

ESAT

Chemistry

Separation, Tests, Air and Water

Free lesson notes

Covers	C8.1 to C8.4, C16.1 to C16.5 and C17.1 to C17.4
Format	Lesson, worked examples, self-check
Price	Free

About this lesson

Practical chemistry is about three jobs: separating the substances in a mixture, identifying what they are, and understanding the biggest mixture of all, the air around us (together with the water we drink). Each job has a small, fixed toolkit of methods, and ESAT questions on this material test whether you can pick the right tool and explain why it works. The reasoning is always the same: separation methods exploit a *difference in a physical property* (size, solubility, boiling point, density), and each chemical test gives a *characteristic observation* (a colour, a precipitate, a gas that behaves in a particular way).

The lesson begins with filtration, evaporation, crystallisation, distillation (simple and fractional), the separating funnel and the centrifuge, then chromatography with R_f values and what they tell you about purity. It then gives the tests for gases, for the anions carbonate, halide and sulfate, for cations using sodium hydroxide, for flame colours and for water. Finally it covers the composition of air and how its gases are separated by fractional distillation, the greenhouse effect, the common air pollutants, and the treatment of drinking water. Specification codes: C8.1–C8.4 (separation), C16.1–C16.5 (tests) and C17.1–C17.4 (air and water).

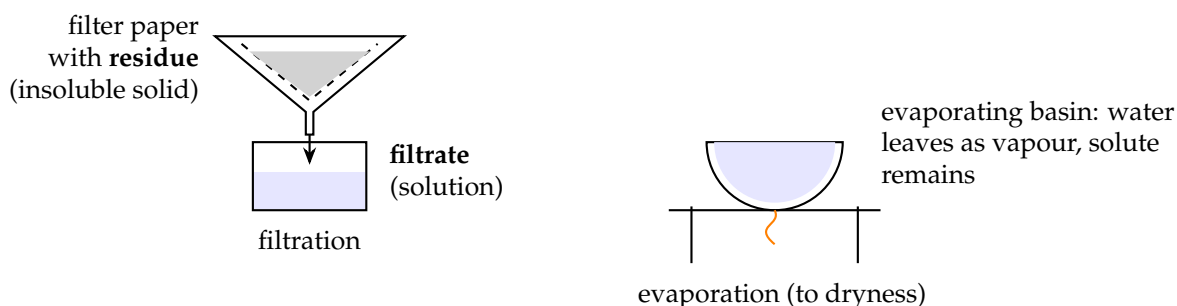
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1 Physical separation: filtering, evaporating, crystallising

Mixtures versus compounds. In a mixture the substances are not chemically joined, so they can be separated by *physical* methods, which depend on differences in properties such as solubility or boiling point and do not make new substances. In a compound the elements are chemically bonded; to get an element out of a compound you need a *chemical* process, such as displacement by a more reactive element, reduction with carbon, or electrolysis. You cannot filter or distil iron out of rust. Everything in this section is physical.

Filtration separates an insoluble solid from a liquid. The mixture is poured through filter paper in a funnel. The tiny holes let the liquid and any dissolved substance through (the **filtrate**) but hold back the solid (the **residue**). Example: sand from a mixture of sand and water.

Evaporation separates a dissolved solid (solute) from its solvent. The solution is heated so the solvent (water) evaporates, leaving the solid. It is quick, but heating to dryness can decompose the solid, and the solvent is lost.



Crystallisation gives larger, purer crystals. Heat the solution to evaporate some of the solvent until it is nearly saturated (a drop on a cold glass rod forms crystals). Then let it cool slowly: the solubility falls as it cools, so crystals form. Filter off the crystals, wash them with a little cold distilled water, and dry them.

Separating soluble and insoluble solids. To separate sand from salt: add water and stir to dissolve the salt; filter (sand is the residue); then evaporate or crystallise the filtrate to get the salt.

Worked example: separating sand and salt

Put these steps in the correct order to obtain dry salt from a mixture of salt and sand: (a) evaporate the filtrate, (b) filter, (c) add water and stir.

