Course Companion

IGCSE Chemistry

Every topic handout in one volume

全部专题讲义合集

exercises.lol

Contents 目录

States of matter

IGCSE Chemistry

The three states of matter

Everything around you is made of tiny **particles** 粒子 — these can be **atoms** 原子, **molecules** 分子, or **ions** 离子. The **kinetic particle theory** 粒子动理论 says these particles are always moving. How close the particles are, how they are arranged, and how they move decides whether matter is a **solid** 固体, a **liquid** 液体, or a **gas** 气体.

Properties you can observe

You do not need a microscope to tell the three states apart. They behave in different ways:

- A solid has a fixed shape and a fixed **volume** 体积. It does not flow and you cannot **compress** 压缩 it (squeeze it smaller).
- A liquid has a fixed volume but no fixed shape. It flows and takes the shape of its container. It is almost impossible to compress.
- A gas has no fixed shape and no fixed volume. It flows and spreads out to fill the whole container. A gas is easy to compress.

The table below sums up these properties. **Density** 密度 means how much **mass** 质量 is packed into a given volume.

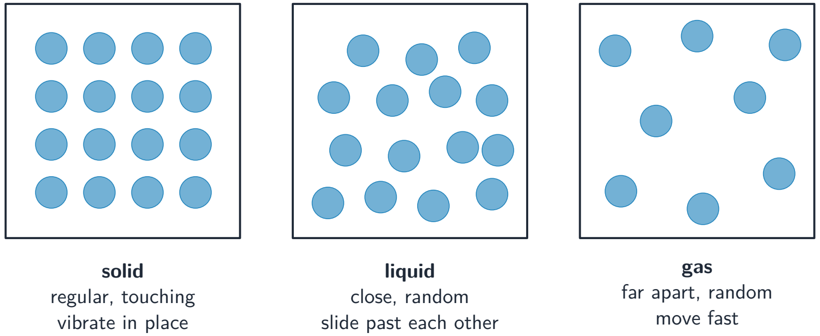
Property	Solid	Liquid	Gas
Shape	fixed	takes the shape of the container	fills the whole container
Volume	fixed	fixed	fills the whole container
Can it be compressed?	no	almost none	yes, easily
Does it flow?	no	yes	yes
Density	high	high	low

The particle picture

The kinetic particle theory explains these properties by looking at three things: the **separation** 间距 of the particles (how far apart they are), their **arrangement** 排列 (the pattern), and their **motion** 运动 (how they move).

	Solid	Liquid	Gas
Separation	touching, very close	close together	far apart
Arrangement	**regular** 规则 pattern	random, no pattern	random, no pattern
Motion	**vibrate** 振动 about fixed positions	move and slide past each other	move quickly in all directions

Strong **forces of attraction** 引力 hold the particles together. In a solid these forces are strong enough to hold every particle in place, so a solid keeps its shape. In a liquid the forces are weaker, so particles can move around. In a gas the particles move so fast that the forces hardly act at all, so the gas spreads out.



Particles are packed and regular in a solid, close and random in a liquid, and far apart in a gas

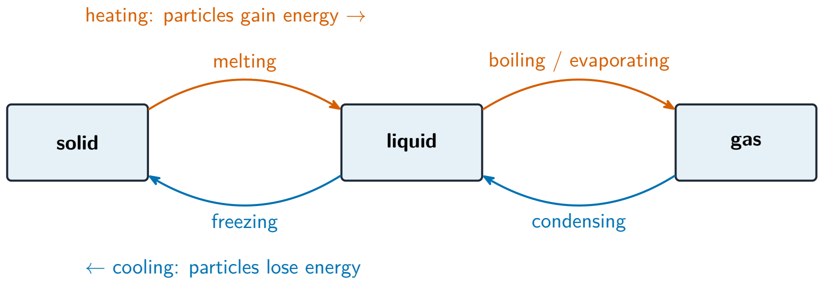
Changes of state

Ice melting to water: a change of state as the solid warms.

When you heat or cool a substance, it can change from one state to another. You must know the name of each change.

Change	What happens	Name
solid → liquid	**melting** 熔化	melting
liquid → solid	**freezing** 凝固	freezing
liquid → gas (at the surface, below the boiling point)	**evaporating** 蒸发	evaporation
liquid → gas (all through the liquid)	**boiling** 沸腾	boiling
gas → liquid	**condensing** 凝结	condensation

A pure solid melts at one fixed temperature, the **melting point** 熔点. A pure liquid boils at one fixed temperature, the **boiling point** 沸点. The same substance freezes at its melting point and condenses at its boiling point.



Heating: solid → liquid → gas; cooling reverses each change

A few substances change straight from solid to gas without melting first. This is called **sublimation** 升华. In the photo below, warmed solid iodine in a beaker turns directly into a purple gas; the gas then cools on the round flask of ice above and turns back into a solid.

Warmed solid iodine turns straight into a purple gas (sublimation)

Explaining changes of state with the particle theory

Each change of state is really a change in the **energy** 能量 of the particles.

- When you heat a solid, the particles gain energy and **vibrate** faster. At the melting point the particles have enough energy to break away from their fixed places and slide around — the solid melts.
- When you heat a liquid, the particles move faster. At the boiling point they have enough energy to fully escape the forces of attraction and become a gas.
- Cooling does the opposite. The particles lose energy, move more slowly, and the forces of attraction pull them back together.

During a change of state the energy goes into breaking the forces of attraction, not into making the particles move faster. This is why the temperature stays the same while a substance is melting or boiling.

Heating and cooling curves

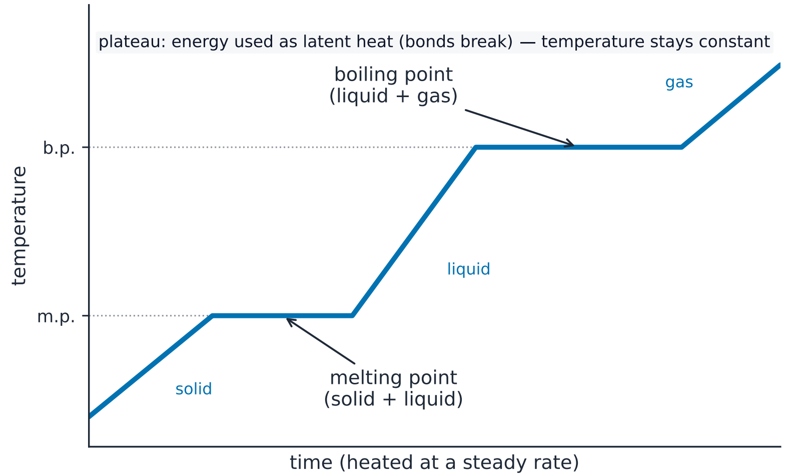
A **heating curve** 加热曲线 is a graph of temperature against time as you heat a substance steadily. A **cooling curve** 冷却曲线 is the same graph as the substance cools.

