

Elements, compounds and mixtures, and separation techniques

These notes cover how to classify substances, write equations, test purity and separate mixtures, in the order of the O Level 5070 and IGCSE 0620 syllabuses.

1. Atoms, elements, compounds and mixtures

1.1 Atoms and molecules

All matter is made of tiny particles. The three kinds of particle you meet in this course are atoms, molecules and ions.

Atom: the smallest particle of an element that can take part in a chemical reaction.

Molecule: a group of two or more atoms chemically bonded together.

Ions are charged atoms or groups of atoms, such as Na^+ and Cl^- ; ionic compounds are made of ions, not molecules.

1.2 Elements

Element: a substance that cannot be broken down into anything simpler by chemical methods. An element contains only one type of atom.

Each element has a symbol of one or two letters. The first letter is always a capital and the second is always lower case: Co is cobalt, but CO is carbon monoxide, a compound of carbon and oxygen.

Some elements exist as single atoms (the noble gases, such as He and Ar). Some exist as diatomic molecules: H_2 , N_2 , O_2 , F_2 , Cl_2 , Br_2 and I_2 . Metals and giant covalent elements such as carbon (diamond and graphite) are written simply with their symbol in equations, for example Fe or C.

1.3 Compounds

Compound: a substance made of two or more different elements chemically combined in a fixed proportion.

The key words are "chemically combined" and "fixed proportion". Water is always H_2O : two hydrogen atoms to every oxygen atom, wherever the water comes from. Because the elements are bonded, a compound:

- has a fixed composition, shown by its formula;
- has properties that are different from those of the elements in it (sodium is a reactive metal and chlorine is a toxic green gas, but sodium chloride is a harmless white solid that we eat);
- can only be separated into its elements by a chemical reaction, such as electrolysis or reduction, not by a physical method such as filtration.



1.4 Mixtures

Mixture: two or more substances that are present together but are not chemically combined.

Air is a mixture of nitrogen, oxygen, argon, carbon dioxide, water vapour and other gases. In a mixture:

- the composition can vary (you can make salt water with a little salt or a lot);
- each substance keeps its own properties (iron filings in a mixture with sulfur are still attracted to a magnet);
- the components can be separated by physical methods such as filtration, distillation or chromatography.

1.5 Comparing compounds and mixtures

Example: a mixture of iron filings and sulfur can be separated with a magnet. Heated, they react to form the compound iron(II) sulfide, FeS, and the iron can no longer be pulled out.

Feature	Compound	Mixture
Composition	Fixed, given by the formula	Variable
Properties	Different from those of its elements	Each component keeps its own properties
Separation	Only by chemical reactions	By physical methods
Energy change on forming	Usually, heat is given out or taken in	Usually none
Melting and boiling point	Sharp, fixed values	Melts or boils over a range of temperatures

1.6 Particle diagrams

To classify particle diagrams:

- All particles identical, each a single circle or identical circles joined: **element**.
- All particles identical, each made of different circles joined together: **compound**.
- Two or more different kinds of particle in the box: **mixture**.

Worked example: classifying substances

Classify each of the following as an element, a compound or a mixture: (a) brass, (b) carbon dioxide, (c) mercury.

(a) Brass is an alloy of copper and zinc. The proportions can vary and the metals are not chemically combined, so it is a **mixture**.

(b) Carbon dioxide, CO₂, contains carbon and oxygen chemically combined in a fixed ratio, so it is a **compound**.

(c) Mercury, Hg, contains only one type of atom, so it is an **element**.

2. Physical and chemical changes

2.1 Physical change

In a physical change no new substance is formed. The particles are rearranged or move differently, but they are the same particles before and after. Examples are melting, boiling and dissolving. Physical changes are usually easy to reverse: freeze water and you can melt it again; dissolve salt and you can get it back by evaporating the water.

2.2 Chemical change

In a chemical change (a chemical reaction) one or more new substances are formed. Atoms are rearranged into new combinations: bonds are broken and new bonds are made. Signs that a chemical change has happened include:

- a colour change that is not simply dilution;
- a gas given off (effervescence);
- a precipitate (insoluble solid) forming when two solutions are mixed;
- a temperature change, or light or sound given out.

None of these signs is proof on its own: boiling water gives off a gas but is a physical change.