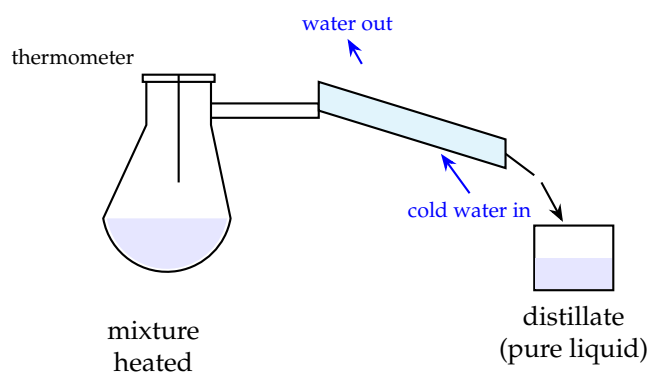
(c) The salt dissolves, the sand does not. (b) The sand stays in the filter paper as the residue; the salt solution passes through. (a) Evaporating the filtrate leaves the salt. Order: c, b, a.

Common mistakes

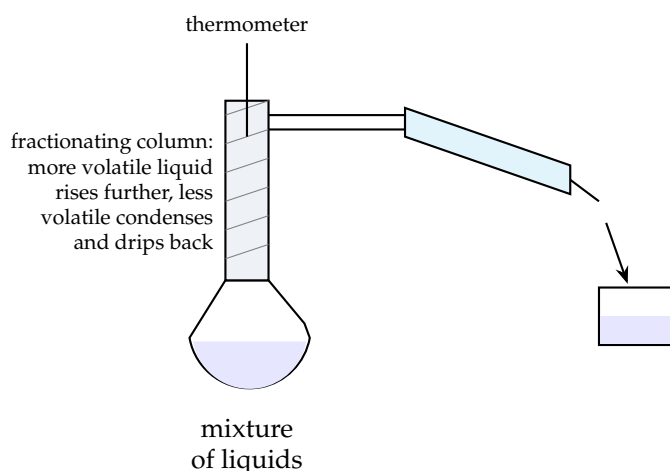
- Using filtration to separate a dissolved solid: it passes through with the liquid.
- Using evaporation when the product must not be heated strongly or when you want the solvent back; use crystallisation or distillation instead.
- Calling the liquid that passes through the residue. The liquid is the *filtrate*; the solid left is the residue.

2 Distillation, separating funnels and centrifuges

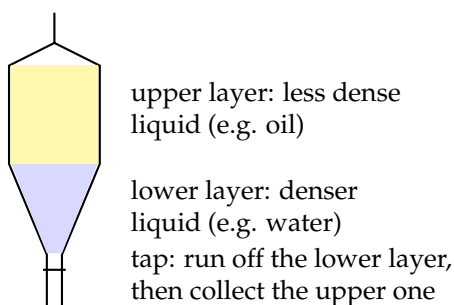
Simple distillation separates a pure liquid from a solution (for example drinking water from sea water). The solution is heated until the liquid boils; the vapour passes into a **condenser**, a tube cooled by water running round it (in at the bottom, out at the top, so that the jacket stays full), and condenses back to liquid, the **distillate**, which is collected. The dissolved solid has a much higher boiling point and stays behind in the flask. The thermometer sits level with the side arm to read the temperature of the vapour leaving.



Fractional distillation separates a mixture of *liquids* with different boiling points that mix completely (for example ethanol, boiling point 78°C , and water, 100°C). A **fractionating column** (a tube packed with glass beads or with a large surface area) is added above the flask. The vapour rises and condenses on the packing; the condensed liquid is reheated by the rising vapour and evaporates again. Each cycle enriches the vapour in the more volatile (lower boiling point) liquid, so the lowest-boiling liquid reaches the top first and is collected first, while less volatile liquids drip back down. As the thermometer reading stays steady at the boiling point of the first liquid and then rises to that of the next, we collect separate **fractions**.



Separating funnel. Two liquids that do *not* mix (are immiscible), such as oil and water, settle into two layers, the denser one at the bottom. The lower layer is run off through the tap and the upper layer collected separately.



Centrifuge. A centrifuge spins a mixture rapidly. The denser, undissolved particles are flung to the bottom of the tube, so a very fine suspension that would clog a filter (for example blood cells in plasma) can be separated; the liquid is then poured off (decanted).