On a heating curve there are two flat (level) parts:

- The first flat part is at the **melting point**. Here solid and liquid are both present. The heat energy breaks the forces holding the solid together, so the temperature does not rise.

- The second flat part is at the **boiling point**. Here liquid and gas are both present, and the temperature again stays constant.

A cooling curve is the reverse. It has a flat part at the boiling point (the gas condenses) and a flat part at the melting point (the liquid freezes). As the particles slow down, **thermal energy** 热能 is released to the surroundings.



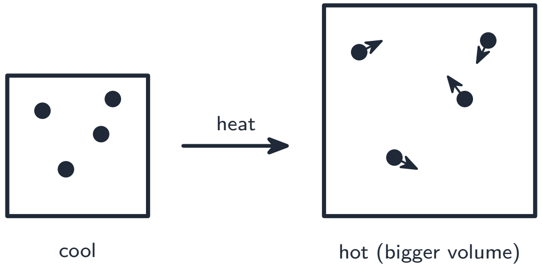
Temperature stays constant at the melting and boiling points while forces of attraction are broken

Gases: temperature, pressure and volume

A gas pushes on the walls of its container. This push, spread over the area of the wall, is the **pressure** 压强 of the gas. Pressure comes from the gas particles hitting the walls.

Effect of temperature

If you heat a fixed mass of gas while keeping the pressure the same, its volume increases.



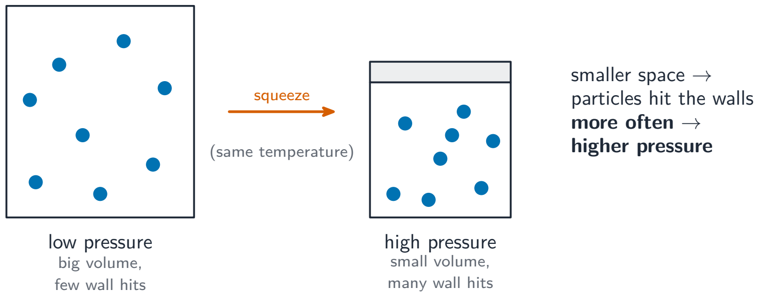
A heated gas: faster particles spread out and take up more space

Using the particle theory: heating gives the particles more **kinetic energy** 动能, so they move faster. They hit the walls harder and more often. To keep the pressure the same, the gas must take up more space, so the volume gets bigger.

If instead the volume is fixed (a sealed, rigid container), heating the gas makes the pressure rise, because the faster particles **collide** 碰撞 with the walls harder and more often.

Effect of pressure

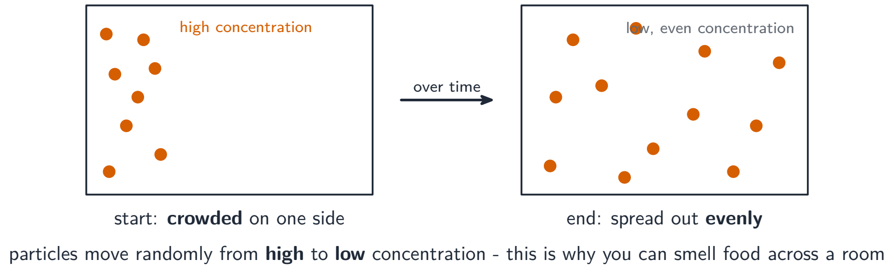
If you increase the pressure on a fixed mass of gas while keeping the temperature the same, its volume decreases. Squeezing the gas into a smaller space means the particles hit the walls more often, which is what a higher pressure means.



Squeezing a gas into a smaller volume makes the particles hit the walls more often, so the pressure rises

Diffusion

Diffusion 扩散 is the spreading of particles from a region where they are crowded to a region where they are spread out — that is, from high **concentration** 浓度 to low concentration. It happens because particles are always moving in random directions.



Particles diffuse from high to low concentration until they are spread out evenly

Diffusion explains why you can smell food from across a room: the smell particles move and mix with the air until they reach your nose. Diffusion happens in gases and in liquids, but not in solids, because solid particles cannot move from place to place.

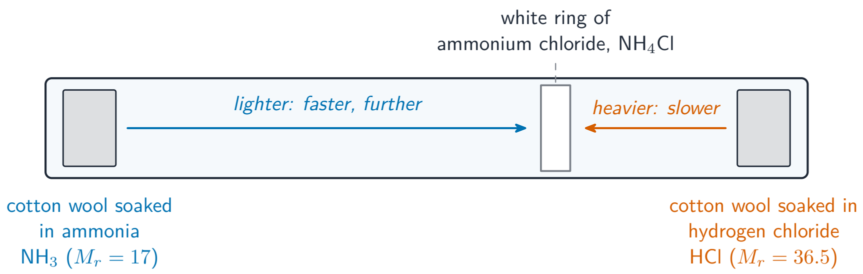
Rate of diffusion and molecular mass

Lighter gas particles move faster than heavier ones at the same temperature. So a gas with a smaller **relative molecular mass** 相对分子质量 (a smaller mass for each molecule) has a faster **rate** 速率 of diffusion.

A classic experiment shows this. Cotton wool soaked in **ammonia** 氨气 (NH_3) is put at one end of a long glass tube. Cotton wool soaked in **hydrogen chloride** 氯化氢 (HCl) is put at the other end. Both gases diffuse along the tube and meet to form a white ring of **ammonium chloride** 氯化铵 (NH_4Cl).

$$NH_3 + HCl \rightarrow NH_4Cl$$

Ammonia has $M_r = 17$ and hydrogen chloride has $M_r = 36.5$. Ammonia is lighter, so it diffuses faster and travels further along the tube. The white ring forms nearer the hydrogen chloride end.



