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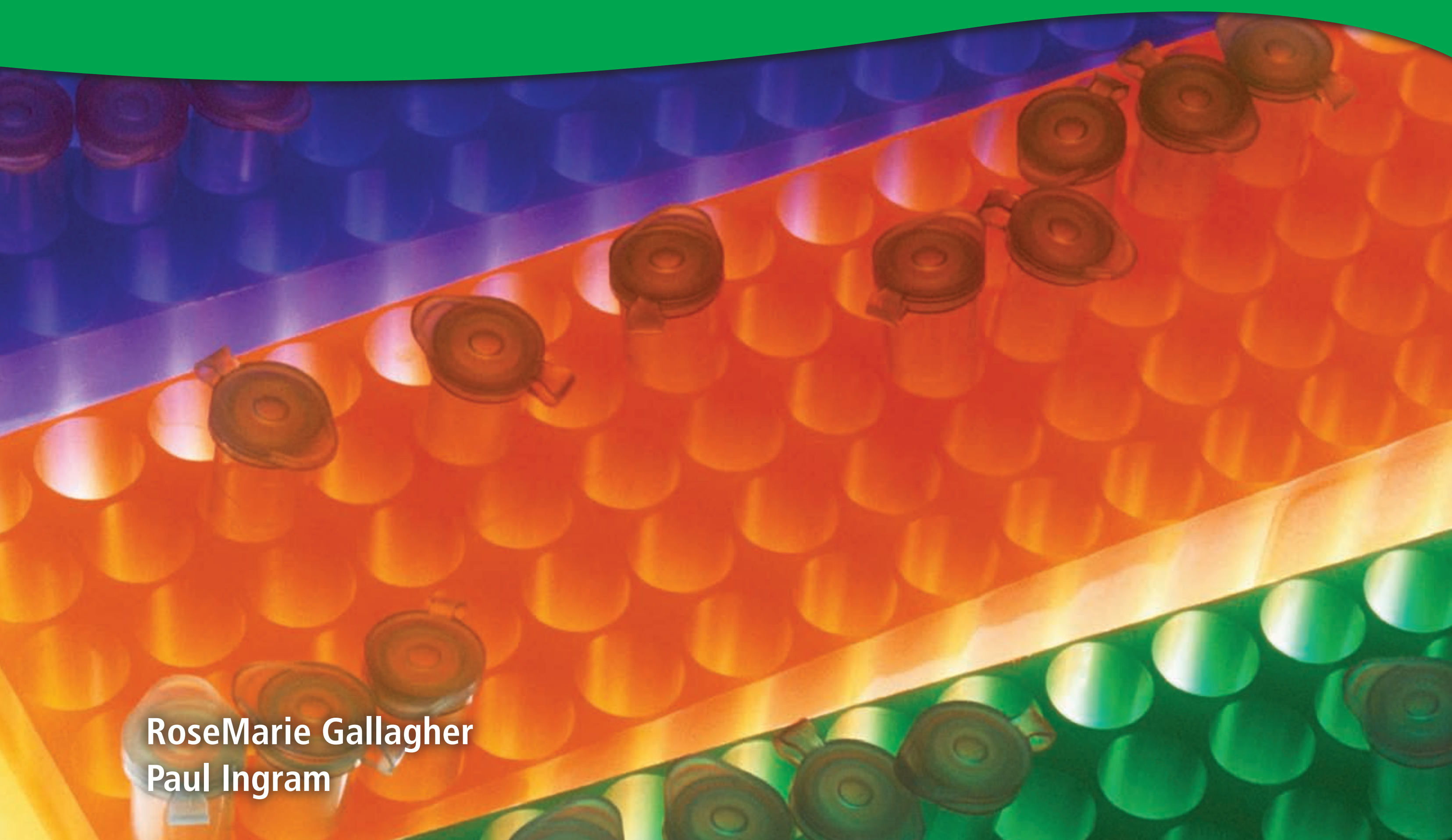

RoseMarie Gallagher
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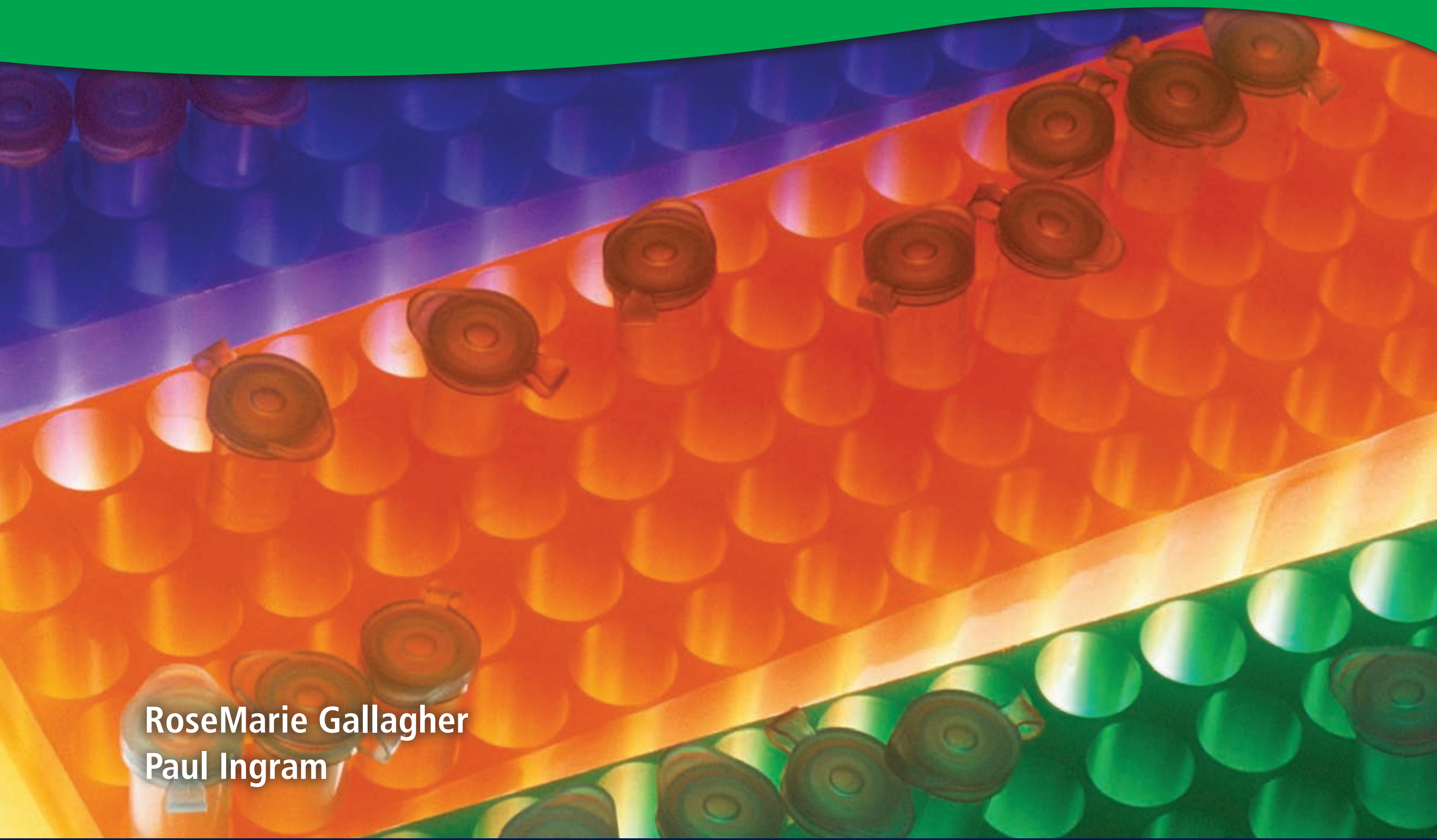

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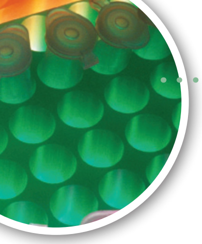


Introduction

If you are taking IGCSE chemistry, using the Cambridge International Examinations syllabus 0620, then this book is for you. It covers the syllabus fully, and has been endorsed by the exam board.

Finding your way around the book

The contents list on the next page shows how the book is organised. Take a look. Note the extra material at the back of the book too: for example the questions from past exam papers, and the glossary.

Finding your way around the chapters

Each chapter is divided into two-page units. Some colour coding is used within the units, to help you use them properly. Look at these notes:

Core curriculum

If you are following the Core curriculum, you can ignore any material with a red line beside it.

Extended curriculum

For this, you need *all* the material on the white pages, including the material marked with a red line.

Extra material

Pages of this colour contain extra material for some topics. We hope that you will find it interesting – but it is not needed for the exam.

Chapter checkups

There is a revision checklist at the end of each chapter, and also a set of exam-level questions about the chapter, on a coloured background.

Making the most of the book and CD

We want you to understand chemistry, and do well in your exams. This book, and the CD, can help you. So make the most of them!

Work through the units The two-page units will help you build up your knowledge and understanding of the chemistry on your syllabus.

Use the glossary If you come across a chemical term that you do not understand, try the glossary. You can also use the glossary to test yourself.

Answer the questions It is a great way to get to grips with a topic. This book has lots of questions: at the end of each unit and each chapter, and questions from past exam papers at the end of the book.

Answers to the numerical questions are given at the back of the book. Your teacher can provide the answers for all the others.

Use the CD The CD has an interactive test for each chapter, advice on revision, sample exam papers, and more.

And finally, enjoy! Chemistry is an important and exciting subject. We hope this book will help you to enjoy it, and succeed in your course.

RoseMarie Gallagher
Paul Ingram

Contents

1.1 Everything is made of particles

Made of particles

Rock, air, and water look very different. But they have one big thing in common: they are all made of very tiny pieces, far too small to see. For the moment, we will call these pieces **particles**.

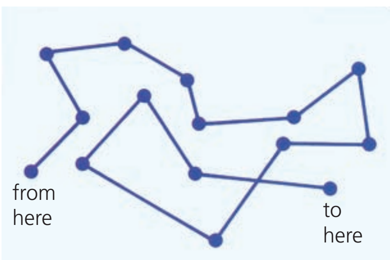
In fact everything around you is made of particles – and so are you!

▲ All made of particles!

Particles on the move

In rock and other solids, the particles are not free to move around. But in liquids and gases, they move freely. As they move they collide with each other, and bounce off in all directions.

So the path of one particle, in a liquid or gas, could look like this:



The particle moves in a random way, changing direction every time it hits another particle. We call this **random motion**.