Exam tip: when asked "Is this a physical or a chemical change? Explain your answer," always name the new substance formed, or say clearly that no new substance is formed. "Because it changes colour" will not score the mark on its own.

3. Word and symbol equations

3.1 Word equations

A word equation names the reactants on the left and the products on the right, joined by an arrow that means "react to form".

magnesium + oxygen → magnesium oxide

hydrochloric acid + sodium hydroxide → sodium chloride + water

3.2 Symbol equations and balancing

A symbol equation uses formulae. Atoms are not created or destroyed in a reaction, so the number of each type of atom must be the same on both sides. This is the law of conservation of mass. You balance an equation by placing numbers (coefficients) in front of formulae. You must never change a formula itself, because that would change the substance.

Worked example: balancing an equation

Write a balanced symbol equation for the burning of magnesium in oxygen.

Step 1, unbalanced: $\text{Mg} + \text{O}_2 \rightarrow \text{MgO}$

Step 2, count atoms: left has 1 Mg and 2 O; right has 1 Mg and 1 O. Oxygen is unbalanced.

Step 3, put 2 in front of MgO: $\text{Mg} + \text{O}_2 \rightarrow 2\text{MgO}$. Now there are 2 O on each side, but 2 Mg on the right and 1 on the left.

Step 4, put 2 in front of Mg: $2\text{Mg} + \text{O}_2 \rightarrow 2\text{MgO}$.

Check: left 2 Mg, 2 O; right 2 Mg, 2 O. Balanced.

3.3 State symbols

State symbols are written after each formula in brackets:

- (s) solid
- (l) liquid
- (g) gas
- (aq) aqueous, meaning dissolved in water

Example: $2\text{Mg(s)} + \text{O}_2\text{(g)} \rightarrow 2\text{MgO(s)}$

Example: $\text{Zn(s)} + \text{H}_2\text{SO}_4\text{(aq)} \rightarrow \text{ZnSO}_4\text{(aq)} + \text{H}_2\text{(g)}$

Take care to use (l) for a pure liquid such as water or ethanol, and (aq) for a solution. Hydrochloric acid is HCl(aq) , not HCl(l) .

4. Purity

4.1 What "pure" means in chemistry

Pure substance: a single element or a single compound, not mixed with any other substance.

In chemistry, orange juice is not pure: it is a mixture. Purity matters for medicines and foods, where impurities may be harmful, and in manufacturing.

4.2 Melting point and boiling point as tests of purity

A pure substance melts at a single, sharp, fixed temperature and boils at a single, fixed temperature (at a given pressure). Pure water, for example, melts at 0 °C and boils at 100 °C at standard atmospheric pressure.

Impurities change these values:

- an impurity **lowers** the melting point and makes the solid melt **over a range** of temperatures instead of at one sharp temperature;
- an impurity usually **raises** the boiling point, and the liquid boils over a range of temperatures.

Worked example: interpreting melting point data

A student makes a sample of aspirin. Pure aspirin melts at about 135 °C. The student's sample begins to melt at 128 °C and has completely melted at 132 °C. Is the sample pure? Explain.

The sample is not pure. It melts over a range of 4 °C (128 to 132 °C) rather than at one sharp temperature, and it melts below the melting point of pure aspirin. Both effects are caused by impurities.

4.3 Heating and cooling curves

On a heating curve a pure substance shows flat sections at its melting and boiling points, because energy is used to overcome the forces between particles. An impure substance gives a sloping section

instead.

4.4 Chromatography as a test of purity

Chromatography (section 5.5) also tests purity. A pure substance gives a single spot on a chromatogram. A mixture usually gives two or more spots.

5. Separation methods

Because the components of a mixture are not chemically combined, they can be separated using differences in their physical properties: particle size, solubility, boiling point, or how strongly they are attracted to the paper in chromatography.

5.1 Filtration

Used to separate: an insoluble solid from a liquid (or from a solution).

Method: fold a filter paper into a cone and place it in a filter funnel over a conical flask or beaker. Pour the mixture into the filter paper. The liquid passes through the tiny holes in the paper and is collected as the **filtrate**. The solid particles are too large to pass through and stay in the paper as the **residue**.

Example: separating sand from salt water. The sand is the residue; the salt solution is the filtrate.

Learn these words:

Filtrate: the liquid or solution that passes through the filter paper.

Residue: the solid left behind in the filter paper.