Ammonia ($M_r = 17$) is lighter, so it diffuses faster and further; the white ring forms nearer the HCl end

Worked example. Bromine ($M_r = 160$) and ammonia ($M_r = 17$) are released at the same moment from opposite ends of a long tube. Which travels further before they meet? Compare the relative molecular masses. Ammonia's M_r is far smaller, so its molecules move faster at the same temperature and it diffuses more quickly. Ammonia therefore travels the greater distance, and the two gases meet nearer the **bromine** end. The rule is always "lighter means faster" - argue from M_r, never from how big the formula looks on paper.

Exam tips

- During **melting** and **boiling** the temperature stays constant (the flat parts of a heating curve), because the energy breaks the forces between particles instead of making them move faster.
- **Evaporation** happens only at the surface and at any temperature; **boiling** happens throughout the liquid at one fixed temperature.
- Explain gas behaviour with the particle theory: heating a gas at fixed volume raises the pressure because the particles hit the walls harder and more often — the particles themselves do not get bigger.
- **Diffusion** is faster for lighter particles (smaller M_r) and cannot happen in solids. In the ammonia/hydrogen chloride tube the lighter ammonia travels further, so the white ring forms nearer the HCl end.

Atoms, elements and compounds

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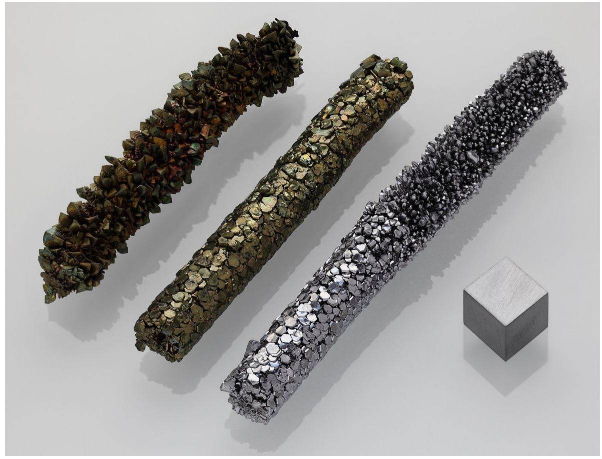
Elements, compounds and mixtures

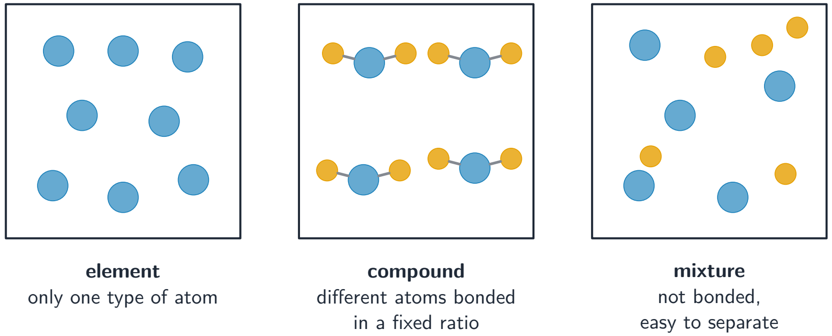


A pure element (vanadium): elements are the simplest substances.

All substances are made from about 100 simple building blocks. Knowing how they are joined lets you sort every substance into one of three groups.

- An **element** 元素 is a substance made of only one type of **atom** 原子. You cannot break it into anything simpler by a chemical reaction. Examples: copper, oxygen, carbon.
- A **compound** 化合物 is two or more elements chemically joined (bonded) together. The atoms are joined in a fixed ratio. Examples: water, carbon dioxide. A compound has different properties from the elements in it.
- A **mixture** 混合物 is two or more substances that are just mixed, not chemically joined. The parts keep their own properties and can be separated by physical methods. Example: air.

The key difference: in a compound the elements are **bonded** and can only be separated by chemical reactions; in a mixture they are not bonded and are easy to separate.

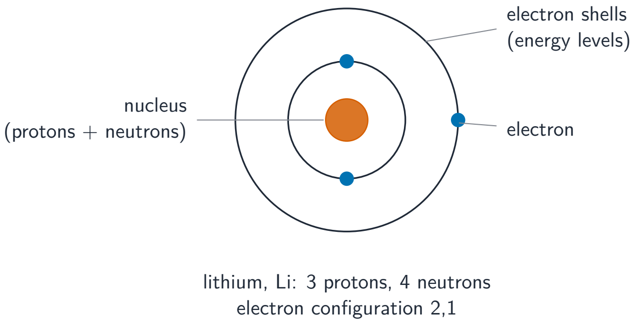


An element has one type of atom; a compound has different atoms bonded in a fixed ratio; a mixture is not bonded

Atomic structure

Inside the atom

Every atom has a small, dense centre called the **nucleus** 原子核. Around it, **electrons** 电子 move in **shells** 电子层 (energy levels). The nucleus contains two kinds of particle: **protons** 质子 and **neutrons** 中子.



An atom has a tiny nucleus of protons and neutrons, with electrons in shells around it

Each particle has a **relative mass** and a **relative charge** 电荷. You must learn these values:

Particle	Relative mass	Relative charge
proton	1	+1
neutron	1	0
electron	$\frac{1}{1840}$ (almost 0)	−1

An atom has no overall charge because it has equal numbers of protons (+1 each) and electrons (−1 each).

Proton number and mass number

Two numbers describe an atom:

- The **proton number** 质子数 (also called the **atomic number** 原子序数) is the number of protons in the nucleus. It tells you which element the atom is.
- The **mass number** 质量数 (also called the **nucleon number** 核子数) is the total number of protons and neutrons in the nucleus.

So the number of neutrons = mass number − proton number.

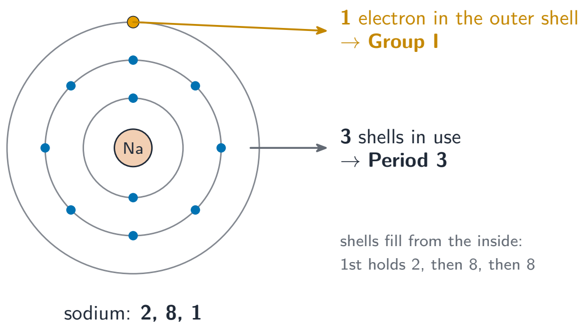
Electronic configuration

The electrons fill the shells from the inside out. The first shell holds up to 2 electrons; the next shells hold up to 8 each (for the first 20 elements). The **electronic configuration** 电子排布 lists how many electrons are in each shell, starting from the inside.