Some evidence for particles

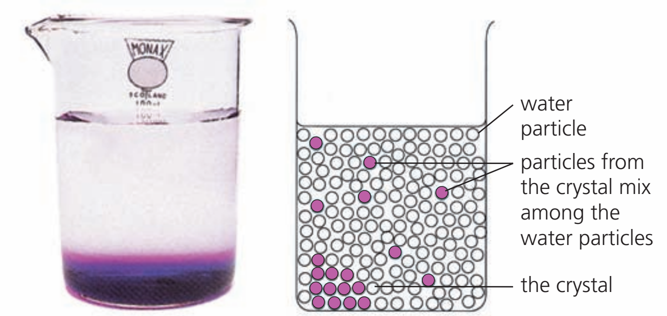
There is evidence all around you that things are made of particles, and that they move around in liquids and gases. Look at these examples.

Evidence outside the lab

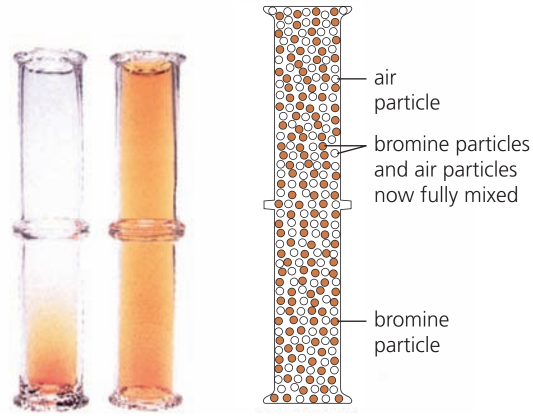
1 Cooking smells can spread out into the street. This is because 'smells' are caused by gas particles mixing with, and moving through, the air. They dissolve in moisture in the lining of your nose.

2 You often see dust and smoke dancing in the air, in bright sunlight. The dust and smoke are clusters of particles. They dance around because they are being bombarded by tiny particles in the air.

Evidence in the lab



1 Place a crystal of potassium manganate(VII) in a beaker of water. The colour spreads through the water. Why? First, particles leave the crystal – it **dissolves**. Then they mix among the water particles.



2 Place an open gas jar of air upside down on an open gas jar containing a few drops of red-brown bromine. The colour spreads upwards because particles of bromine vapour mix among the particles of air.

Diffusion

In all those examples, particles mix by colliding with each other and bouncing off in all directions. This mixing process is called **diffusion**.

The overall result is the flow of particles from where they are more concentrated to where they are less concentrated, until they are evenly spread out.

So what are these particles?

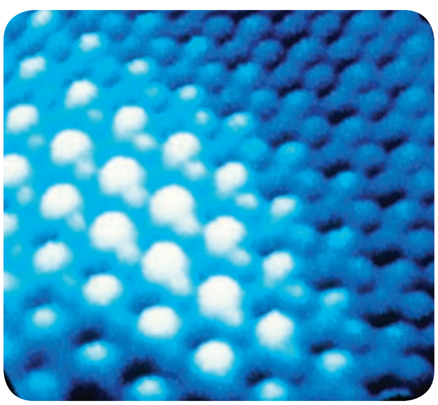
The very smallest particles, that we cannot break down further by chemical means, are called **atoms**.

- In some substances, the particles are just single atoms. For example argon, a gas found in air, is made up of single argon atoms.
- In many substances, the particles consist of two or more atoms joined together. These particles are called **molecules**. Water, bromine, and the gases nitrogen and oxygen in air, are made up of molecules.
- In other substances the particles consist of atoms or groups of atoms that carry a charge. These particles are called **ions**. Potassium manganate(VII) is made of ions.

You'll find out more about all these particles in Chapters 2 and 3.

'Seeing' particles

We are now able to 'see' the particles in some solids, using very powerful microscopes. For example the image on the right shows palladium atoms sitting on carbon atoms. In this image, the atoms appear over 70 million times larger than they really are!



▲ This image was taken using a tunneling electron microscope. The white blobs are palladium atoms, the blue ones are carbon. (The colour was added to help us see them.)

Q

1 The particles in liquids and gases show *random motion*. What does that mean, and why does it occur?

2 Why does the purple colour spread when a crystal of potassium manganate(VII) is placed in water?

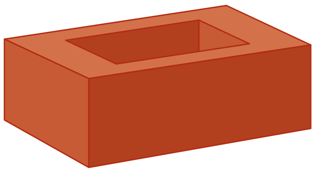
3 Bromine vapour is heavier than air. Even so, it spreads upwards in the experiment above. Why?

4 **a** What is *diffusion*? **b** Use the idea of diffusion to explain how the smell of perfume travels.

1.2 Solids, liquids, and gases

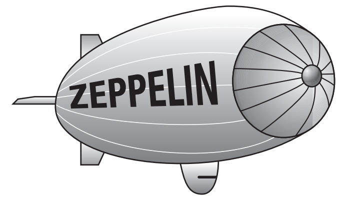
What's the difference?

It is easy to tell the difference between a solid, a liquid and a gas:



A solid has a fixed shape and a fixed volume. It does not flow. Think of all the solid things around you: their shapes and volumes do not change.

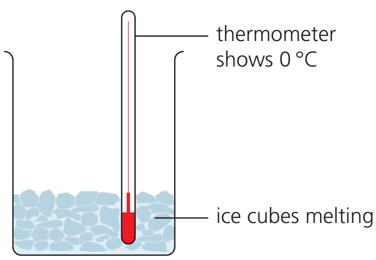
A liquid flows easily. It has a fixed volume, but its shape changes. It takes the shape of the container you pour it into.



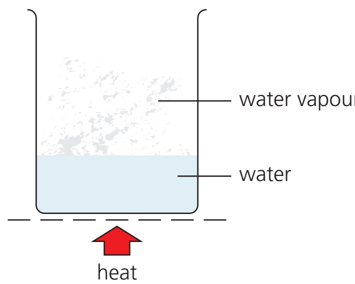
A gas does not have a fixed volume or shape. It spreads out to fill its container. It is much lighter than the same volume of solid or liquid.

Water: solid, liquid and gas

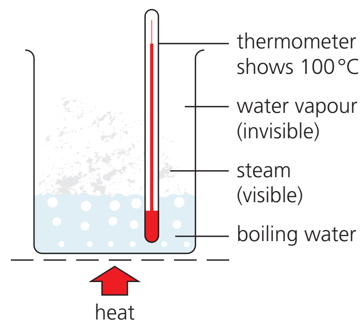
Water can be a solid (ice), a liquid (water), and a gas (water vapour or steam). Its state can be changed by heating or cooling:



1 **Ice** slowly changes to **water**, when it is put in a warm place. This change is called **melting**. The thermometer shows 0 °C until all the ice has melted. So 0 °C is called its **melting point**.

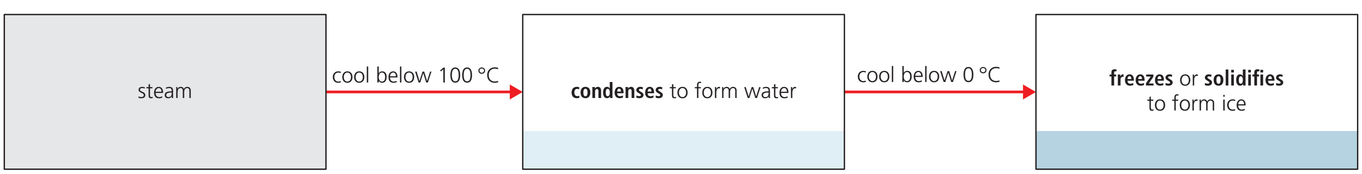


2 When the water is heated its temperature rises, and some of it changes to **water vapour**. This change is called **evaporation**. The hotter the water gets, the more quickly it evaporates.



3 Soon bubbles appear in the water. It is **boiling**. The water vapour shows up as steam. The thermometer stays at 100 °C while the water boils off. 100 °C is the **boiling point** of water.

And when steam is cooled, the opposite changes take place:



You can see that:

- condensing is the opposite of evaporating
- freezing is the opposite of melting
- the freezing point of water is the same as the melting point of ice, 0 °C.

Other things can change state too

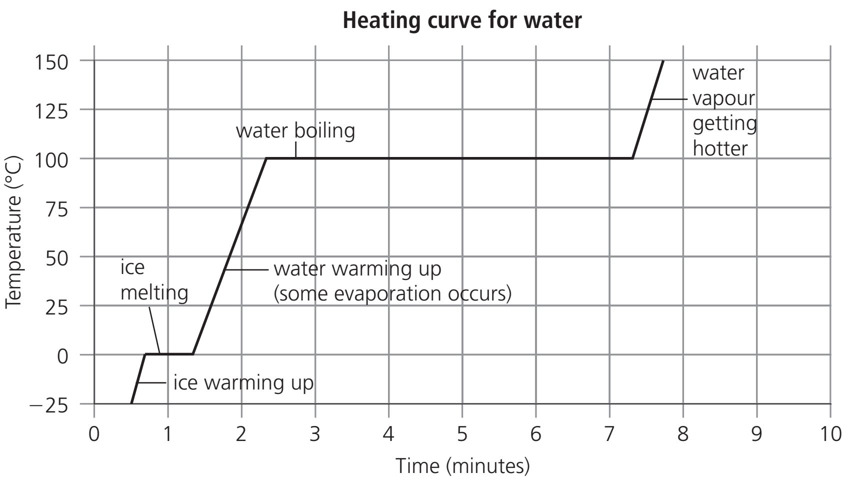
It's not just water! Nearly all substances can exist as solid, liquid and gas. Even iron and diamond can melt and boil! Some melting and boiling points are given below. Look how different they are.

Substance	Melting point/°C	Boiling point/°C
oxygen	–219	–183
ethanol	–15	78
sodium	98	890
sulfur	119	445
iron	1540	2900
diamond	3550	4832

▲ Molten iron being poured out at an iron works. Hot – over 1540 °C!

Showing changes of state on a graph

Look at this graph. It shows how the temperature changes as a block of ice is steadily heated. First the ice melts to water. Then the water gets warmer and warmer, and eventually turns to steam:



A graph like this is called a **heating curve**.

Look at the step where the ice is melting. Once melting starts, the temperature stays at 0 °C until *all* the ice has melted. When the water starts to boil, the temperature stays at 100 °C until *all* the water has turned to steam. So the melting and boiling points are clear and sharp.

▲ Evaporation in the sunshine …

Q

1 Write down two properties of a solid, two of a liquid, and two of a gas.

2 Which word means the opposite of:

a boiling? **b** melting?