5.2 Evaporation and crystallisation

Used to separate: a dissolved solid (solute) from its solution.

Evaporation to dryness is quick but gives a powder, and some salts decompose on strong heating.

Crystallisation gives pure, well-shaped crystals:

1. Heat the solution in an evaporating basin to evaporate some of the water, until the solution is saturated (close to the point where no more solid can stay dissolved).
2. Test for this point by dipping a cold glass rod into the solution and lifting it out: if small crystals form on the rod as it cools, the solution is ready. This is called the crystallisation point.
3. Leave the solution to cool. The solubility of most solids falls as temperature falls, so crystals form.
4. Filter off the crystals, wash them with a small amount of cold distilled water, and dry them by pressing between filter papers or leaving them in a warm place.

Washing with **cold** water and only a **small** amount keeps the loss of crystals low, because fewer crystals dissolve. Crystallisation is used to make hydrated salts such as copper(II) sulfate crystals, $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$, which would lose their water of crystallisation if evaporated to dryness.

Key definitions:

Solute: the substance that dissolves.

Solvent: the liquid in which the solute dissolves.

Solution: the mixture formed when a solute dissolves in a solvent.

Saturated solution: a solution containing the maximum amount of solute that can dissolve at that temperature.

5.3 Simple distillation

Used to separate: a solvent from a solution, when you want to keep the solvent. For example, obtaining pure water from sea water or from copper(II) sulfate solution.

Apparatus: a distillation flask (or round-bottomed flask) heated from below, a thermometer with its bulb level with the side arm, a Liebig condenser with cold water entering at the bottom (so the jacket stays full and cooling is efficient) and leaving at the top, and a receiver (beaker or conical flask) to collect the distillate. Anti-bumping granules are added to the flask so the liquid boils smoothly.

How it works:

1. The solution is heated. The solvent boils and its vapour rises, leaving the dissolved solid behind in the flask.
2. The vapour passes into the condenser, where it is cooled by the cold water jacket and condenses back to a liquid.
3. The pure liquid, the **distillate**, drips into the receiver.

5.4 Fractional distillation

Used to separate: two or more miscible liquids (liquids that mix completely) with different boiling points. Examples are ethanol and water, the fractions in crude oil, and the gases in liquefied air.

Apparatus: as for simple distillation, but with a **fractionating column** fitted between the flask and the condenser. The column is packed with glass beads or has glass shelves, which give a large surface area. The thermometer sits at the top of the column, level with the outlet to the condenser.

How it works (ethanol and water):

1. The mixture is heated. Both liquids evaporate, but the vapour contains more of the liquid with the lower boiling point, ethanol (boiling point about 78 °C).
2. The column is hotter at the bottom and cooler at the top. Vapour condenses on the glass beads and is re-evaporated many times. Water, with the higher boiling point of 100 °C, condenses and runs back into the flask.
3. Almost pure ethanol vapour reaches the top of the column. The thermometer reads about 78 °C and stays steady while ethanol is collected.
4. When all the ethanol has distilled, the temperature rises. The receiver is changed, and when the reading reaches 100 °C the water distils over.

Exam tip: to explain how you know when one liquid has finished distilling, say "the thermometer reading rises above the boiling point of the first liquid". Simple distillation is not good enough for ethanol and water because their boiling points are fairly close, so both evaporate together and the distillate would still be a mixture.

5.5 Paper chromatography

Used to separate: a mixture of soluble substances, usually coloured, such as the dyes in ink or food colourings. It is also used to identify substances and to test purity.

Method:

1. Draw a **baseline** in **pencil** about 1 to 2 cm from the bottom of a strip of chromatography paper. Pencil is used because graphite does not dissolve in the solvent, whereas ink would dissolve and run up the paper with the samples.
2. Put a small, concentrated spot of each sample on the baseline. Spots of known substances can be added alongside for comparison.
3. Stand the paper in a beaker containing a shallow layer of solvent. The solvent level must be **below** the baseline, otherwise the spots would dissolve into the solvent in the beaker instead of travelling up the paper.
4. Cover the beaker so the solvent does not evaporate from the paper.
5. Let the solvent rise up the paper. Remove the paper before the solvent reaches the top and immediately mark the **solvent front** in pencil.
6. Leave the paper to dry. The dried paper is the **chromatogram**.