For example, an atom with 13 electrons has the configuration $2, 8, 3$. Sodium (proton number 11) is $2, 8, 1$. Calcium (proton number 20) is $2, 8, 8, 2$.

The configuration links to the **Periodic Table** 周期表:

- A **Group** 族 number (Groups I to VII) equals the number of electrons in the outer shell. So $2, 8, 1$ is in Group I.
- A **Period** 周期 number equals the number of shells that hold electrons. So $2, 8, 1$ has three shells, so it is in Period 3.
- The **noble gases** 稀有气体 in Group VIII (or 0) have a full outer shell, which makes them very unreactive.



Sodium's configuration 2,8,1 links to the Periodic Table: one outer electron means Group I, three shells means Period 3

Isotopes

Isotopes 同位素 are atoms of the same element that have the same number of protons but different numbers of neutrons. Because the proton number is the same, they are the same element. Because the neutron number is different, they have different mass numbers.

You write an atom with its mass number on top and proton number below, like ${}^{12}_{6}\mathrm{C}$. For an ion you add the charge, like ${}^{35}_{17}\mathrm{Cl}^{-}$.

Isotopes of an element have the **same chemical properties**. This is because chemical reactions only involve electrons, and isotopes have the same number of electrons and the same electronic configuration. (The extra neutrons change only the mass.)

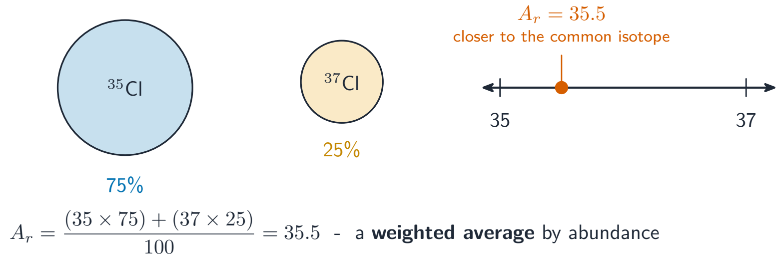
Calculating relative atomic mass

The **relative atomic mass** 相对原子质量 (A_r) of an element is the average mass of its atoms, taking into account how common each isotope is. The **abundance** 丰度 is the percentage of each isotope.

$$A_r = \frac{\sum(\text{isotope mass} \times \text{abundance})}{100}$$

For example, chlorine is 75% ${}^{35}\mathrm{Cl}$ and 25% ${}^{37}\mathrm{Cl}$:

$$A_r = \frac{(35 \times 75) + (37 \times 25)}{100} = 35.5$$



Relative atomic mass is a weighted average: chlorine is 75 percent Cl-35 and 25 percent Cl-37, so A_r is 35.5

Worked example. Boron has two isotopes, ${}^{10}\mathrm{B}$ and ${}^{11}\mathrm{B}$, and its A_r is 10.8. Find the percentage of each. Let the abundance of ${}^{11}\mathrm{B}$ be x, so the abundance of ${}^{10}\mathrm{B}$ is $(100 - x)$. Then

$$\frac{11x + 10(100 - x)}{100} = 10.8$$

so $11x + 1000 - 10x = 1080$, giving $x = 80$. Boron is **80%** ${}^{11}\mathrm{B}$ and **20%** ${}^{10}\mathrm{B}$. Check it against common sense: 10.8 lies closer to 11, so the heavier isotope must be the more common one. If your answer gives the majority to the isotope further from A_r, you have them the wrong way round.

Ions and ionic bonds

An **ion** 离子 is an atom (or group of atoms) that has lost or gained electrons, so it has an electric charge.

- A metal atom **loses** electrons to form a positive ion, called a **cation** 阳离子.
- A non-metal atom **gains** electrons to form a negative ion, called an **anion** 阴离子.

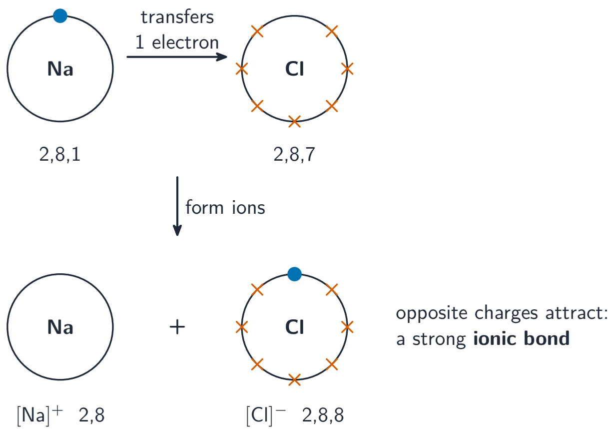
Atoms do this to get a full outer shell, like a noble gas.

How an ionic bond forms

An **ionic bond** 离子键 is a strong **electrostatic attraction** 静电引力 between oppositely charged ions (a + ion and a − ion pull together).

Ionic bonds form between a **metal** 金属 and a **non-metal** 非金属. Take sodium chloride, NaCl. Sodium $(2, 8, 1)$ gives its one outer electron to chlorine $(2, 8, 7)$. Now sodium is Na^+ $(2, 8)$ and chlorine is Cl^- $(2, 8, 8)$. Both have full outer shells, and the opposite charges attract.

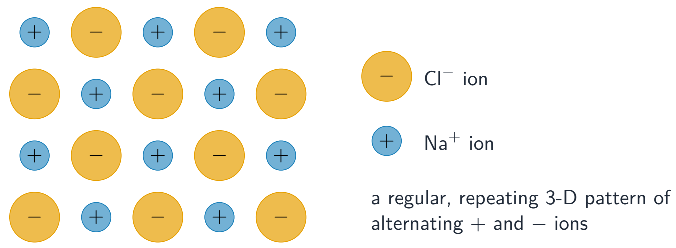
You can show this with a **dot-and-cross diagram**: draw each atom's outer-shell electrons as dots for one element and crosses for the other, then show the electron moving from the metal to the non-metal.



Sodium gives its outer electron to chlorine; both reach full outer shells and the opposite charges attract (the blue electron came from sodium)

The structure and properties of ionic compounds

An **ionic compound** 离子化合物 is not made of separate **molecules** 分子. The ions pack together into a giant **lattice** 晶格 — a regular pattern of huge numbers of **alternating** 交替 positive and negative ions.