3 Which has a lower freezing point, oxygen or ethanol?

4 Which has a higher boiling point, oxygen or ethanol?

5 Look at the heating curve above.

a About how long did it take for the ice to melt, once melting started?

b How long did boiling take to complete, once it started?

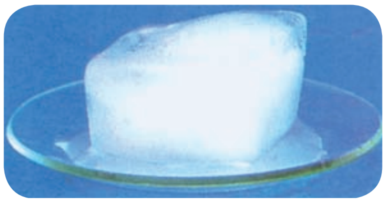
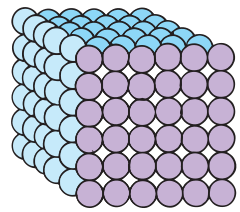
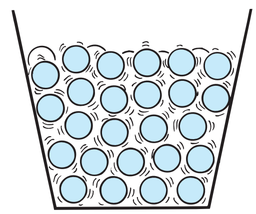
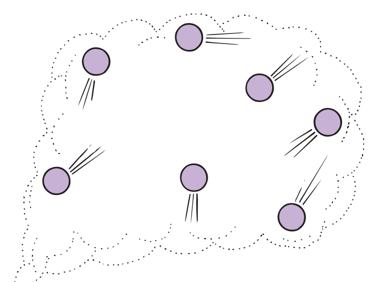
c Try to think of a reason for the difference in **a** and **b**.

6 See if you can sketch a heating curve for sodium.

1.3 The particles in solids, liquids, and gases

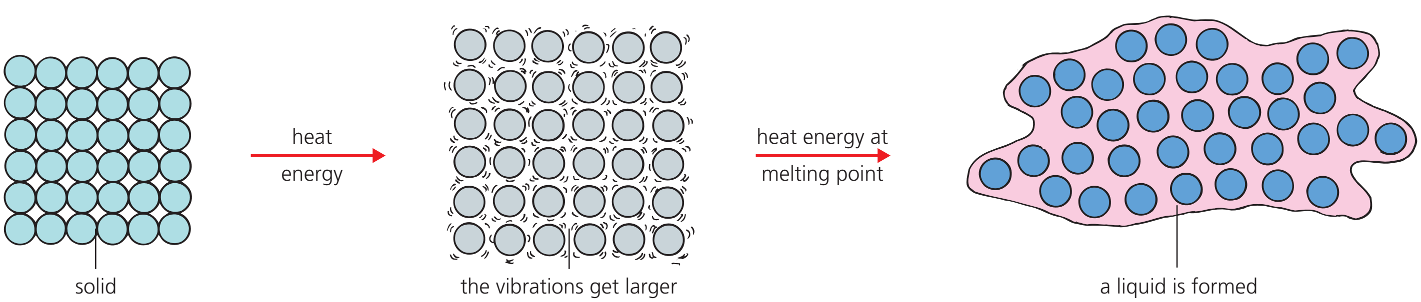
How the particles are arranged

Water can change from solid to liquid to gas. Its *particles* do not change. They are the same in each state. But their *arrangement* changes. The same is true for all substances.

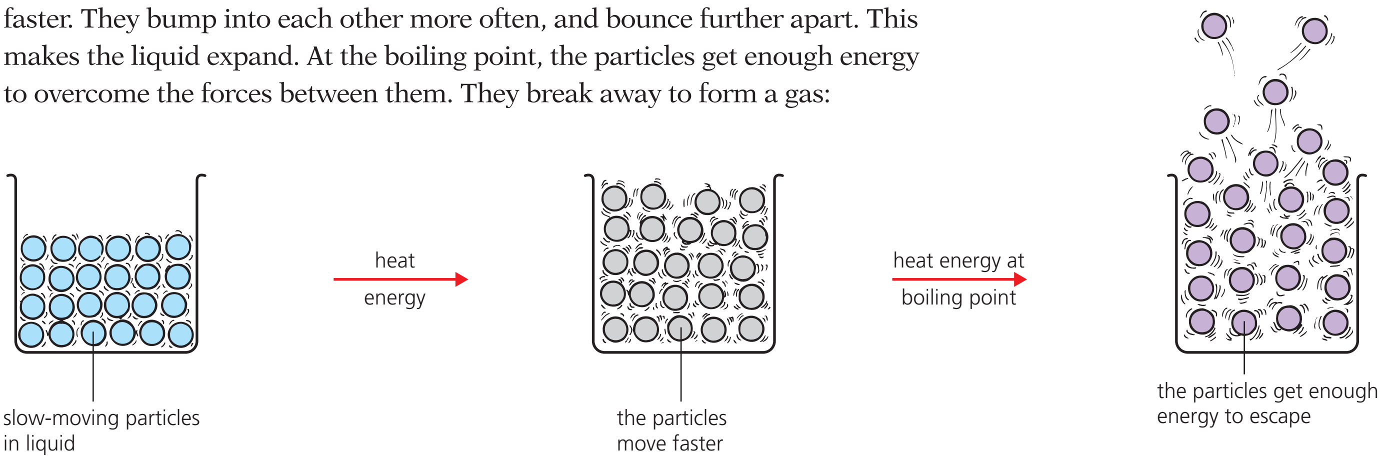
State	How the particles are arranged	Diagram of particles
Solid 	The particles in a solid are arranged in a fixed pattern or **lattice**. Strong forces hold them together. So they cannot leave their positions. The only movements they make are tiny vibrations to and fro.	
Liquid 	The particles in a liquid can move about and slide past each other. They are still close together, but not in a lattice. The forces that hold them together are weaker than in a solid.	
Gas 	The particles in a gas are far apart, and they move about very quickly. There are almost no forces holding them together. They collide with each other and bounce off in all directions.	

Changing state

Melting When a solid is heated, its particles get more energy and vibrate more. This makes the solid **expand**. At the melting point, the particles vibrate so much that they break away from their positions. The solid turns liquid.



Boiling When a liquid is heated, its particles get more energy and move faster. They bump into each other more often, and bounce further apart. This makes the liquid expand. At the boiling point, the particles get enough energy to overcome the forces between them. They break away to form a gas:



Evaporating Some particles in a liquid have more energy than others. Even well below the boiling point, some have enough energy to escape and form a gas. This is called **evaporation**. It is why puddles of rain dry up in the sun.

How much heat is needed?

The amount of heat needed to melt or boil a substance is different for every substance. That's because the particles in each substance are different, with different forces between them.

The stronger the forces, the more heat energy is needed to overcome them. So the higher the melting and boiling points will be.

Reversing the changes

You can reverse those changes again by cooling. As a gas cools, its particles lose energy and move more slowly. When they collide, they do not have enough energy to bounce away. So they stay close, and form a liquid. On further cooling, the liquid turns to a solid.

Look at this diagram for water:

on heating, the particles gain energy →

ice (solid) — **melts at 0 °C** → water (liquid) — as it warms up, some **evaporates**; the rest **boils** at **100 °C** → steam (gas)

ice ← **freezes (solidifies) at 0 °C** — water ← as you cool it below **100 °C**, the water vapour begins to **condense** or **liquify** — steam

← on cooling, the particles lose energy and move more slowly; as they get closer together the forces of attraction take over

The kinetic particle theory

Look at the key ideas you have met:

- A substance can be a solid, a liquid, or a gas, and change from one state to another.
- It has different characteristics in each state. (For example, solids do not flow.)
- The differences are due to the way its particles are arranged, and move, in each state.

Together, these ideas make up the **kinetic particle theory**.
(*Kinetic* means *about motion*.)

Q

1 Using the idea of particles, explain why:
  a you can pour liquids **b** solids expand on heating

2 Draw a diagram to show what happens to the particles, when a liquid cools to a solid.

3 Oxygen is the gas we breathe in. It can be separated from the air. It boils at –219 °C and freezes at –183 °C.
  a In which state is oxygen, at: **i** 0 °C? **ii** –200 °C?
  b How would you turn oxygen gas into solid oxygen?

1.4 A closer look at gases

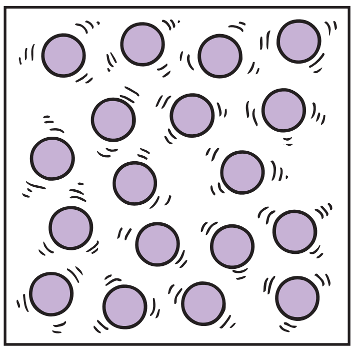
What is gas pressure?

When you blow up a balloon, you fill it with air particles. They collide with each other. They also hit the sides of the balloon, and exert **pressure** on it. This pressure keeps the balloon inflated.

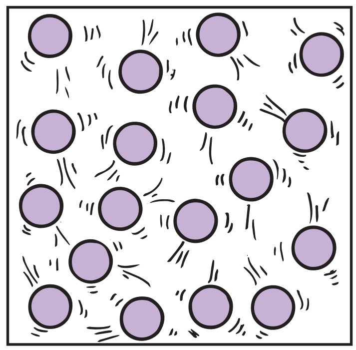
In the same way, *all* gases exert a pressure. The pressure depends on the **temperature** of the gas and the **volume** it takes up, as you'll see below.

▲ The harder you blow, the greater the pressure inside the balloon.

When you heat a gas



The particles in this gas are moving fast. They hit the walls of the container and exert pressure on them. If you now heat the gas . . .

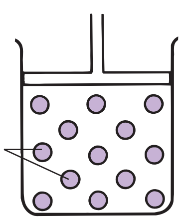


. . . the particles take in heat energy and move even faster. They hit the walls more often, and with more force. So the gas pressure increases.

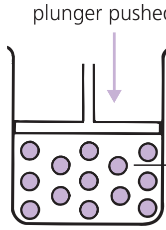
The same happens with all gases:
When you heat a gas in a closed container, its pressure increases.
That is why the pressure gets very high inside a pressure cooker.

▲ In a pressure cooker, water vapour (gas) is heated to well over 100 °C. So it is at high pressure. You must let a pressure cooker cool before you open it!

When you squeeze a gas into a smaller space



There is a lot of space between the particles in a gas. You can **compress** the gas, or force its particles closer, by pushing in the plunger …



… like this. Now the particles are in a smaller space – so they hit the walls more often. So the gas pressure increases.

The same thing is true for all gases:
When a gas is compressed into a smaller space, its pressure increases.

All gases can be compressed. If enough force is applied, the particles can be pushed so close that the gas turns into a liquid. But liquids and solids cannot be compressed, because their particles are already very close together.

▲ When you blow up a bicycle tyre, you compress air into the inner tube.