How it works: each substance has a different solubility in the solvent and a different attraction to the paper. A substance that is very soluble in the solvent and weakly attracted to the paper travels further. So the components separate into different spots.

Interpreting a chromatogram:

- one spot: the sample is probably a pure substance;
- several spots: the sample is a mixture of at least that many substances;
- a spot at the same height as a known substance (in the same solvent): the sample probably contains that substance;
- a spot left on the baseline: that substance is insoluble in the solvent used.

5.6 R_f values

R_f value = distance moved by the substance ÷ distance moved by the solvent front

Both distances are measured from the **baseline**. To the centre of the spot is the usual convention.

An R_f value has no units and is always between 0 and 1, because a substance can never travel further than the solvent. For a given solvent and paper, a substance always has the same R_f value, so it can be used to identify the substance.

Worked example: calculating an R_f value

On a chromatogram the solvent front is 8.0 cm above the baseline. A red spot has its centre 5.2 cm above the baseline. Calculate the R_f value of the red dye.

$$R_f = \text{distance moved by substance} \div \text{distance moved by solvent} = 5.2 \div 8.0 = 0.65$$

The R_f value is 0.65 (no units).

5.7 Locating agents

Colourless substances, such as amino acids, are made visible by spraying the dried chromatogram with a locating agent, which reacts to form coloured spots.

5.8 Other methods you may meet

- **Using a separating funnel:** separates two immiscible liquids (liquids that do not mix), such as oil and water. The denser liquid forms the lower layer and is run off through the tap.
- **Magnetic separation:** removes a magnetic substance (iron, nickel, cobalt, steel) from a mixture.
- **Dissolving then filtering:** separates a soluble solid from an insoluble one, such as salt from sand.

6. Choosing a separation method

6.1 Matching the method to the mixture

Ask yourself: what states are the components in, and which physical property is different between them?

Mixture	Property that differs	Method
Insoluble solid and liquid	Particle size, solubility	Filtration
Soluble solid in solution, want the solid	Solvent evaporates, solute does not	Crystallisation (or evaporation to dryness)
Soluble solid in solution, want the solvent	Boiling point	Simple distillation
Two or more miscible liquids	Boiling point	Fractional distillation
Two immiscible liquids	Density, do not mix	Separating funnel
Dissolved coloured substances	Solubility and attraction to paper	Paper chromatography
Soluble solid and insoluble solid	Solubility in water	Dissolve in water, filter, then crystallise the filtrate
Magnetic and non-magnetic solids	Magnetism	Magnet

6.2 Multi-step separations

Many questions combine steps. Write each step in order and say why.

Worked example: rock salt

Rock salt is a mixture of sodium chloride and sand. Describe how you would obtain pure, dry crystals of sodium chloride from rock salt.

1. Crush the rock salt with a pestle and mortar to increase the surface area.
2. Add the powder to warm water and stir, so that the sodium chloride dissolves. Sand is

insoluble and does not dissolve.

3. Filter the mixture. The sand stays in the filter paper as the residue; the sodium chloride solution passes through as the filtrate.
4. Heat the filtrate in an evaporating basin until the crystallisation point is reached (crystals form on a cold glass rod dipped in it).
5. Leave to cool so that crystals form, filter them off, wash with a little cold distilled water and dry between filter papers.

Quick check

1. State the meaning of the term *element*. [1]
2. Define the term *compound*. [2]
3. Classify each of the following as an element, a compound or a mixture: (a) sea water, (b) nitrogen, (c) sodium chloride, (d) steel. [4]
4. When iron filings and sulfur powder are mixed, the iron can be removed with a magnet. After the mixture is heated strongly, it cannot. Explain this difference. [3]
5. State whether each of these is a physical or a chemical change, and give a reason: (a) candle wax melting, (b) a match burning. [4]
6. Balance the equation: $\text{Al} + \text{O}_2 \rightarrow \text{Al}_2\text{O}_3$ [2]
7. Write a balanced symbol equation, with state symbols, for the reaction of solid calcium carbonate with dilute hydrochloric acid to form calcium chloride solution, water and carbon dioxide. [3]
8. A sample of a solid melts between 76 °C and 79 °C. The pure substance melts sharply at 81 °C. State and explain what this shows about the sample. [2]
9. Describe how to obtain dry crystals of copper(II) sulfate from copper(II) sulfate solution. [4]
10. Explain why the cold water enters the condenser at the bottom in distillation. [1]
11. Ethanol boils at about 78 °C and water at 100 °C. Explain how fractional distillation separates a mixture of the two. [4]
12. Give two reasons why the baseline in paper chromatography is drawn in pencil and placed above the solvent level. [2]
13. On a chromatogram the solvent front moved 9.0 cm and a blue spot moved 3.6 cm from the baseline. Calculate the R_f value of the blue dye. [2]
14. A dye X has an R_f value of 0.40 in a certain solvent. On a new chromatogram in the same solvent, the solvent front moved 7.5 cm. Calculate how far from the baseline a spot of X would be expected. [2]
15. Suggest the most suitable method to separate each of the following: (a) oil from water, (b) the dyes in a black ink, (c) chalk from water, (d) nitrogen and oxygen from liquefied air. [4]