Worked example: which method?

Choose the best method: (a) pure water from sea water; (b) ethanol from an ethanol–water mixture; (c) cooking oil from water.

(a) Simple distillation: the salt is non-volatile. (b) Fractional distillation: the two liquids mix but have different boiling points (78 and 100 °C). (c) Separating funnel: oil and water are immiscible, with the oil as the upper layer.

Exam tip

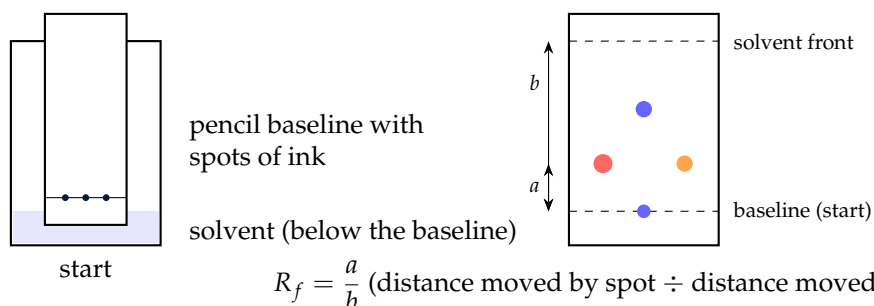
Two questions pick the method. Is the thing to be separated a solid, or are both parts liquids? And do the liquids mix? Solid in liquid: filter (insoluble) or evaporate/distil (dissolved). Mixed liquids: fractional distillation. Immiscible liquids: separating funnel.

Common mistakes

- Putting the condenser water in at the top. It enters at the bottom so that the jacket fills completely.
- Using simple distillation when the boiling points of two liquids are close together: this will not separate them cleanly.
- Forgetting that the *lower* boiling point liquid comes off first.

3 Chromatography and purity

How it works. In paper chromatography a spot of the mixture is placed on a pencil baseline near the bottom of chromatography paper, and the bottom edge of the paper dips into a solvent (below the baseline so the spots do not wash off). The solvent soaks up the paper and carries the substances with it. Each substance spends its time partly dissolved in the moving solvent and partly attracted to the paper (the stationary phase). A substance that is more soluble in the solvent and less strongly held by the paper is carried further. So the components separate into spots at different heights.



The baseline is drawn in *pencil* because pencil (graphite) is insoluble and does not run, whereas ink would dissolve in the solvent and move up with the substances.

The R_f value. The retention factor

$$R_f = \frac{\text{distance moved by the substance (to the centre of its spot)}}{\text{distance moved by the solvent (to the solvent front)}}$$

has no units, always lies between 0 and 1, and is the same for the same substance in the same solvent. Both distances are measured from the baseline. R_f can be compared with known values to identify a substance.

Purity. A *pure* substance gives a single spot (in every solvent tried). A mixture gives more than one spot. To check whether an unknown contains certain substances, run known samples next to it on the same paper: spots at the same height as a known sample suggest the same substance is present.

Worked example: calculating an R_f

A spot is 2.4 cm above the baseline and the solvent front is 6.0 cm above the baseline. Find R_f . How far will a substance with $R_f = 0.30$ travel?

$R_f = 2.4/6.0 = 0.40$. A substance with $R_f = 0.30$ moves $0.30 \times 6.0 = 1.8$ cm in the same experiment.

Worked example: is it pure?

Chromatograms of an ink gave one spot in water and two spots in ethanol. Is the ink pure?

No. A pure substance gives one spot in *every* solvent. Two spots in ethanol show that it is a mixture; in water the two components happened to travel the same distance (the same R_f in that solvent).

Common mistakes

- Drawing the baseline in ink, or putting the solvent level above the baseline.
- Measuring distances from the bottom of the paper instead of from the baseline.
- Giving an R_f greater than 1: this means the distances were swapped.