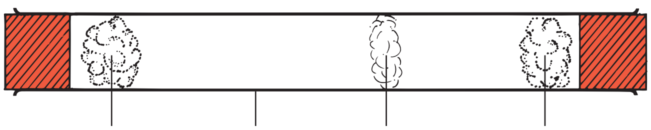
The rate of diffusion of gases

On page 7 you saw that gases **diffuse** because the particles collide with other particles, and bounce off in all directions. But gases do not all diffuse at the same rate, every time. It depends on these two factors:

1 The mass of the particles

The particles in hydrogen chloride gas are twice as heavy as those in ammonia gas. So which gas do you think will diffuse faster? Let's see:

- Cotton wool soaked in ammonia solution is put into one end of a long tube (at A below). It gives off ammonia gas.
- *At the same time*, cotton wool soaked in hydrochloric acid is put into the other end of the tube (at B). It gives off hydrogen chloride gas.
- The gases diffuse along the tube. White smoke forms where they meet:



The white smoke forms closer to B. So the ammonia particles have travelled further than the hydrogen chloride particles – which means they have travelled *faster*.

The lower the mass of its particles, the faster a gas will diffuse.

That makes sense when you think about it. When particles collide and bounce away, the lighter particles will bounce further.

The particles in the two gases above are molecules. The mass of a molecule is called its **relative molecular mass**. So we can also say:

The lower its relative molecular mass, the faster a gas will diffuse.

2 The temperature

When a gas is heated, its particles take in heat energy, and move faster. They collide with more energy, and bounce further away. So the gas diffuses faster. **The higher the temperature, the faster a gas will diffuse.**

▲ The scent of flowers travels faster in a warm room. Can you explain why?

▲ The faster a particle is moving when it hits another, the faster and further it will bounce away. Just like snooker balls!

Q

1. What causes the *pressure* in a gas?
2. Why does a balloon burst if you keep on blowing?
3. A gas is in a sealed container. How do you think the pressure will change if the container is cooled? Explain your answer.
4. A gas flows from one container into a larger one. What do you think will happen to its pressure? Draw diagrams to explain.
5. **a** Why does the scent of perfume spread?
   b Why does the scent of perfume wear off faster in warm weather than in cold?
6. Of all gases, hydrogen diffuses fastest at any given temperature. What can you tell from this?
7. Look at the glass tube above. Suppose it was warmed a little in an oven, before the experiment. Do you think that would change the result? If so, how?

Checkup on Chapter 1

Revision checklist

Core curriculum

Make sure you can …

- ☐ give two examples of evidence, from the lab, that matter is made of particles
- ☐ explain what *diffusion* is, and how it happens
- ☐ name the three states of matter, and give their physical properties (hard, fixed shape, and so on)
- ☐ describe, and sketch, the particle arrangement in each state
- ☐ describe how a substance changes state when you heat it, and explain this using the idea of particles
- ☐ explain, and use, these terms:

  melt *boil* *evaporate* *condense*
  melting point *boiling point* *freezing point*
- ☐ sketch, and label, a heating curve
- ☐ explain why a gas exerts a pressure
- ☐ explain why the pressure increases when you:
  - heat a gas
  - push it into a smaller space

Extended curriculum

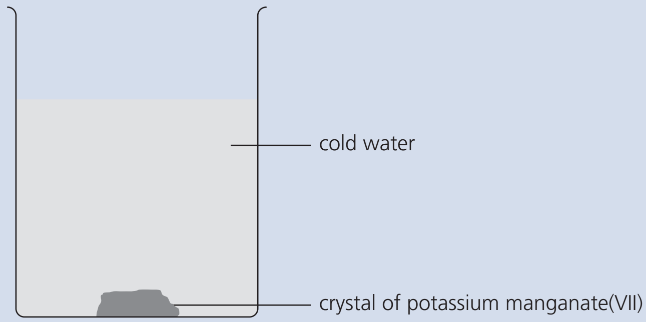
Make sure you can also …

- ☐ describe an experiment to show that a gas will diffuse faster than another gas that has heavier particles
- ☐ say how, and why, the temperature affects the rate at which a gas diffuses

Questions

Core curriculum

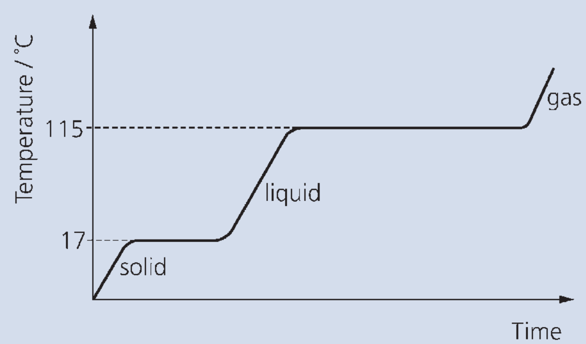
1 A large crystal of potassium manganate(VII) was placed in the bottom of a beaker of cold water, and left for several hours.



a Describe what would be seen:
i after five minutes **ii** after several hours
b Explain your answers using the idea of particles.
c Name the two processes that took place during the experiment.

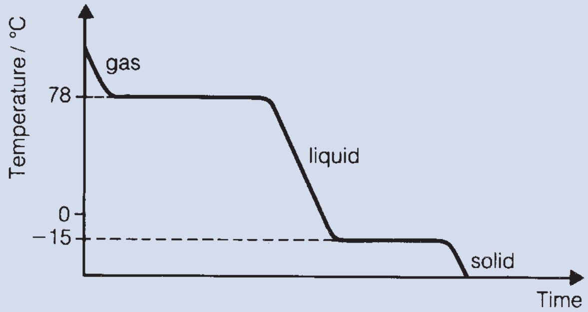
2 Use the idea of particles to explain why:
a solids have a definite shape
b liquids fill the bottom of a container
c you can't store gases in open containers
d you can't squeeze a sealed plastic syringe that is completely full of water
e a balloon expands as you blow into it.

3 Below is a heating curve for a pure substance. It shows how the temperature rises over time, when the substance is heated until it melts, then boils.



a What is the melting point of the substance?
b What happens to the temperature while the substance changes state?
c The graph shows that the substance takes longer to boil than to melt. Suggest a reason for this.
d How can you tell that the substance is not water?
f Sketch a rough heating curve for pure water.

4 A **cooling curve** is the opposite of a heating curve. It shows how the temperature of a substance changes with time, as it is cooled from a gas to a solid. Here is the cooling curve for one substance:



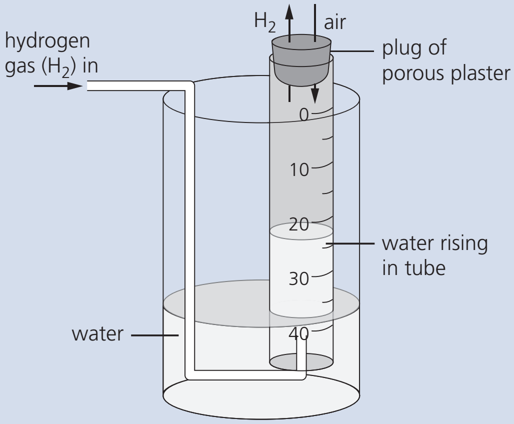
a What is the state of the substance at room temperature (20 °C)?
b Use the list of melting and boiling points on page 9 to identify the substance.
c Sketch a cooling curve for pure water.

5 Using the idea of particles explain why:
a the smell of burnt food travels through the house
b when two solids are placed on top of each other, they do not mix
c pumping up your bike tyres gives a smooth ride
d smokers can cause lung damage in other people
e heating a gas in a closed container will increase its pressure
f a liquid is used in a car's breaking system, to transfer the pressure from the brake pedal
g poisonous gases from a factory chimney can affect a large area.

6 **a** Which of these are examples of diffusion?
i a helium-filled balloon rising in air
ii a hydrogen-filled balloon deflating, due to gas passing through the skin
iii the smell of perfume from a person standing on the other side of a room
iv sucking a drink from a bottle, using a straw
v an ice lolly turning liquid when it is left out of the freezer
vi the tea in the cup changing colour when you add milk, without stirring
vii a light, coloured gas, spreading down through a gas jar
viii a blue crystal forming a blue solution, when it is left sitting in a glass of water
ix spraying paint from a spray can.
b For *one* of the examples of diffusion, draw a diagram showing the particles before and after diffusion has taken place.

Extended curriculum

7 You can measure the rate of diffusion of a gas using this apparatus. The gas enters through the thin tube:



The measuring tube is sealed at the top with a plug of porous plaster. Air and other gases can diffuse in and out through the tiny holes in the plug.

The water rises in the measuring tube if the chosen gas diffuses out through the plug faster than air diffuses in. Air is mainly nitrogen and oxygen.

a When you use hydrogen gas, the water rises in the measuring tube. Why?
b What does this tell you about the rate of diffusion of hydrogen, compared to the gases in air?
c Explain your answer to **b.** Use the term *mass*!
d The molecules in carbon dioxide are heavier than those in nitrogen and oxygen.
So what do you think will happen to the water in the measuring tube, when you use carbon dioxide? Explain your answer.

8

Gas	Formula	Relative atomic or molecular mass
methane	CH_4	16
helium	He	4
oxygen	O_2	32
nitrogen	N_2	28
chlorine	Cl_2	71

Look at the table above.
a Which two gases will mix fastest? Explain.
b Which gas will take least time to escape from a gas syringe?
c Would you expect chlorine to diffuse more slowly than the gases in air? Explain.
d An unknown gas diffuses faster than nitrogen, but more slowly than methane. What you can say about its relative molecular mass?

2.1 Mixtures, solutions, and solvents

Mixtures

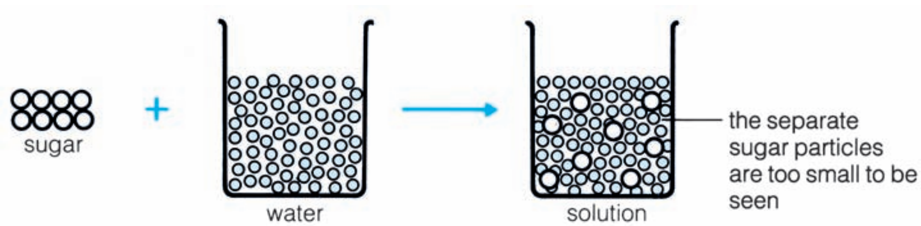
A **mixture** contains more than one substance. The substances are just mixed together, and not chemically combined. For example:

- air is a mixture of nitrogen, oxygen, and small amounts of other gases
- shampoo is a mixture of several chemicals and water.

▲ A mixture of sugar and water. This mixture is a solution.

