilise the emulsion a substance called an emulsifier needs to be used. Emulsifiers often contain molecules that have long chains of carbon atoms at one end (the hydrophobic or water-hating end of the molecule) and a group of atoms which is attracted to water (the hydrophilic or water-loving end of the molecule).

DIAGRAM 03:



Extension Question

Q5. What is the difference between clear and colourless?

It is important to note that a clear solution is not necessarily colourless. Copper sulphate solution, for example, is a clear blue solution. Colourless means that the solution has no colour, like pure water.

A sugar cube will dissolve in a cup of tea

- **Suggested Films**
  - **- Solutions**
  - **- Salt: Salt and Ice**

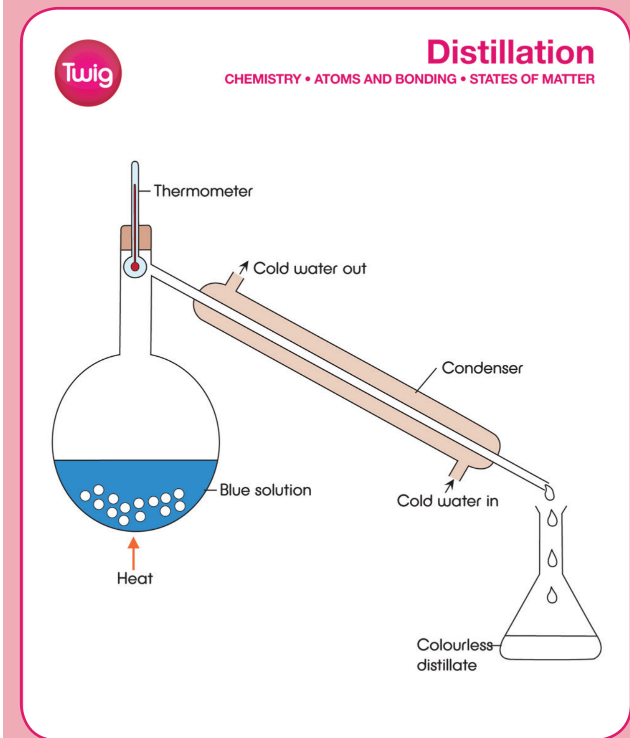
• How can we separate mixtures of substances?

The method we use to separate mixtures depends on the type of mixture, and the properties of the components in the mixture.

Magnetic and non-magnetic materials: Iron is a magnetic material and copper is non-magnetic, which means we can use a magnet to pick out pieces of iron from a mixture of iron and copper. This method will work for any alloy of iron, such as steel, and also for cobalt and nickel, which are the other two magnetic metal elements.

Soluble and insoluble materials: Table salt (sodium chloride) is soluble in water, whereas, sand is insoluble. If a mixture of table salt and sand are placed in water and stirred, the table salt will dissolve, leaving the sand as a solid and making a solution of table salt. The solid can then be filtered off by pouring the mixture through a filter funnel with a piece of filter paper inside. The insoluble sand will be left behind as the residue and the salty water will pass through the filter paper as the filtrate.

DIAGRAM 04:



Substances of different boiling points:

Dissolved solids: Water boils at 100°C and sodium chloride boils at 1415°C. If salty water is boiled the water evaporates off and leaves the sodium chloride behind.

Mixtures of liquids: Mixtures of liquids can be separated if there is a big difference in their boiling points. This is done by boiling the liquid and condensing the vapour. For example, if you boil a mixture of water, which boils at 100°C, and ethanol, which boils at 78°C, and condense the vapour, the ethanol will boil off and condense first, leaving water (and some ethanol) behind. This process is called distillation and if repeated many times we can obtain almost pure ethanol. When a mixture contains many components, such as crude oil, the process is essentially the same but requires more advanced apparatus for condensing the vapours of the components. This process is called fractional distillation.

• Suggested Films
- Salt: Separating Mixtures
- Fractional Distillation

• Worksheet Questions
- Questions 5 and 6

• What is chromatography and how can it separate different substances?

Chromatography (literally 'colour writing') was originally developed to separate different dyes from one another. In its simplest form, a pencil line is drawn on a piece of rectangular filter paper. A blob of a mixture of inks is placed on the pencil line, and the paper is placed in a beaker containing a small amount of water. The water rises up the paper and carries the different dyes as it moves. The dyes that are held weakly by the paper move the furthest and those that are held strongly by the paper do not move as far.

The final position of the water is called the solvent front. If you measure the distance from the pencil line to the position of an ink spot you can work out the ratio between how far the ink has travelled in relation to how far the solvent (in this case water) has travelled. This ratio can be calculated as follows:

$$R_f = \frac{\text{Distance travelled by spot}}{\text{Distance travelled by solvent}}$$

This is called the R_f value for that particular ink, and different inks will have different R_f values, meaning they can be distinguished from one another.