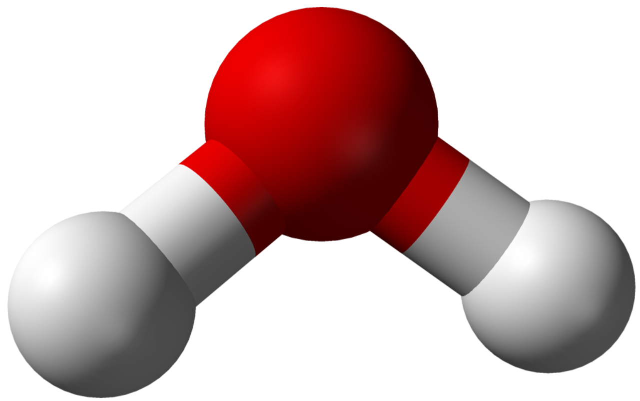


Ions pack into a giant lattice: a regular, repeating pattern of alternating positive and negative ions

This structure explains the properties:

Property	Reason
high **melting point** 熔点 and **boiling point** 沸点	the strong electrostatic attraction between ions needs a lot of energy to break
poor **electrical conductivity** 导电性 when solid	the ions are fixed in place and cannot move
good conductor when **molten** 熔融 or **aqueous** 水溶液	the ions are now free to move and carry charge

Simple molecules and covalent bonds



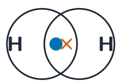
A model of a water molecule: atoms share electrons in covalent bonds.

A **covalent bond** 共价键 forms when two atoms **share** a pair of electrons. By sharing, each atom gets a full outer shell (a noble gas configuration). Covalent bonds form between non-metal atoms.

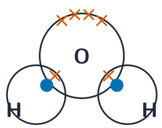
Some molecules to know:

- H_2 — two hydrogen atoms share one pair of electrons (a single bond).
- Cl_2, HCl — one shared pair each.
- H_2O — oxygen shares one pair with each of two hydrogen atoms.
- NH_3 — nitrogen shares a pair with each of three hydrogen atoms.
- CH_4 — carbon shares a pair with each of four hydrogen atoms.
- O_2 and CO_2 have double bonds (two shared pairs); N_2 has a triple bond (three shared pairs); C_2H_4 and CH_3OH also use shared pairs.

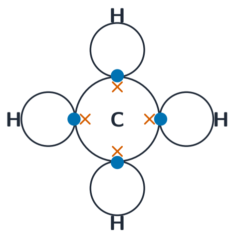
In a dot-and-cross diagram for a molecule, you draw the outer electrons of each atom and show which pairs are shared in the overlap between the atoms.



hydrogen, H_2
one shared pair



water, H_2O
two shared pairs



methane, CH_4
four shared pairs

In a covalent bond, atoms share pairs of electrons so each reaches a full outer shell

Properties of simple molecular compounds

These substances are made of small, separate molecules.

- They have **low** melting points and boiling points. The covalent bonds inside each molecule are strong, but the **intermolecular forces** 分子间作用力 (the forces between one molecule and the next) are weak, so little energy is needed to separate the molecules.
- They are **poor conductors** of electricity, because the molecules have no overall charge and no free electrons or ions to carry charge.

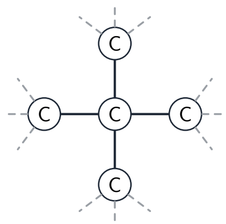
Giant covalent structures

Some covalent substances are not small molecules. Instead, millions of atoms are joined by covalent bonds into one **giant covalent structure** 巨型共价结构. The two you must know are both forms of carbon.

Diamond 金刚石: each carbon atom is bonded to four other carbon atoms. This makes a very strong, rigid 3-D network. Diamond is extremely hard, so it is used in **cutting tools** 切割工具.

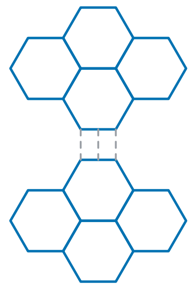
Graphite 石墨: each carbon atom is bonded to only three others, forming flat **layers** 层. There are weak forces between the layers, so the layers can slide over each other — this makes graphite a good **lubricant** 润滑剂. The fourth outer electron of each carbon is free; these **delocalised electrons** 离域电子 can move, so graphite conducts electricity and is used as an **electrode** 电极.

diamond



each carbon bonded to **4** others: a hard 3-D network

graphite



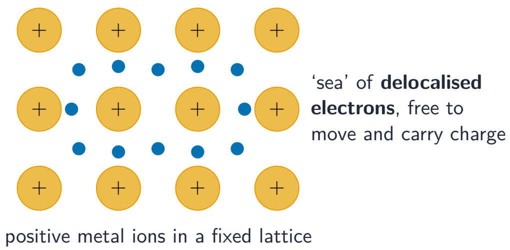
flat layers of hexagonal rings (each C bonded to **3**); weak forces let the layers slide

Diamond bonds each carbon to four others (hard); graphite forms flat layers with weak forces between them (slippery)

Silicon(IV) oxide 二氧化硅 (SiO_2) has a giant covalent structure like diamond, so it is also very hard and has a very high melting point.

Metallic bonding

A metal is a giant structure of positive ions surrounded by a 'sea' of **delocalised electrons** that are free to move through the whole metal. **Metallic bonding** 金属键 is the strong electrostatic attraction between these positive ions and the sea of electrons.



A metal is positive ions in a 'sea' of delocalised electrons that are free to move and carry charge

This explains two key properties of metals:

- **Good electrical conductivity**: the delocalised electrons are free to move and carry charge through the metal.
- **Malleability** 展性 (can be hammered into sheets) and **ductility** 延性 (can be pulled into wires): the layers of positive ions can slide over each other without breaking the metallic bond, so the metal changes shape instead of shattering.

Exam tips

- Number of neutrons = mass number − proton number. The **proton number** is what decides which element an atom is.
- **Isotopes** have the same chemical properties because reactions involve only electrons, and isotopes share the same electron configuration; only the mass differs.
- Match structure to properties: **ionic** = giant lattice (high melting point; conducts only when molten or aqueous); **simple molecular** = weak forces *between* molecules (low melting point; no conduction); **giant covalent** = very hard, very high melting point.
- **Graphite** conducts and is slippery (one free electron per carbon; layers slide); **diamond** does neither (all four electrons bonded, so hard and non-conducting). Metals conduct and bend thanks to the sea of **delocalised electrons**.
- For relative atomic mass, take the weighted average: $A_r = \dfrac{\sum(\text{isotope mass} \times \text{abundance})}{100}$.