Solutions

When you mix sugar with water, the sugar seems to disappear. That is because its particles spread all through the water particles, like this:



The sugar has **dissolved** in the water, giving a mixture called a **solution**. Sugar is the **solute**, and water is the **solvent**:

solute + solvent = solution

You can't get the sugar out again by filtering.

▲ A mixture of chalk powder and water. This is not a solution. The tiny chalk particles do not separate and spread through the water particles. They stay in clusters big enough to see. In time, most sink to the bottom.

Not everything dissolves so easily

Now think about chalk. If you mix chalk powder with water, most of the powder eventually sinks to the bottom. You can get it out again by filtering.

Why is it so different for sugar and chalk? Because their particles are very different! How easily a substance dissolves depends on the particles in it. Look at the examples in this table:

Compound	Mass (g) dissolving in 100 g of water at 25 °C
silver nitrate	241.3
calcium nitrate	102.1
sugar (glucose)	91.0
potassium nitrate	37.9
potassium sulfate	12.0
calcium hydroxide	0.113
calcium carbonate (chalk)	0.0013
silver chloride	0.0002

decreasing solubility

So silver nitrate is much more soluble than sugar – but potassium nitrate is a lot less soluble than sugar. It all depends on the particles.

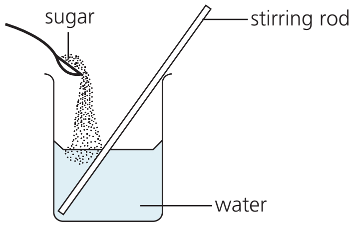
Look at calcium hydroxide. It is only very slightly or **sparingly soluble** compared with the compounds above it. Its solution is called **limewater**.

Now look at the last two substances in the table. They are usually called **insoluble** since so very little dissolves.

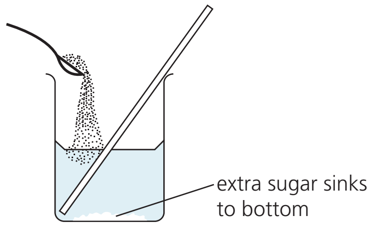
What's soluble, what's not?

- The solubility of every substance is different.
- But there are some overall patterns. For example *all* sodium compounds are soluble.
- Find out more on page 160.

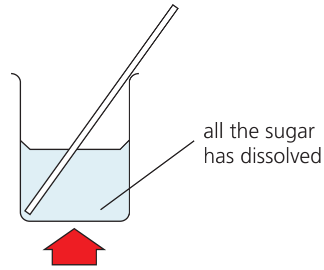
Helping a solute dissolve



Sugar dissolves quite slowly in water at room temperature. If you stir the liquid, that helps. But if you keep on adding sugar …



… eventually no more of it will dissolve, no matter how hard you stir. The extra sinks to the bottom. The solution is now **saturated**.



But look what happens if you heat the solution. The extra sugar dissolves. Add more sugar and it will dissolve too, as the temperature rises.

So sugar is **more soluble** in hot water than in cold water.

A soluble solid usually gets more soluble as the temperature rises.

A solution is called *saturated* when it can dissolve no more solute, at that temperature.

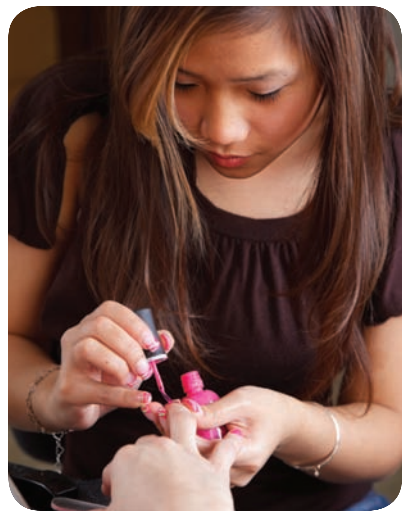
Water is not the only solvent

Water is the world's most common solvent. A solution in water is called an **aqueous solution** (from *aqua*, the Latin word for water).

But many other solvents are used in industry and about the house, to dissolve substances that are insoluble in water. For example:

Solvent	It dissolves
white spirit	gloss paint
propanone (acetone)	grease, nail polish
ethanol	glues, printing inks, the scented substances that are used in perfumes and aftershaves

All three of these solvents evaporate easily at room temperature – they are **volatile**. This means that glues and paints dry easily. Aftershave feels cool because ethanol cools the skin when it evaporates.



▲ Nail polish is insoluble in water. It can be removed later by dissolving it in propanone.

About volatile liquids

- A **volatile** liquid is one that evaporates easily.
- This is a sign that the forces between its particles are weak.
- So volatile liquids have low boiling points too. (Propanone boils at 56.5 °C.)

Q

1 Explain each term in your own words:
  a soluble **b** insoluble **c** aqueous solution

2 Look at the table on page 16.
  a Which substance in it is the most soluble?
  b About how many times more soluble is this substance than potassium sulfate, at 25 °C?
  c The substance in **a** gives a colourless solution. What will you see if you add 300 g of it to 100 g of water at 25 °C?
  d What will you see if you heat up the mixture in **c**?

3 Now turn to the table at the top of page 160.
  a Name two metals that have *no* insoluble salts.
  b Name one other group of salts that are *always* soluble.

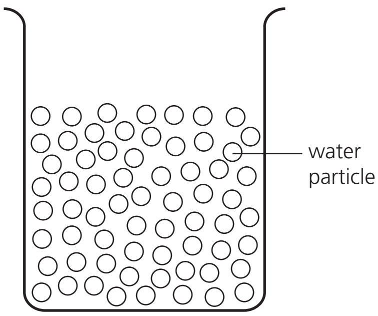
4 See if you can give three examples of:
  a solids you dissolve in water, at home
  b insoluble solids you use at home.

5 Name two solvents other than water that are used in the home. What are they used for?

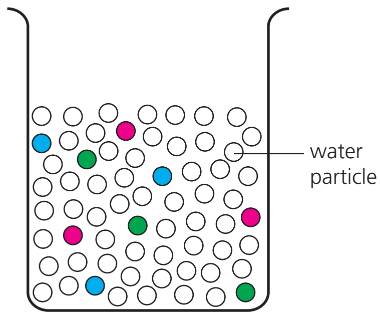
6 Many gases dissolve in water. Try to give some examples.

2.2 Pure substances and impurities

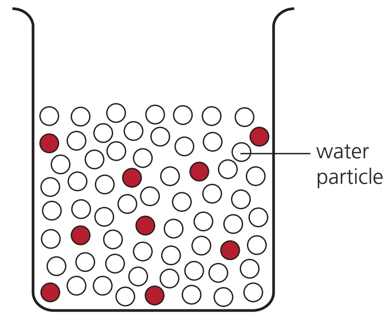
What is a pure substance?



This is water. It has only water particles in it, and nothing else. So it is 100% **pure**.



This water has particles of other substances mixed with it. So it is not pure.



This water has particles of a harmful substance in it. So it is not pure – and could make you ill.

A pure substance has no particles of any other substance mixed with it.

In real life, very few substances are 100% pure. For example tap water contains small amounts of many different particles (such as calcium ions and chloride ions). The particles in it are not usually harmful – and some are even good for you.

Distilled water is much purer than tap water, but still not 100% pure. For example it may contain particles of gases, dissolved from the air.

Does purity matter?

Often it does not matter if a substance is not pure. We wash in tap water, without thinking too much about what is in it. But sometimes purity is very important. If you are making a new medical drug, or a flavouring for food, you must make sure it contains nothing that could harm people.

An unwanted substance, mixed with the substance you want, is called an **impurity**.

▲ Baby foods and milk powder are tested in the factory, to make sure they contain no harmful impurities.

▲ Getting ready for a jab. Vaccines and medicines must be safe, and free of harmful impurities. So they are tested heavily.

How can you tell if a substance is pure?

Chemists use some complex methods to check purity. But there is one simple method *you* can use in the lab: **you can check melting and boiling points**.

- A pure substance has a definite, sharp, melting point and boiling point. These are different for each substance. You can look them up in tables.
- When a substance contains an impurity:
  - its melting point falls and its boiling point rises
  - it melts and boils over a range of temperatures, not sharply.
- The more impurity there is:
  - the bigger the change in melting and boiling points
  - the wider the temperature range over which melting and boiling occur.

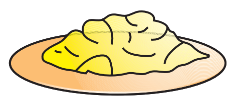
ID check!

- Every substance has a unique pair of melting and boiling points.
- So you can also use melting and boiling points to **identify** a substance.
- First, measure them. Then look up data tables to find out what the substance is.

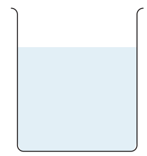
For example:

Substance	sulfur	water
Melts at (°C)	119	0
Boils at (°C)	445	100

These are the melting and boiling points for two pure substances: sulfur and water.



This sulfur sample melts sharply at 119 °C and boils at 445 °C. So it must be pure.



This water freezes around −0.5 °C and boils around 101 °C. So it is not pure.

Separation: the first step in obtaining a pure substance

When you carry out a reaction, you usually end up with a *mixture* of substances. Then you have to separate the one you want.

The table below shows some separation methods. These can give quite pure substances. For example when you filter off a solid, and rinse it well with distilled water, you remove a lot of impurity. But it is just not possible to remove every tiny particle of impurity, in the school lab.

Method of separation	Used to separate...
filtration	a solid from a liquid
crystallisation	a solute from its solution
evaporation	a solute from its solution
simple distillation	a solvent from a solution
fractional distillation	liquids from each other
paper chromatography	different substances from a solution

There is more about these methods in the next three units.

▲ At the end of this reaction, the beaker may contain several products, plus reactants that have not reacted. Separating them can be a challenge!

Q

1 What does *a pure substance* mean?

2 You mix instant coffee with water, to make a cup of coffee. Is the coffee an *impurity*? Explain.

3 Explain why melting and boiling points can be used as a way to check purity.

4 Could there be impurities in a gas? Explain.

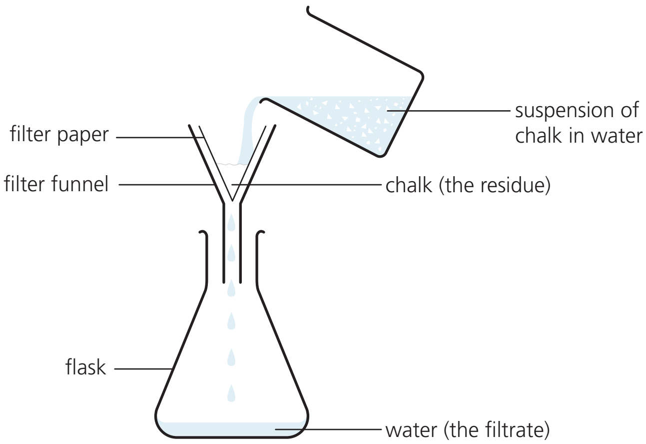
2.3 Separation methods (part I)

Separating a solid from a liquid

Which method should you use? It depends on whether the solid is dissolved, and how its solubility changes with temperature.