DIAGRAM 05:

Paper Chromatography

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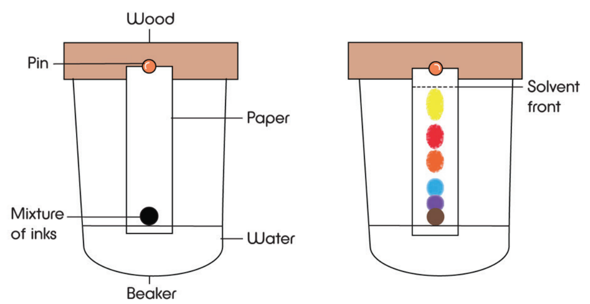


All types of chromatography depend on a solvent (of some sort) moving, known as the mobile phase, and something which holds on to the components of the mixture, known as the stationary phase. In paper chromatography water is the mobile phase and paper is the stationary phase.

Extension Questions

Q6. How is chromatography used in DNA profiling?

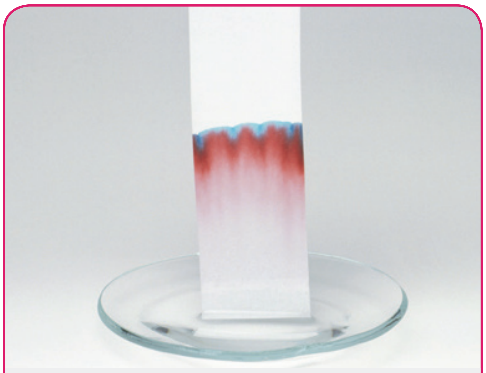
Chromatography can be used to separate many types of substances, including fragments of DNA, which can be separated using a gel as the stationary phase and an electric field to make the DNA fragments move. Different fragments move at different speeds and 'DNA fingerprinting' uses, essentially, this technique to establish relationships between parents and children. It can also be used in forensic work to prove that a DNA sample from a crime scene can be linked to an individual with a high degree of certainty.

Q7. Can solvents other than water be used for paper chromatography?

Yes, any suitable solvent can be used, as long as it dissolves the substances that are being studied and does not react with paper.

Q8. Can chromatography be used to investigate substances that are colourless?

Yes, for instance amino acids can be separated using paper chromatography. The paper is dried and then sprayed with a compound called ninhydrin, which when heated reacts with the amino acids and turns purple. By measuring the R_f values of the amino acids they can be identified.



Paper chromatography can be used to separate out mixtures of ink

• Suggested Films

- Forensics: Chromatography
- Salt: Separating Mixtures
- DNA and Crime
- Forensics: Bog Bodies
- Forensics: DNA Profiling
- Forensics: Tools of CSI
- FactPack: Forensics

• Suggested Activity

- Research the use of DNA profiling in criminal cases

• Worksheet

Q1. Give the states of the following substances at 20°C:

(a) helium, **(b)** bromine, **(c)** iodine, **(d)** silicon dioxide, **(e)** chlorine, **(f)** potassium, **(g)** sodium chloride, **(h)** ammonia, **(i)** graphite, **(j)** mercury, **(k)** ethanol

(a) __________ **(b)** __________ **(c)** __________ **(d)** __________

(e) __________ **(f)** __________ **(g)** __________ **(h)** __________

(i) __________ **(j)** __________ **(k)** __________

Q2. Give the correct names for these changes of state:

(a) $Br_2(l) \rightarrow Br_2(g)$, **(b)** $Hg(l) \rightarrow Hg(s)$, **(c)** $I_2(s) \rightarrow I_2(g)$, **(d)** $NaCl(s) \rightarrow NaCl(l)$, **(e)** $NH_3(g) \rightarrow NH_3(l)$

(a) __________ **(b)** __________ **(c)** __________

(d) __________ **(e)** __________

Q3. Liquid air at -200°C is a mixture containing mainly the following components (boiling points in brackets): nitrogen (-196°C), oxygen (-183°C), argon (-186°C). If the liquid air is heated, in which order will the gases boil off?

(1st) __________ **(2nd)** __________ **(3rd)** __________

• Worksheet

Q4 Put these hydrocarbons in order of their boiling points, with the compound with the lowest boiling point first (You can assume their molecules all have straight chains):

$C_{10}H_{22}$, $C_{12}H_{26}$, C_6H_{14}, C_3H_8

(1st) ______________________ (2nd) ______________________

(3rd) ______________________ (4th) ______________________

Q5. Put these noble gases in order of their boiling points, with the element with the lowest boiling point first:

Xe, Rn, He, Kr, Ne, Ar

(1st) ________________ (2nd) ________________ (3rd) ________________

(4th) ________________ (5th) ________________ (6th) ________________

Q6. Suggest methods for separating these mixtures:

(a) iodine from sand, **(b)** nickel powder from a mixture of nickel powder and copper powder, **(c)** hexane and octane, **(d)** copper sulphate from sand

(a) ____

(b) ____

(c) ____

(b) ____

• Worksheet Answers

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(a) gas **(b)** liquid **(c)** solid **(d)** solid

(e) gas **(f)** solid **(g)** solid **(h)** gas

(i) solid **(j)** liquid **(k)** liquid

Q2. Give the correct names for these changes of state:

(a) $Br_2(l) \rightarrow Br_2(g)$, **(b)** $Hg(l) \rightarrow Hg(s)$, **(c)** $I_2(s) \rightarrow I_2(g)$, **(d)** $NaCl(s) \rightarrow NaCl(l)$, **(e)** $NH_3(g) \rightarrow NH_3(l)$

(a) evaporation/boiling **(b)** freezing **(c)** sublimation

(d) melting **(e)** condensing

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(1st) Nitrogen **(2nd)** Argon **(3rd)** Oxygen

The gas with the lowest boiling point boils off first.