Stoichiometry

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Stoichiometry 化学计量 is the study of the amounts of substances in a reaction — how much reacts and how much is made. This topic is mostly about counting atoms and doing calculations.

Chemical formulae

A **formula** 化学式 shows which **atoms** 原子 are in a substance, and how many of each. There are two kinds of formula you must know.

- The **molecular formula** 分子式 is the actual number of each atom in one **molecule** 分子. For glucose it is $C_6H_{12}O_6$.
- The **empirical formula** 实验式 is the simplest whole-number **ratio** 比例 of the atoms or **ions** 离子 in a **compound** 化合物. For glucose it is CH_2O.

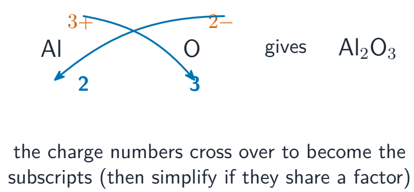
Working out a formula

If you are given a model or diagram, just count the atoms of each element and write them as a formula.

For an **ionic compound** 离子化合物 you can work out the formula from the charges on the ions. The total positive charge must balance the total negative charge, because the compound has no overall charge. Some common ions:

Positive ions	**Negative ions**
Na^+, K^+, H^+	Cl^-, OH^-, NO_3^-
Mg^{2+}, Ca^{2+}, Cu^{2+}	O^{2-}, SO_4^{2-}, CO_3^{2-}
Al^{3+}	N^{3-}

For example, Na^+ and O^{2-}: you need two Na^+ to balance one O^{2-}, so the formula is Na_2O.



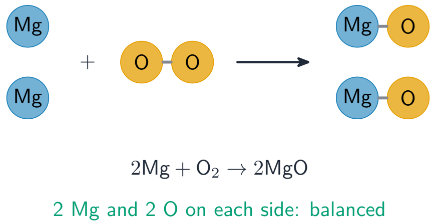
For an ionic compound, the ion charges cross over to give the formula (here Al_2O_3)

Writing equations

An equation shows how **reactants** 反应物 (the starting substances) change into **products** 生成物 (the substances made).

- A **word equation** 文字方程式 uses names: *magnesium + oxygen → magnesium oxide*.
- A **symbol equation** 化学方程式 uses formulae and must be **balanced** 配平 — the same number of each atom on both sides.

$$2\mathrm{Mg} + \mathrm{O_2} \rightarrow 2\mathrm{MgO}$$



A balanced symbol equation has the same number of each atom on both sides

You add **state symbols** 状态符号 in brackets to show the physical state: (s) solid, (l) liquid, (g) gas, and (aq) for **aqueous** 水溶液 (dissolved in water).

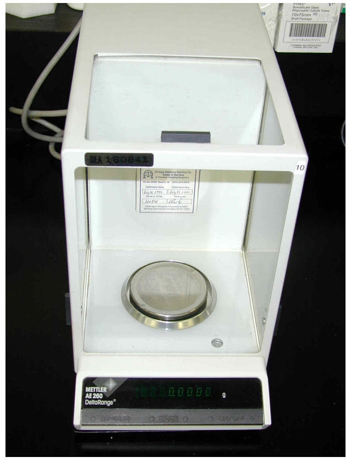
$$\mathrm{Zn}(s) + 2\mathrm{HCl}(aq) \rightarrow \mathrm{ZnCl_2}(aq) + \mathrm{H_2}(g)$$

Ionic equations

An **ionic equation** 离子方程式 shows only the ions that actually change. Ions that are the same on both sides are **spectator ions** 旁观离子 and are left out. For example, when an acid reacts with an alkali:

$$\mathrm{H^+}(aq) + \mathrm{OH^-}(aq) \rightarrow \mathrm{H_2O}(l)$$

Relative masses



A laboratory balance measures mass — the basis of mole calculations.

The **relative atomic mass** 相对原子质量 (A_r) of an **element** 元素 is the average **mass** 质量 of its atoms compared to $\frac{1}{12}$ of the mass of one ^{12}C atom.

The **relative molecular mass** 相对分子质量 (M_r) is the sum of the relative atomic masses of all the atoms in the molecule. For ionic compounds we use the **relative formula mass** 相对式量, found the same way from the formula.

$$M_r(\mathrm{H_2O}) = (2 \times 1) + 16 = 18$$

Reacting masses by simple proportion

You can sometimes find a reacting mass without the mole. If 24 g of magnesium makes 40 g of magnesium oxide, then 12 g of magnesium (half as much) makes 20 g of magnesium oxide.

The mole

The **mole** 摩尔 (symbol mol) is the unit for the **amount of substance** 物质的量. One mole of any substance contains 6.02×10^{23} **particles** 粒子 (atoms, ions or molecules). This number is the **Avogadro constant** 阿伏伽德罗常数.

The **molar mass** 摩尔质量 is the mass of one mole, in grams per mole (g/mol). Its number is the same as the A_r or M_r. The key relationship is:

$$\text{amount (mol)} = \frac{\text{mass (g)}}{\text{molar mass (g/mol)}}$$

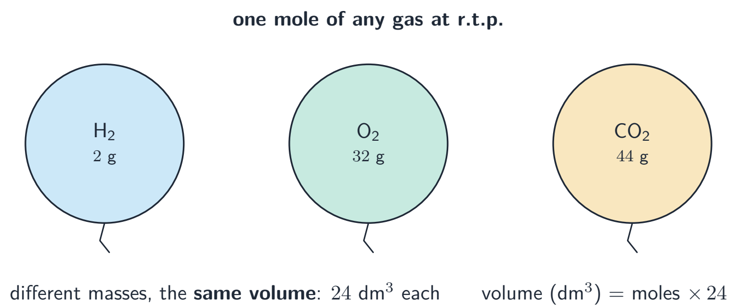
Worked example. How many moles are in 36 g of water? Molar mass of water = 18 g/mol.

$$n = \frac{36}{18} = 2 \text{ mol}$$

To find the number of particles, multiply the moles by the Avogadro constant.

Volumes of gases

At room temperature and pressure (r.t.p.), one mole of any gas takes up the same **volume** 体积. This **molar gas volume** 摩尔气体体积 is 24 dm^3.



One mole of any gas fills 24 cubic decimetres at room temperature and pressure

$$\text{volume of gas (dm}^3) = \text{amount (mol)} \times 24$$

Worked example. What volume does 0.25 mol of carbon dioxide occupy at r.t.p.?