1 By filtering

For example, chalk is insoluble in water. So it is easy to separate by filtering. The chalk is trapped in the filter paper, while the water passes through. The trapped solid is called the **residue**. The water is the **filtrate**.



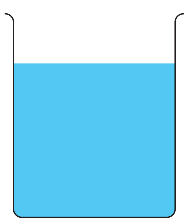
▲ Filtering in the kitchen …

Saturated solutions

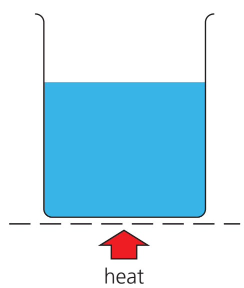
- Remember, most solutes get *more* soluble as the temperature rises – so *less* soluble as it falls!
- A saturated solution can hold no more solute, at that temperature.

2 By crystallisation

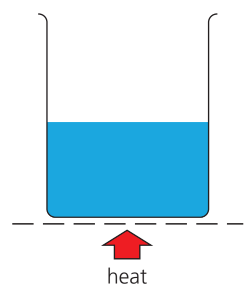
You can obtain many solids from their solutions by letting crystals form. The process is called **crystallisation**. It works because soluble solids tend to be *less soluble at lower temperatures*. For example:



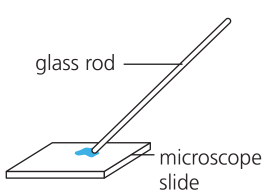
1 This is a solution of copper(II) sulfate in water. You want to obtain solid copper(II) sulfate from it.



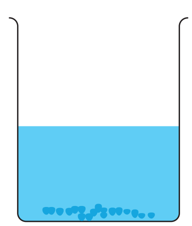
2 So you heat the solution to evaporate some of the water. It becomes more concentrated.



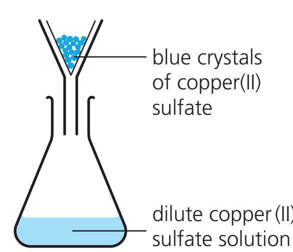
3 Eventually the solution becomes **saturated**. If you cool it now, crystals will start to form.



4 Check that it is ready by placing a drop on a microscope slide. Crystals will form quickly on the cool glass.



5 Leave the solution to cool. Crystals start to form in it, as the temperature falls.

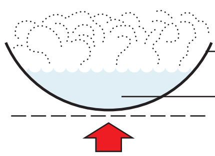


6 Remove the crystals by filtering. Then rinse them with distilled water and dry them with filter paper.

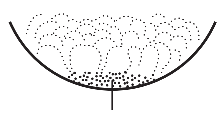
◀ Making a living from crystallisation. Seawater is led into shallow ponds. The water evaporates in the sun. He collects the sea salt, and sells it.

3 By evaporating all the solvent

For some substances, the solubility changes very little as the temperature falls. So crystallisation does not work for these. Salt is an example.



To obtain salt from an aqueous solution, you need to keep heating the solution, to evaporate the water.



When there is only a little water left, the salt will start to appear. Heat carefully until it is dry.

▲ Evaporating the water from a solution of salt in water.

Separating a mixture of two solids

To separate two solids, you could choose a solvent that will dissolve just one of them.

For example, water dissolves salt but not sand. So you could separate a mixture of salt and sand like this:

1 Add water to the mixture, and stir. The salt dissolves.
2 Filter the mixture. The sand is trapped in the filter paper, but the salt solution passes through.
3 Rinse the sand with water, and dry it in an oven.
4 Evaporate the water from the salt solution, to give dry salt.

Water could *not* be used to separate salt and sugar, because it dissolves both. But you could use ethanol, which dissolves sugar but not salt. Ethanol is flammable, so should be evaporated over a water bath, as shown here.

▲ Evaporating the ethanol from a solution of sugar in ethanol, over a water bath.

Q

1 What does this term mean? Give an example.
  a filtrate **b** residue

2 You have a solution of sugar in water. You want to obtain the sugar from it.
  a Explain why filtering will not work.
  b Which method will you use instead?

3 Describe how you would crystallise potassium nitrate from its aqueous solution.

4 How would you separate salt and sugar? Mention any special safety precaution you would take.

5 Now see if you can think of a way to get clean sand from a mixture of sand and little bits of iron wire.

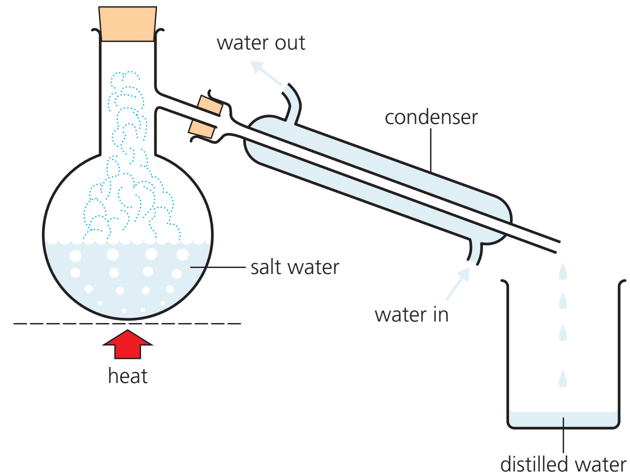
2.4 Separation methods (part II)

Simple distillation

This is a way to obtain the *solvent* from a solution. The apparatus is shown on the right. It could be used to obtain water from salt water, for example. Like this:

1 Heat the solution in the flask. As it boils, water vapour rises into the condenser, leaving salt behind.
2 The condenser is cold, so the vapour condenses to water in it.
3 The water drips into the beaker. It is called **distilled water**. It is almost pure.

You could get drinking water from seawater, in this way. Many countries in the Middle East obtain drinking water by distilling seawater in giant distillation plants.

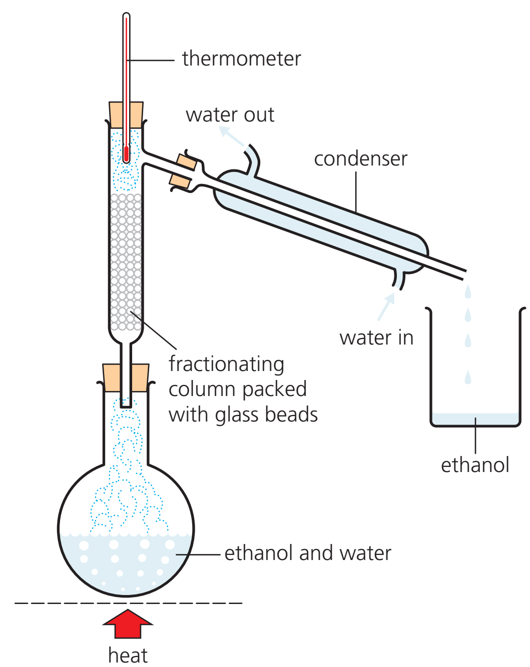


Fractional distillation

This is used to separate *a mixture of liquids* from each other. It makes use of their different boiling points. You could use it to separate a mixture of ethanol and water, for example. The apparatus is shown on the right.

These are the steps:

1 Heat the mixture in the flask. At about 78 °C, the ethanol begins to boil. Some water evaporates too. So a mixture of ethanol and water vapours rises up the column.
2 The vapours condense on the glass beads in the column, making them hot.
3 When the beads reach about 78 °C, ethanol vapour no longer condenses on them. Only the water vapour does. So water drips back into the flask. The ethanol vapour goes into the condenser.
4 There it condenses. Pure liquid ethanol drips into the beaker.
5 Eventually, the thermometer reading rises above 78 °C – a sign that all the ethanol has gone. So you can stop heating.



Fractional distillation in industry

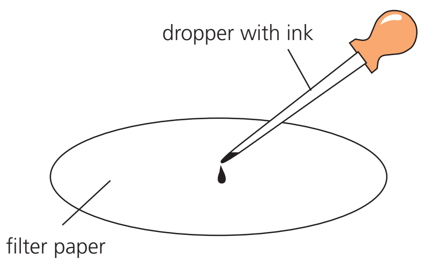
Fractional distillation is very important in industry. It is used:

- in the petroleum industry, to **refine** crude oil into petrol and other groups of compounds. The oil is heated and the vapours rise to different heights, up a tall steel fractionating column. See page 247.
- in producing **ethanol**. The ethanol is made by fermentation, using sugar cane or other plant material. It is separated from the fermented mixture by fractional distillation. Ethanol is used as a solvent, and as car fuel. See page 256.
- to separate the gases in **air**. The air is cooled until it is liquid, then warmed up. The gases boil off one by one. See page 212.

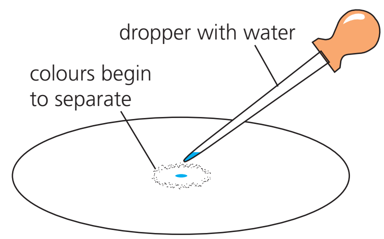
▲ A petroleum refinery. It produces petrol and many other useful substances, with the help of fractional distillation.

Paper chromatography

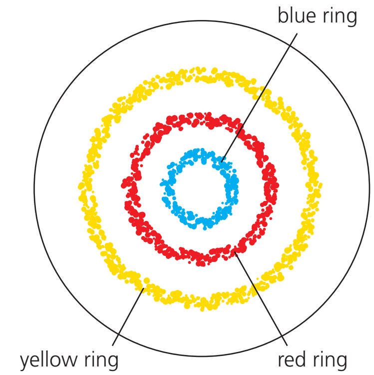
This method can be used to separate a mixture of substances.
For example, you could use it to find out how many different dyes there are in black ink:



1 Place a drop of black ink in the centre of some filter paper. Let it dry. Then add three or four more drops on the same spot, in the same way.



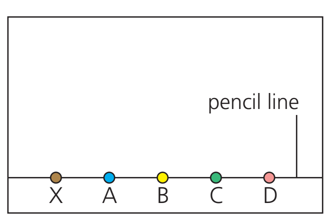
2 Now drip water onto the ink spot, one drop at a time. The ink slowly spreads out and separates into rings of different colours.