• Worksheet Answers

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$C_{10}H_{22}$, $C_{12}H_{26}$, C_6H_{14}, C_3H_8

(1st) C_3H_8 **(2nd)** C_6H_{14}

(3rd) $C_{10}H_{22}$ **(4th)** $C_{12}H_{26}$

Longer molecules have more electrons per molecule, so the intermolecular forces are stronger. More energy is needed to pull the molecules apart, so the boiling points increase.

Q5. Put these noble gases in order of their boiling points, with the element with the lowest boiling point first:

Xe, Rn, He, Kr, Ne, Ar

(1st) He **(2nd)** Ne **(3rd)** Ar

(4th) Kr **(5th)** Xe **(6th)** Rn

As the atoms become larger there are more electrons per atoms, so the intermolecular forces become stronger. More energy is needed to pull the atoms apart, so the boiling points of the noble gases increase from He to Rn.

Q6. Suggest methods for separating these mixtures:

(a) iodine from sand, **(b)** nickel powder from a mixture of nickel powder and copper powder, **(c)** hexane and octane, **(d)** copper sulphate from sand

(a) Heat – iodine will sublime, leaving sand behind

(b) Use a magnet – will pick up nickel, leaving copper behind

(c) Distill – hexane will boil off first, as it has a lower boiling point than octane

(d) Add water – copper sulphate will dissolve, leaving sand behind. The sand can then be filtered off

• Quizzes

Solids, Liquids and Gases

Basic

• Which one of these is a solid at room temperature?

A – hydrogen

B – mercury

C – bromine

D – iron

• Which of these statements is NOT true of gases?

A – they cannot flow

B – they fill the container they are in

C – they are easy to compress

D – they have no fixed shape

• In a gas the particles

A – attract one another very strongly

B – are very close together

C – are in constant motion

D – do not attract one another

• Which of these is NOT true of solids?

A – they have a fixed shape

B – they are easy to compress

C – they have a constant volume

D – their particles cannot move freely

Advanced

• We now think that the Brownian motion of pollen grains is caused by

A – water particles colliding with pollen grains

B – pollen grains swimming about

C – water flowing round the pollen grains

D – air currents blowing pollen grains

•Which of these is NOT true of liquids?

A – their particles are far apart

B – they have a constant volume

C – they can flow

D – liquid particles are in constant random motion

• The first person to give the correct explanation of Brownian motion was

A – Robert Brown

B – Antoine Lavoisier

C – Albert Einstein

D – Humphry Davy

• Which of these statements is correct?

A – all substances are made of moving particles

B – only gases and liquids are made of moving particles

C – only solids and liquids are made of moving particles

D – only solids and gases are made of moving particles

Changing States of Matter

Basic

• When a solid becomes a liquid we say it is

A – boiling
B – melting
C – condensing
D – freezing

• The change from a gas to a liquid is called

A – boiling
B – evaporation
C – melting
D – condensing

• If pure water is in contact with ice, its temperature will be

A – 0°C
B – 50°C
C – 100°C
D – 200°C

• When particles near the surface of a liquid escape, we call the process

A – condensing
B – boiling
C – melting
D – evaporating

Advanced

• When a solid is heated its particles

A – become larger
B – vibrate more rapidly
C – move randomly
D – move closer together

• Which of these processes does NOT take in energy?

A – boiling
B – freezing
C – evaporating
D – melting

• If the metal gallium is at 35°C it will be a

A – solid
B – liquid
C – gas
D – solution

• Changing a substance from a liquid to a gas is a physical change because the particles

A – are the same
B – are moving further apart
C – are colliding with one another
D – no longer attract one another

Intermolecular Forces

Basic

• Molecules

A – always attract one another

B – always repel one another

C – sometimes attract one another

D – sometimes repel one another

• The strength of the intermolecular forces depends on all these factors EXCEPT for

A – the distance between the molecules

B – the number of electrons per molecule

C – the size of the molecules

D – number of neutrons per molecule

• When a solid is heated, its particles

A – become larger

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• When you boil water, you are

A – breaking covalent O-H bonds

B – strengthening intermolecular forces

C – overcoming intermolecular forces

D – making new molecules

Advanced

• Polymers are solids because

A – the forces of attraction between the molecules are strong

B – they contain carbon atoms

C – they are made from crude oil

D – they are used to make plastic bags

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