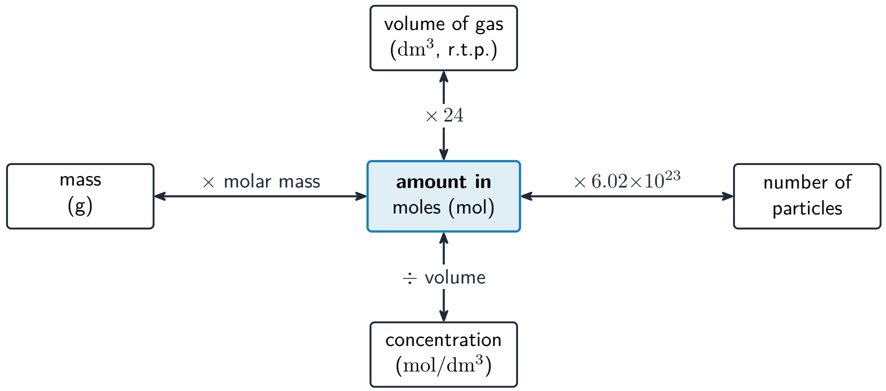
$$\text{volume} = 0.25 \times 24 = 6 \text{ dm}^3$$

Concentration of solutions

The **concentration** 浓度 of a **solution** 溶液 can be given in g/dm^3 or in mol/dm^3.

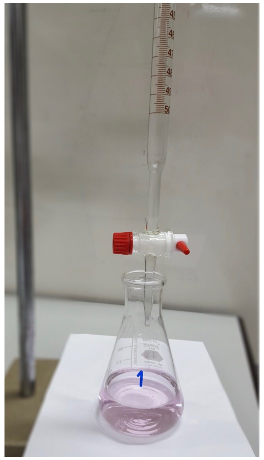
$$\text{concentration (mol/dm}^3) = \frac{\text{amount of solute (mol)}}{\text{volume (dm}^3)}$$

Remember to convert volume: 1 dm^3 = 1000 cm^3, so divide a volume in cm^3 by 1000.



Moles sit at the centre: multiply going outwards, divide coming back (concentration is moles ÷ volume)

Doing reaction calculations



A titration measures exactly how much acid reacts with a base.

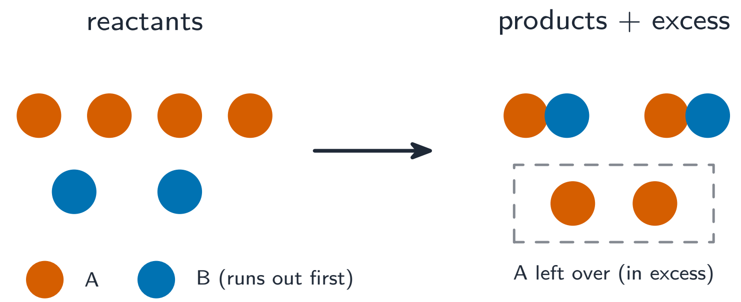
Most calculations follow the same steps: change the known amount into moles, use the balanced equation to find the moles of what you want, then change back into mass, volume or concentration.

Worked example. What mass of magnesium oxide forms when 12 g of magnesium burns completely? $2Mg + O_2 \rightarrow 2MgO$. ($A_r$: Mg = 24, O = 16.)

Moles of Mg = 12/24 = 0.5 mol. The ratio Mg : MgO is 1 : 1, so 0.5 mol of MgO forms. Its molar mass is 24 + 16 = 40 g/mol, so the mass is $0.5 \times 40 = 20$ g — the same answer as the simple-proportion method above.

Limiting reactant

When two reactants are mixed, often one runs out first. This is the **limiting reactant** 限量反应物. It decides how much product can form; any other reactant is in excess (left over).



B runs out first, so it is the limiting reactant and sets how much product forms; the spare A is left over in excess

Worked example. 8 g of hydrogen reacts with 8 g of oxygen: $2H_2 + O_2 \rightarrow 2H_2O$. Which is the limiting reactant, and what mass of water forms? (A_r: H = 1, O = 16.)

Moles of H_2 = 8/2 = 4 mol; moles of O_2 = 8/32 = 0.25 mol. The equation needs $2H_2$ for every one O_2, so 0.25 mol of O_2 reacts with only 0.5 mol of H_2. There is far more hydrogen than that, so **oxygen is the limiting reactant** and the hydrogen is in excess. The oxygen makes $2 \times 0.25 = 0.5$ mol of water, so the mass is $0.5 \times 18 = 9$ g. Always work in moles, not masses — the reactant with the smaller mass is not always the one that runs out.

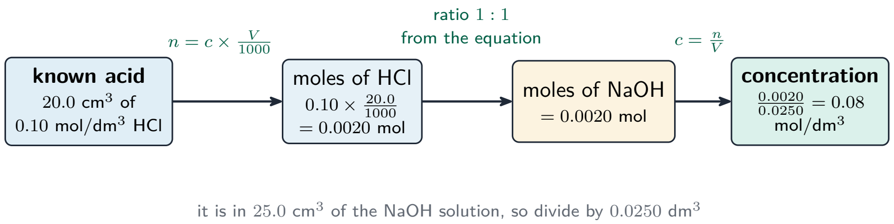
Titration calculation

In a **titration** 滴定 you measure the volume of one solution that reacts with another. From the volume and concentration you find the moles of one **solute** 溶质, then use the equation ratio to find the moles, concentration or volume of the other.

Worked example. 25.0 cm^3 of sodium hydroxide solution is exactly neutralised by 20.0 cm^3 of 0.10 mol/dm^3 hydrochloric acid. $NaOH + HCl \rightarrow NaCl + H_2O$. Find the concentration of the sodium hydroxide.

Moles of HCl $= 0.10 \times \dfrac{20.0}{1000} = 0.0020$ mol. The ratio is 1 : 1, so there are 0.0020 mol of NaOH in 25.0 cm^3:

$$\text{concentration} = \frac{0.0020}{25.0/1000} = 0.08 \text{ mol/dm}^3$$



The titration calculation: known solution to moles, ratio, then the unknown concentration

Empirical and molecular formulae from data

To find an empirical formula from masses or percentages:

1. Divide each element's mass (or %) by its A_r.
2. Divide all the answers by the smallest one to get the simplest ratio.

To find the molecular formula, compare the empirical formula mass with the real M_r and multiply up.