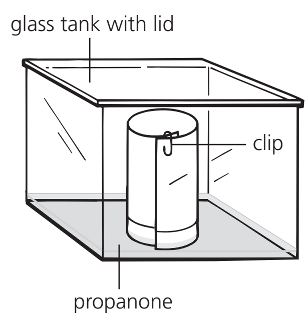
3 Suppose there are three rings: yellow, red and blue. This shows that the ink contains three dyes, coloured yellow, red and blue.

The dyes in the ink have different solubilities in water. So they travel across the paper at different rates. (The most soluble one travels fastest.) That is why they separate into rings. The filter paper with the coloured rings is called a **chromatogram**. (*Chroma* means *colour*.)

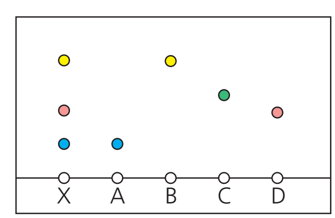
Paper chromotography can also be used to **identify** substances. For example, mixture **X** is thought to contain substances **A**, **B**, **C**, and **D**, which are all soluble in propanone. You could check the mixture like this:



1 Prepare concentrated solutions of **X**, **A**, **B**, **C**, and **D**, in propanone. Place a spot of each along a line, on chromatography paper. Label them.



2 Stand the paper in a little propanone, in a covered glass tank. The solvent rises up the paper. When it's near the top, remove the paper.



3 **X** has separated into three spots. Two are at the same height as **A** and **B**, so **X** must contain substances **A** and **B**. Does it also contain **C** and **D**?

Note that you must use a pencil to draw the line on the chromatography paper. If you use a biro or felt-tipped pen, the ink will run.

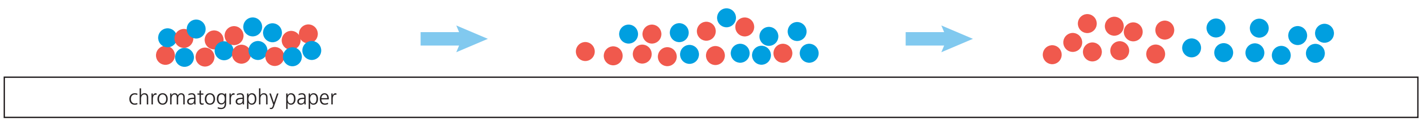
Q

1. How would you obtain pure water from seawater? Draw the apparatus, and explain how the method works.
2. Why are *condensers* called that? What is the cold water for?
3. You would not use *exactly* the same apparatus you described in **1**, to separate ethanol and water. Why not?
4. Explain how fractional distillation works.
5. In the last chromatogram above, how can you tell that **X** does *not* contain substance **C**?
6. Look at the first chromatogram above. Can you think of a way to separate the coloured substances from the paper?

2.5 More about paper chromatography

How paper chromatography works

Paper chromatography depends on how the substances in a mixture interact with the chromatography paper and the solvent.



1 These coloured dots represent a mixture of two substances. The mixture is dissolved in a suitable solvent.

2 The two substances travel over the paper at different speeds, because of their different solubilities in the solvent, and attraction to the paper.

3 Eventually they get completely separated from each other. Now you can identify the substances – and even collect them if you wish.

The more soluble a substance is in the solvent, the further it will travel up the chromatography paper.

Making use of paper chromatography

You can use paper chromatography to:

- identify a substance
- separate mixtures of substances
- purify a substance, by separating it from its impurities.

Example: Identify substances in a colourless mixture

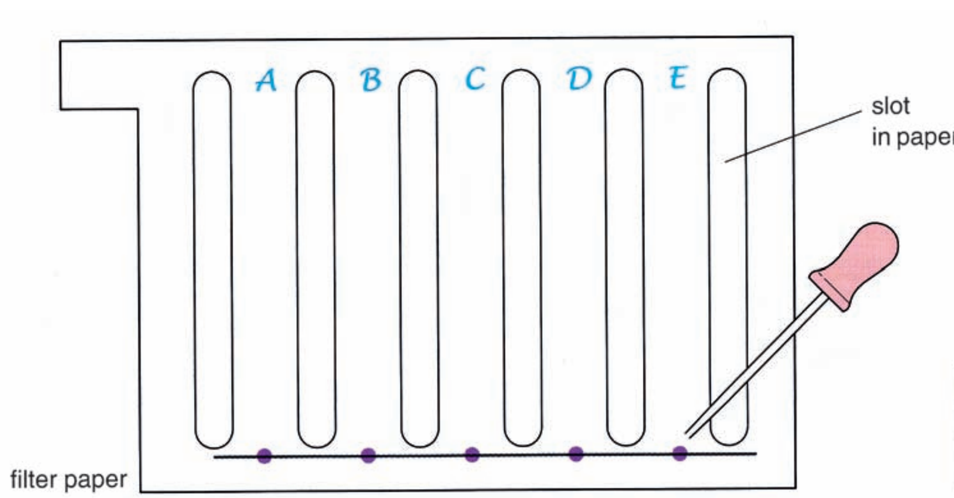
On page 23, paper chromatography was used to identify *coloured* substances. Now for a bigger challenge!

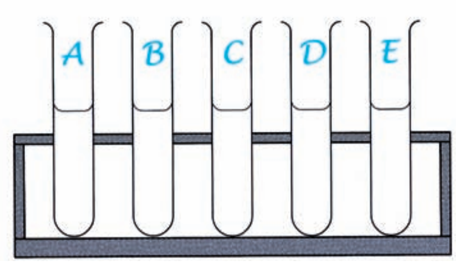
Test-tubes **A–E** on the right below contain five *colourless* solutions of amino acids, dissolved in water. The solution in **A** contains several amino acids. The other solutions contain just one each.

Your task is to identify *all* the amino acids in **A–E**.

1 Place a spot of each solution along a line drawn in pencil on slotted chromatography paper, as shown below. (The purpose of the slots is to keep the samples separate.)
Label each spot in pencil at the *top* of the paper.

▲ Amino acids coming up! When you digest food, the proteins in it are broken down to amino acids. Your body needs 20 different amino acids to stay healthy.





▲ The five mystery solutions.

2 Place a suitable solvent in the bottom of a beaker. (For amino acids, a mixture of water, ethanoic acid and butanol is suitable.)

3 Roll the chromatography paper into a cylinder and place it in the beaker. Cover the beaker.

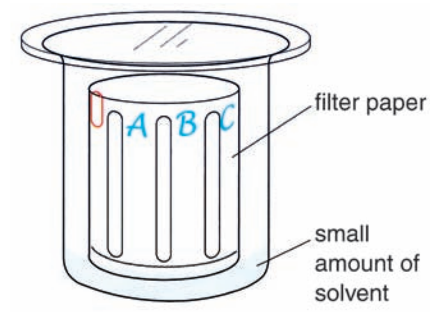
4 The solvent rises up the paper. When it has almost reached the top, remove the paper.

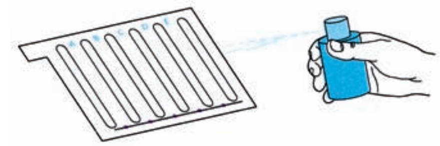
5 Mark a line in pencil on it, to show where the solvent reached. (You can't tell where the amino acids are, because they are colourless.)

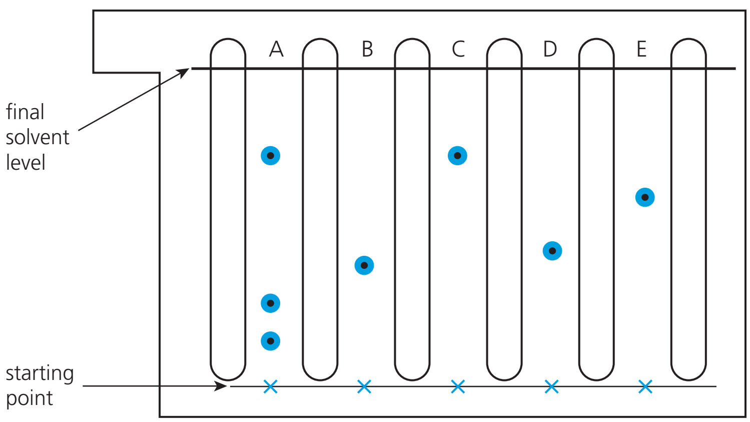
6 Put the paper in an oven to dry out.

7 Next spray it with a **locating agent** to make the amino acids show up. **Ninhydrin** is a good choice. (Use it in a fume cupboard!) After spraying, heat the paper in the oven for 10 minutes. The spots turn purple. So now you have a proper chromatogram.

8 Mark a pencil dot at the centre of each spot. Measure from the base line to each dot, and to the line showing the final solvent level.







9 Now work out the R_f value for each amino acid. Like this:

$$R_f \text{ value} = \frac{\text{distance moved by amino acid}}{\text{distance moved by solvent}}$$

10 Finally, look up R_f tables to **identify** the amino acids. Part of an R_f table for the solvent you used is shown on the right. The method works because: **the R_f value of a compound is always the same for a given solvent, under the same conditions**.

***R_f* values for amino acids**
(for water/butanol/ethanoic acid as solvent)

amino acid	R_f value
cysteine	0.08
lysine	0.14
glycine	0.26
serine	0.27
alanine	0.38
proline	0.43
valine	0.60
leucine	0.73

Q

1 Explain in your own words how paper chromatography works.

2 a What do you think a *locating agent* is?
b Why would you need one, in an experiment to separate amino acids by chromatography?

3 What makes R_f values so useful?

4 For the chromatogram above:
a Were any of the amino acids in **B–E** also present in **A**? How can you tell at a glance?
b Using a ruler, work out the R_f values for the amino acids in **A–E**.
c Now use the R_f table above to name them.

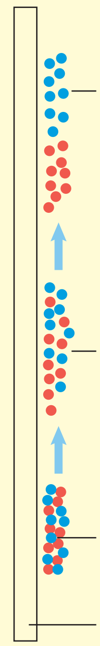
The chromatography detectives

▲ After a crime, the forensic detectives move in, looking for fingerprints and other samples they can use in evidence.

The key ideas in chromatography.

Much of chromatography is detective work. You have already met paper chromatography. There are many other kinds too. But the key ideas are always the same.

- You need two phases:
  - a non-moving or **stationary** phase, such as filter paper
  - a moving or **mobile** phase. This consists of the mixture you want to separate, dissolved in a solvent.
- The substances in the mixture separate because each has different levels of attraction to the solvent and the stationary phase. Look at the diagram on the right.
- You can then identify each separated substance. Depending on the technique you use, you can also collect them.



▲ How chromatography works.