4 Tests for gases and for water

Four gas tests.

hydrogen	oxygen	carbon dioxide	chlorine
			
lighted splint: squeaky pop	glowing splint: relights	limewater: turns milky	damp blue litmus paper: bleached (white)

gas	test and positive result
hydrogen, H_2	hold a lighted splint at the mouth of the tube: a squeaky pop (the hydrogen burns explosively with oxygen in air)
oxygen, O_2	insert a glowing splint : it relights
carbon dioxide, CO_2	bubble through limewater (calcium hydroxide solution): it turns milky (calcium carbonate precipitate forms)
chlorine, Cl_2	hold damp blue litmus paper in the gas: it turns red (the gas is acidic) and is then bleached white

The reaction in the limewater test is $Ca(OH)_2 + CO_2 \longrightarrow CaCO_3 + H_2O$. If carbon dioxide is bubbled for too long the milkiness disappears again, because it forms soluble calcium hydrogencarbonate.

Test for water. Water turns **anhydrous copper(II) sulfate** from **white to blue** ($CuSO_4 + 5H_2O \longrightarrow CuSO_4 \cdot 5H_2O$). This shows that water is present but not that it is pure, since any liquid containing water gives the same result. Pure water has a precise boiling point of $100^\circ C$ and a freezing point of $0^\circ C$ (at normal atmospheric pressure).

Worked example: naming the gas

A metal reacts with dilute acid. The gas given off gives a squeaky pop with a lighted splint, and the metal is more reactive than hydrogen. Name the gas and write the general equation.
The gas is hydrogen. Metal + acid → salt + hydrogen, for example $\text{Mg} + 2\text{HCl} \longrightarrow \text{MgCl}_2 + \text{H}_2$.

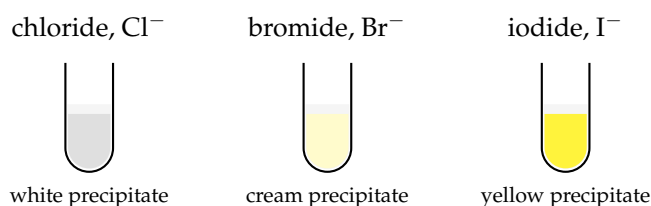
Common mistakes

- Using a lighted splint to test for oxygen (it only burns brighter) or a glowing splint for hydrogen.
- Saying that blue to white shows water. It is *white to blue*, with anhydrous copper(II) sulfate.
- Saying that anhydrous copper(II) sulfate proves the water is pure.

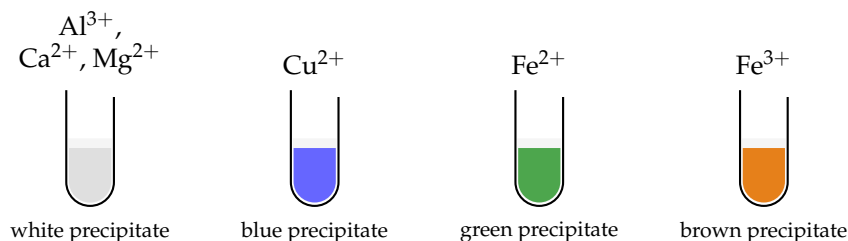
5 Tests for ions: anions, cations and flame tests

Anions (negative ions).

- **Carbonate**, CO_3^{2-} . Add dilute acid: it fizzes, giving CO_2 , which turns limewater milky.
- **Halides** (chloride, bromide, iodide). Add dilute *nitric* acid, then *silver nitrate* solution. A precipitate of the silver halide forms: **white** for chloride, **cream** for bromide, **yellow** for iodide. For example $\text{Ag}^+ + \text{Cl}^- \longrightarrow \text{AgCl}$. (The nitric acid first removes carbonate ions, which would also form a precipitate with silver nitrate.)
- **Sulfate**, SO_4^{2-} . Add dilute *hydrochloric* acid, then *barium chloride* solution: a **white** precipitate of barium sulfate forms, $\text{Ba}^{2+} + \text{SO}_4^{2-} \longrightarrow \text{BaSO}_4$. The acid removes carbonate ions (which would give a false positive with barium).