1. An element is a substance that cannot be broken down into anything simpler by chemical methods; it contains only one type of atom.

2. A compound is a substance made of two or more different elements (1) chemically combined in

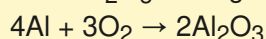
a fixed proportion (1).

3. (a) Mixture: water with dissolved salts, not chemically combined and variable in composition. (b) Element: only nitrogen atoms (as N_2 molecules). (c) Compound: sodium and chlorine chemically combined in a fixed ratio, NaCl . (d) Mixture: steel is an alloy of iron with carbon and sometimes other elements, and the composition varies.

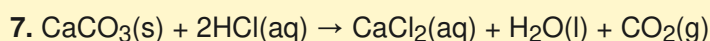
4. Before heating, the iron and sulfur are a mixture: they are not chemically combined, so the iron keeps its magnetic property (1). On heating, a chemical reaction takes place (1) and a new compound, iron(II) sulfide, FeS , is formed, whose properties are different from those of iron, so the iron cannot be pulled out with a magnet (1).

5. (a) Physical change (1): no new substance is formed; the wax only changes from solid to liquid and it solidifies again on cooling (1). (b) Chemical change (1): new substances such as carbon dioxide and water are formed, and the change cannot be reversed (1).

6. Oxygen: 2 on the left, 3 on the right. The lowest common multiple of 2 and 3 is 6, so use 3O_2 and $2\text{Al}_2\text{O}_3$. This gives 4 Al on the right, so use 4Al on the left.



Check: 4 Al and 6 O on each side.



Correct formulae (1), balancing with 2HCl (1), correct state symbols (1). Check: 1 Ca, 1 C, 3 O, 2 H and 2 Cl on each side.

8. The sample is impure (1). It melts over a range of temperatures rather than at one sharp point, and below the melting point of the pure substance; impurities cause both effects (1).

9. Heat the solution in an evaporating basin to evaporate some of the water (1) until the crystallisation point, tested by dipping in a glass rod and seeing crystals form on it as it cools (1). Leave the solution to cool so that crystals form (1). Filter off the crystals, wash with a little cold distilled water and dry between filter papers (1).

10. So that the condenser jacket stays completely full of cold water, which gives the most efficient cooling.

11. The mixture is heated and both liquids evaporate, but the vapour is richer in ethanol, which has the lower boiling point (1). The fractionating column is hotter at the bottom and cooler at the top (1). Vapour repeatedly condenses and re-evaporates on the glass beads; water condenses and runs back into the flask, so the vapour reaching the top is almost pure ethanol (1). Ethanol is collected while the thermometer reads about 78°C ; when the temperature rises towards 100°C , the receiver is changed and water distils over (1).

12. Pencil (graphite) is insoluble in the solvent, so it does not run up the paper and mix with the spots, unlike ink (1). The baseline is above the solvent level so that the samples do not dissolve into the solvent in the beaker but are carried up the paper (1).

13. $R_f = \text{distance moved by substance} \div \text{distance moved by solvent front}$ (1) = $3.6 \div 9.0 = 0.40$ (1). No units.

14. Rearranging: distance moved by substance = $R_f \times \text{distance moved by solvent front}$ (1) = $0.40 \times 7.5 = 3.0 \text{ cm}$ (1).

15. (a) Separating funnel, because oil and water are immiscible and form two layers. (b) Paper

chromatography, because the dyes are dissolved coloured substances. (c) Filtration, because chalk is an insoluble solid. (d) Fractional distillation of liquid air, because nitrogen and oxygen are miscible liquids with different boiling points.