Ringing the changes

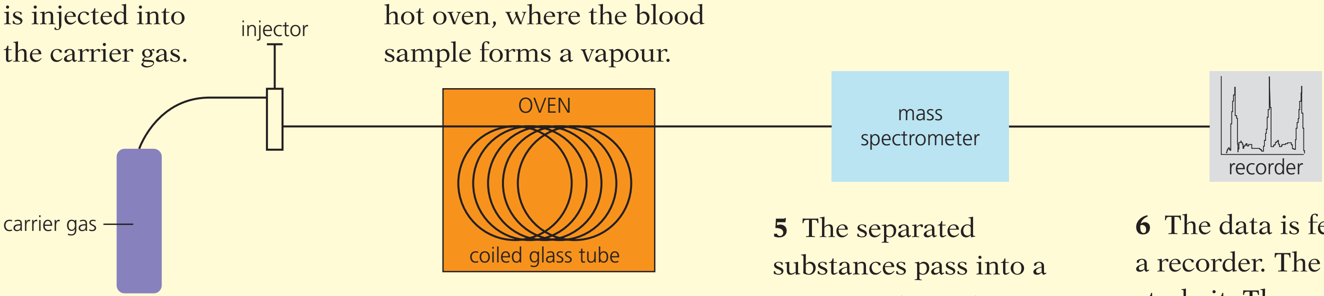
Although those key ideas are always the same, the techniques used for chromatography can be quite different. For example:

The stationary phase could be ...	The mobile phase could be ...	To analyse the substances, you could ...
• paper, as in paper chromatography • a thin coat of an adsorbent substance on a glass plate, or inside a tube • plastic beads packed into a tube	• a mixture of substances dissolved in a liquid, as in paper chromatography • a mixture of gases, carried in an **inert** (unreactive) gas; this is called **gas chromatography**	• study the coloured spots on the chromatogram, as in paper chromatography • pass them through a machine that will help you analyse them

Chromatography and crime detection

Chromatography is widely used in crime detection. For example it is used to analyse samples of fibre from crime scenes, check people's blood for traces of illegal drugs, and examine clothing for traces of explosives.

This shows how a blood sample could be analysed, for traces of illegal drugs, or a poison, using gas chromatography:



1 The carrier gas is fed in. It could be helium or nitrogen, for example.

2 A sample of blood is injected into the carrier gas.

3 The mixture goes into a hot oven, where the blood sample forms a vapour.

4 The vapour moves over the stationary phase: an adsorbent substance lining a coiled glass tube.

5 The separated substances pass into a mass spectrometer, where they are analysed.

6 The data is fed into a recorder. The police study it. They might make an arrest …

Other uses

Chromatography can be used on a small scale in the lab, or on a very large scale in industry. For example it is used on a small scale to:

- identify substances (such as amino acids, on page 277)
- check the purity of substances
- help in crime detection (as above)
- identify pollutants in air, or in samples of river water.

It is used on a large scale to:

- separate pure substances (for example for making medical drugs or food flavourings) from tanks of reaction mixtures, in factories
- separate individual compounds from the groups of compounds (fractions) obtained in refining petroleum.

So chromatography is a really powerful and versatile tool.

▲ Injecting a sample into the carrier gas, at the start of gas chromatography.

◄ Collecting water samples, to analyse for pollutants. The factories that produce them could then be identified – and fined.

Checkup on Chapter 2

Revision checklist

Core curriculum

Make sure you can …

- ☐ define and use these terms:
  mixture *solute* *solvent*
  solution *aqueous solution*
- ☐ give at least three examples of solvents
- ☐ state that most solids become more soluble as the temperature of the solvent rises
- ☐ explain what these terms mean:
  pure substance *impurity*
- ☐ give examples of where purity is very important
- ☐ say how melting and boiling points change, when an impurity is present
- ☐ decide whether a substance is pure, from melting and boiling point data
- ☐ describe these methods for separating mixtures, and sketch and label the apparatus:
  filtration
  crystallisation
  evaporation to dryness
  simple distillation
  fractional distillation
  paper chromatography
- ☐ explain why each of those separation methods works
- ☐ say which method you would choose for a given mixture, and why
- ☐ identify the coloured substances present in a mixture, using chromatography

Extended curriculum

Make sure you can also …

- ☐ explain what a *locating agent* is
- ☐ describe how to carry out chromatography, to identify colourless substances
- ☐ define *R_f value*
- ☐ identify the substances in a mixture, given a chromatogram and a table of R_f values.

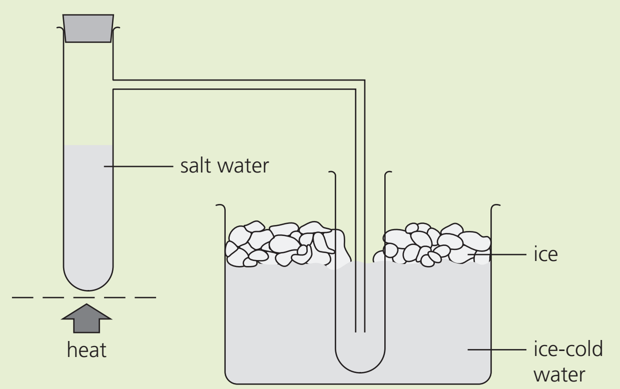
Questions

Core curriculum

1 This question is about ways to separate and purify substances. Match each term on the left with the correct description on the right.

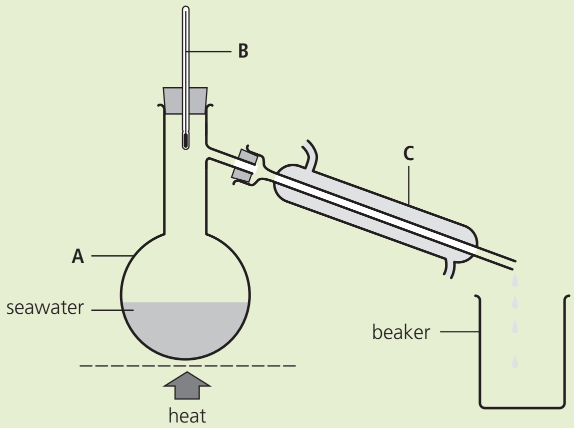
A	evaporation	**i**	a solid appears as the solution cools
B	condensing	**ii**	used to separate a mixture of two liquids
C	filtering	**iii**	the solvent is removed as a gas
D	crystallising	**iv**	this method allows you to recycle a solvent
E	distillation	**v**	a gas changes to a liquid, on cooling
F	fractional distillation	**vi**	separates an insoluble substance from a liquid

2 This apparatus can be used to obtain pure water from salt water.



a What is the purpose of the ice-cold water?
b The glass arm must reach far down into the second test-tube. Why?
c Where in the apparatus does this take place?
  i evaporation
  ii condensation
d What is this separation method called?
e What will remain in the first test-tube, at the end of the experiment?

3 Seawater can be purified using this apparatus:



a **i** What is the maximum temperature recorded on the thermometer, during the distillation?

ii How does this compare to the boiling point of the seawater?

b In which piece of apparatus does evaporation take place? Give its name.

c **i** Which is the condenser, A, B, or C?

ii Where does the supply of cold water enter?

d Distillation is used rather than filtration, to purify seawater for drinking. Why?

4 Gypsum is insoluble in water. You are asked to purify a sample of gypsum that is contaminated with a soluble salt.

a Which of these pieces of apparatus will you use?

Bunsen burner	filter funnel	tripod
distillation flask	conical flask	pipette
thermometer	condenser	gauze
stirring rod	filter paper	beaker

b Write step-by-step instructions for the procedure.

5 Argon, oxygen, and nitrogen are obtained from air by fractional distillation. Liquid air, at $-250\,°C$, is warmed up, and the gases are collected one by one.

a Is liquid air a mixture, or a pure substance?

b Explain why fractional distillation is used, rather than simple distillation.

c During the distillation, nitrogen gas is obtained first, then argon and oxygen. What can you say about the boiling points of these three gases?

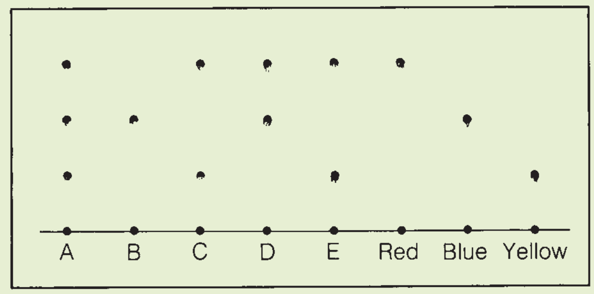
6 A mixture of salt and sugar has to be separated, using the solvent ethanol.

a Draw a diagram to show how you will separate the salt.

b How could you obtain sugar crystals from the sugar solution, *without* losing the ethanol?

c Draw a diagram of the apparatus for **b**.

7 In a chromatography experiment, eight coloured substances were spotted onto a piece of filter paper. Three were the basic colours red, blue, and yellow. The others were unknown substances, labelled A–E. This shows the resulting chromatogram:



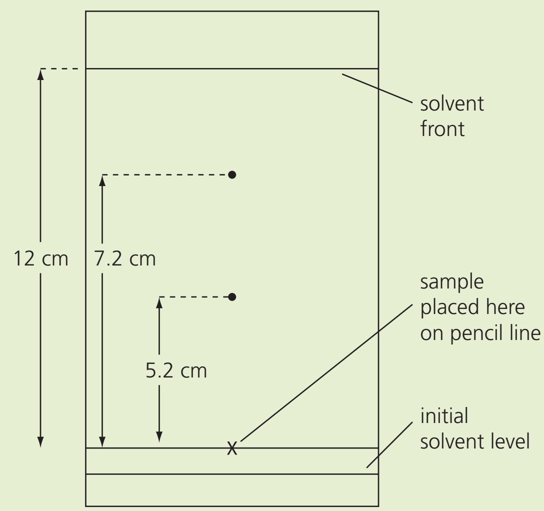
a Which one of substances A–E contains only one basic colour?

b Which contains all three basic colours?

c The solvent was propanone. Which of the three basic colours is the most soluble in propanone?

Extended curriculum

8 The diagram below shows a chromatogram for a mixture of amino acids.



The solvent was a mixture of water, butanol, and ethanoic acid.

a Using the table of R_f values on page 25, identify the two amino acids.

b Which of them is less soluble in the solvent?

c How will the R_f values change if the solvent travels only 6 cm?

9 You have three colourless solutions. Each contains an amino acid you must identify.
Explain how to do this using chromatography.
Use the terms R_f and *locating agent* in your answer, and show that you understand what they mean.