Cations (positive ions) with sodium hydroxide. Add sodium hydroxide solution to the solution under test. Many metal ions form an insoluble *hydroxide* precipitate, whose colour identifies the metal:



ion	precipitate with NaOH	equation (example)
$\text{Al}^{3+}, \text{Ca}^{2+}, \text{Mg}^{2+}$	white	$\text{Mg}^{2+} + 2\text{OH}^- \longrightarrow \text{Mg}(\text{OH})_2$
Cu^{2+}	blue	$\text{Cu}^{2+} + 2\text{OH}^- \longrightarrow \text{Cu}(\text{OH})_2$
Fe^{2+}	green	$\text{Fe}^{2+} + 2\text{OH}^- \longrightarrow \text{Fe}(\text{OH})_2$
Fe^{3+}	brown (red-brown)	$\text{Fe}^{3+} + 3\text{OH}^- \longrightarrow \text{Fe}(\text{OH})_3$

The three white precipitates cannot be told apart by this test alone: use a flame test to distinguish calcium (orange-red flame), and note that the aluminium hydroxide precipitate dissolves in excess sodium hydroxide while magnesium and calcium hydroxides do not.

Flame tests. Dip a clean wire loop in the solid or solution and hold it in a hot Bunsen flame. Excited electrons in the metal ion give out light of a characteristic colour:

ion	Li ⁺	Na ⁺	K ⁺	Ca ²⁺	Cu ²⁺
colour	crimson	yellow-orange	lilac	orange-red	green

A mixture can give a mixed colour, with the strong yellow of sodium masking weaker ones, which is why flame tests are not reliable for mixtures.

Worked example: identify the compound

A white solid gives a lilac flame. Its solution gives a cream precipitate when acidified with nitric acid and silver nitrate is added. Name the compound.

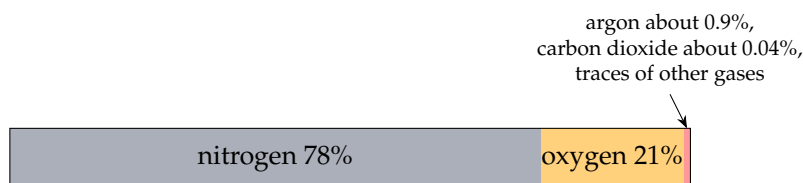
Lilac flame: potassium, K⁺. Cream precipitate: bromide, Br⁻. The compound is potassium bromide, KBr.

Common mistakes

- Using sulfuric acid to acidify before the silver nitrate test: it would add sulfate (and silver sulfate precipitates).
- Calling the iron(III) precipitate green. Green is iron(II), brown is iron(III).
- Confusing calcium (orange-red) with sodium (yellow) or copper (green) in a flame test.

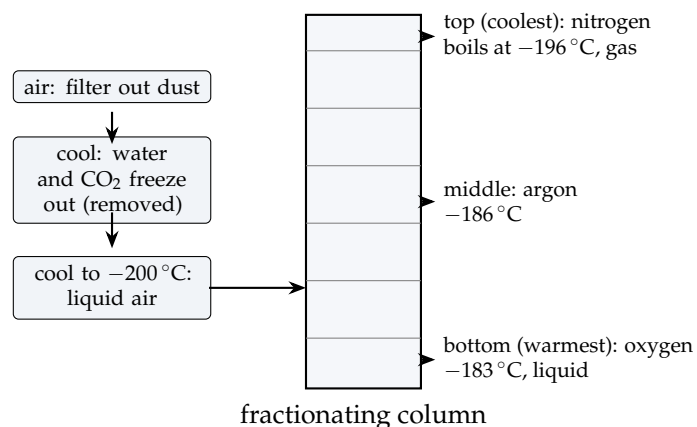
6 Air: composition and fractional distillation

Composition of dry air. Air is a mixture of gases:



About 78% nitrogen, 21% oxygen, 0.9% argon and 0.04% carbon dioxide, with traces of other noble gases and (in damp air) varying amounts of water vapour. Because it is a mixture, the proportions can change and its components can be separated by physical methods. The proportion of oxygen can be measured by heating a known volume of air over hot copper in a syringe: the oxygen forms black copper(II) oxide, $2\text{Cu} + \text{O}_2 \rightarrow 2\text{CuO}$, and the volume falls by about one fifth.

Separating the gases: fractional distillation of liquid air. The gases in air have different boiling points, so liquid air can be separated by fractional distillation.



First the air is filtered to remove dust, and cooled so that water vapour and carbon dioxide freeze and are removed (otherwise they would block the pipes). The remaining gas is compressed and cooled to about -200 °C to give liquid air. The liquid air enters a fractionating column that is warmest at the bottom and coldest at the top. The component with the lowest boiling point, **nitrogen** (-196 °C), boils off first and rises to the top; **argon** (-186 °C) comes off in the middle; **oxygen** (-183 °C) has the highest boiling point of the three and stays as a liquid at the bottom. Uses: nitrogen (to freeze

foods and as an unreactive atmosphere, and to make ammonia), oxygen (medicine, steel-making and welding), argon (filament lamps and welding).

Worked example: volume of oxygen

A syringe holds 100 cm^3 of air. It is passed back and forth over hot copper until there is no further change. What is the final volume of gas, approximately?

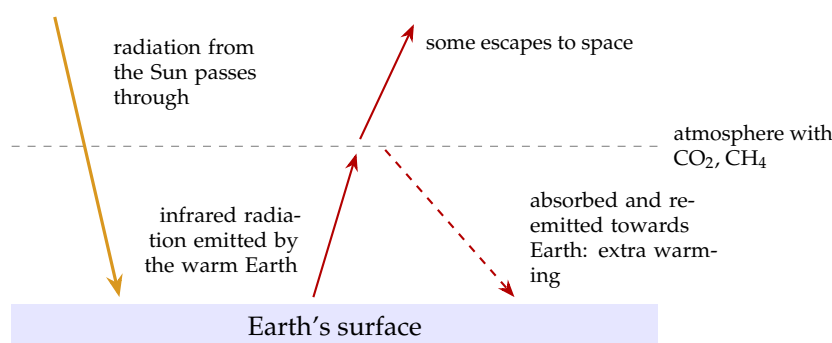
About 21% of the air is oxygen, which is removed: $100 - 21 = 79\text{ cm}^3$ is left (mainly nitrogen).

Common mistakes

- Giving the composition of air as “80% nitrogen and 20% oxygen” when the question asks for the more exact figures 78% and 21%.
- Saying the gases are separated by boiling the air. The air is first *liquefied*; then the liquid is warmed so the gases boil off in order of boiling point.
- Forgetting that carbon dioxide and water must be removed before liquefying the air.

7 Greenhouse gases, pollutants and drinking water

The greenhouse effect. The Earth is warmed by short-wavelength radiation from the Sun, which passes through the atmosphere. The warm surface re-emits energy as *infrared* radiation. Greenhouse gases, mainly **carbon dioxide** and **methane** (and also water vapour), absorb some of this infrared and re-emit it in all directions, including back towards the surface. This keeps the Earth warmer than it would otherwise be; increased concentrations strengthen the effect and contribute to global warming and climate change.



Carbon dioxide is added by burning fossil fuels, by respiration and by deforestation; methane by cattle, rice paddies, landfill sites and gas leaks. The main fix is to reduce the use of fossil fuels.

Air pollutants.

- **Carbon monoxide, CO.** Formed by *incomplete* combustion of fuels containing carbon (when there is too little oxygen, e.g. in a faulty boiler or engine). It is a colourless, odourless, *toxic* gas: it combines with haemoglobin in the blood and prevents it carrying oxygen.
- **Sulfur dioxide, SO₂.** Formed when fuels containing sulfur impurities burn ($\text{S} + \text{O}_2 \longrightarrow \text{SO}_2$). It dissolves in rain to form acid rain, which damages buildings and kills trees and aquatic life, and it causes breathing problems.
- **Oxides of nitrogen, NO_x** (NO and NO₂). Formed when nitrogen and oxygen from the air react at the very high temperatures inside engines (not from the fuel itself). They cause acid rain and respiratory problems and contribute to photochemical smog. Catalytic converters in vehicle exhausts remove CO and NO, for example $2\text{CO} + 2\text{NO} \longrightarrow 2\text{CO}_2 + \text{N}_2$.

Drinking water. Water for drinking is obtained from rivers, reservoirs and groundwater and must be treated: coarse screens and sedimentation remove large solids, filtration removes smaller particles, and **chlorine** is added to kill microorganisms that cause disease. In some areas **fluoride** is also added, because it strengthens tooth enamel and reduces tooth decay. Chlorine and fluoride are both toxic in large amounts, so the dose is controlled; some people object to fluoride being added to a public supply without individual consent, while others point to the dental health benefit. Where fresh water is scarce, sea water can be desalinated by distillation, which is very energy-intensive.

Worked example: why is it a pollutant?

A car engine produces nitrogen oxides although petrol contains almost no nitrogen. Explain. The nitrogen comes from the air. In the hot engine, nitrogen and oxygen of the air react: $\text{N}_2 + \text{O}_2 \longrightarrow 2\text{NO}$ (needs a high temperature, and the NO is oxidised further to NO_2).

Exam tip

For a “make a judgement” question on pollutants or water treatment, give one benefit and one concern for each point, e.g. chlorine kills microbes (benefit); too much chlorine is harmful and can taste unpleasant (concern).

Common mistakes

- Saying that carbon monoxide is formed by complete combustion. Complete combustion gives carbon dioxide.
- Saying that CO_2 causes acid rain. Acid rain is mainly due to sulfur dioxide and nitrogen oxides.
- Confusing the two uses of the word “pollutant”: carbon dioxide is a greenhouse gas but is not toxic in the way that carbon monoxide is.

8 Putting it together: identifying an unknown

Questions often give a series of observations about an unknown solid or solution. Treat each result as a clue to *one* ion, and combine them.

Method

Order of work. (1) Cation: flame colour and/or the precipitate with NaOH. (2) Anion: carbonate (acid, fizz), halide (nitric acid then AgNO_3 , colour), sulfate (HCl then BaCl_2 , white). (3) Name the compound: metal first (cation), then the non-metal (anion).

Worked example: two clues

A white solid dissolves in water. The solution gives a white precipitate with sodium hydroxide, a white precipitate with acidified silver nitrate, and the solid gives an orange-red flame. Name the compound. Orange-red flame: calcium. White precipitate with NaOH: consistent with calcium (white). White precipitate with acidified AgNO_3 : chloride. The compound is calcium chloride, CaCl_2 .

Worked example: avoid a false positive

Why must a solution be acidified with hydrochloric acid before barium chloride is added in a sulfate test? Barium carbonate is also a white precipitate. If carbonate ions are present, the acid destroys them (making CO_2 and water), so that only barium sulfate (which is insoluble in acid) can give the white precipitate.

Worked example: choose the separation

A mixture contains sand, salt and a liquid, ethanol, in which neither dissolves. Suggest a way to obtain (i) the ethanol, and (ii) dry sand. Filter the mixture: the ethanol (and any dissolved solute) passes through. Dry the residue to get the sand. Simple distillation of the filtrate then gives the pure ethanol.

Common mistakes

- Reporting a test result without the name of the ion: always say both the observation and the conclusion.
- Testing for chloride with silver nitrate in a solution containing carbonate without first adding acid.
- Concluding that a white precipitate with NaOH alone identifies the metal. Three metal ions give white precipitates.

Check yourself

Try these without looking back, then compare with the answers on the next page.

1. Which separation method would you use for sand and water?
2. What is the test for oxygen?
3. What colour is the flame of a lithium compound, and of a potassium compound?
4. A solution gives a yellow precipitate with acidified silver nitrate. Which ion is present?
5. Why is nitrogen the first gas to leave the fractionating column for liquid air?
6. A spot travels 3.0 cm when the solvent front travels 5.0 cm. Find R_f .
7. Name the gas formed by incomplete combustion and say why it is dangerous.
8. Give one reason why chlorine is added to drinking water.

Answers to the self-check

1. Filtration.
2. A glowing splint relights.
3. Crimson; lilac.
4. Iodide, I^- .
5. It has the lowest boiling point ($-196\text{ }^{\circ}\text{C}$) of the main components.
6. $3.0/5.0 = 0.60$.
7. Carbon monoxide: it binds to haemoglobin so blood cannot carry oxygen.
8. It kills microorganisms (bacteria) that cause disease.

Next step

Heurisco's *ESAT Chemistry: Separation, Tests, Air and Water Practice Set* has twenty original exam-style questions on this lesson, with chromatograms, distillation graphs and apparatus, in order of difficulty, with a full worked solution for each.