Worked example. A compound contains 40% calcium, 12% carbon and 48% oxygen by mass. Find its empirical formula. (A_r: Ca = 40, C = 12, O = 16.)

Divide each percentage by its A_r: Ca = 40/40 = 1, C = 12/12 = 1, O = 48/16 = 3. The ratio is 1 : 1 : 3, so the empirical formula is $CaCO_3$.

Percentages

- **Percentage yield** 产率 compares how much product you actually got with the most you could get: $\frac{\text{actual}}{\text{theoretical}} \times 100$.
- **Percentage composition by mass** 质量分数 of an element = $\frac{\text{mass of the element}}{M_r} \times 100$.
- **Percentage purity** 纯度 = $\frac{\text{mass of pure substance}}{\text{mass of impure sample}} \times 100$.

Worked example. Find the percentage by mass of nitrogen in ammonium nitrate, NH_4NO_3. (A_r: N = 14, H = 1, O = 16.)

$M_r = (2 \times 14) + (4 \times 1) + (3 \times 16) = 80$. The mass of nitrogen is $2 \times 14 = 28$, so

$$\% \text{ nitrogen} = \frac{28}{80} \times 100 = 35\%$$

Worked example. A reaction could make at most 5.0 g of product, but only 4.0 g is actually collected. Find the percentage yield.

$$\% \text{ yield} = \frac{4.0}{5.0} \times 100 = 80\%$$

Some product is always lost — left behind in the apparatus, or used up in side reactions — so the yield is almost never 100%.

Worked example. A 50 g sample of impure calcium carbonate contains 45 g of pure calcium carbonate. Find its percentage purity.

$$\% \text{ purity} = \frac{45}{50} \times 100 = 90\%$$

Exam tips

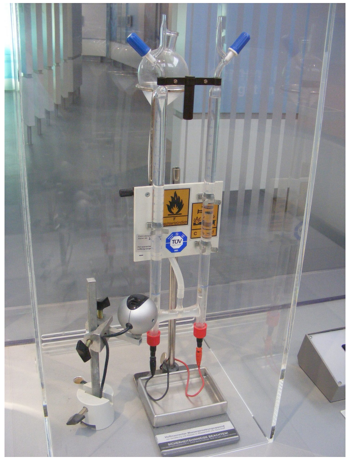
- Always turn masses, gas volumes and concentrations into **moles** first, use the balanced equation's ratio, then convert back. Never compare masses directly across an equation.
- Key formulas: $n = \frac{\text{mass}}{M_r}$, gas volume $= n \times 24$ dm^3 at r.t.p., and concentration $= \frac{n}{\text{volume in dm}^3}$. Change cm^3 to dm^3 by dividing by 1000.
- To balance a symbol equation you may only change the big numbers *in front* of a formula, never the small subscripts inside it.
- The **limiting reactant** is the one that runs out (fewest moles once you allow for the ratio); it sets how much product forms. The other reactant is in excess.
- **Percentage yield** = actual ÷ theoretical × 100; **percentage purity** = mass of pure substance ÷ mass of sample × 100. Both are always 100% or less.

Electrochemistry

IGCSE Chemistry

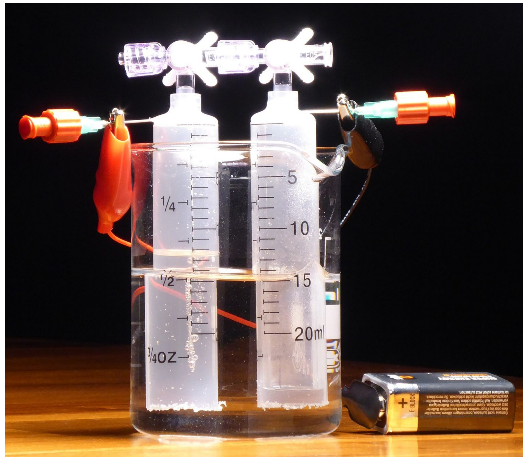
Electrolysis

Electrolysis 电解 is the breaking down (**decomposition** 分解) of an **ionic compound** 离子化合物 — when it is **molten** 熔融 or in **aqueous** 水溶液 solution — by passing an **electric current** 电流 through it.



An electrolysis cell splits a compound using an electric current.

It only works when the substance is molten or dissolved, because then the **ions** 离子 are free to move and carry the charge. A solid ionic compound cannot be electrolysed because its ions are locked in place.



Electrolysis of water: gas bubbles off at each electrode and collects in the tubes above, with about twice as much hydrogen as oxygen

The electrolytic cell

The set-up is called an **electrolytic cell** 电解池. Two **electrodes** 电极 (solid conductors) dip into the **electrolyte** 电解质 — the molten or aqueous substance being broken down.

- The **anode** 阳极 is the positive (+) electrode.
- The **cathode** 阴极 is the negative (−) electrode.

The electrodes are often **inert** 惰性 (they do not react), such as **platinum** 铂 or carbon/**graphite** 石墨.

What is formed at each electrode

There is a simple rule:

cathode (−) ⟶ metal or hydrogen

anode (+) ⟶ non-metal

Metals and hydrogen form at the cathode; non-metals at the anode

- **Metals** 金属 or **hydrogen** 氢气 are formed at the cathode.

- **Non-metals** 非金属 (other than hydrogen) are formed at the anode.

For aqueous solutions, the product can depend on whether the solution is **dilute** 稀 or **concentrated** 浓. Here are the three Core examples:

Electrolyte	At the cathode (−)	At the anode (+)
molten lead(II) bromide, $PbBr_2$	**lead** 铅 (silvery liquid)	**bromine** 溴 (red-brown vapour)
concentrated aqueous sodium chloride	hydrogen (bubbles of gas)	**chlorine** 氯气 (pale green gas)
dilute **sulfuric acid** 硫酸	hydrogen (bubbles of gas)	**oxygen** 氧气 (bubbles of gas)

Worked example. Predict the products of electrolysing **molten** zinc chloride, $ZnCl_2$. Because it is molten, only zinc ions and chloride ions are present - there is no water to complicate things. Zinc is a metal, so it forms at the **cathode**: Zn^{2+} ions gain electrons and silvery zinc appears. Chlorine is a non-metal, so it forms at the **anode**: pale green chlorine gas bubbles off. Always check the state first. A **molten** compound simply gives you its own two elements, while an **aqueous** one brings water into the competition - which is why concentrated sodium chloride solution gives hydrogen at the cathode rather than sodium.

How the charge moves

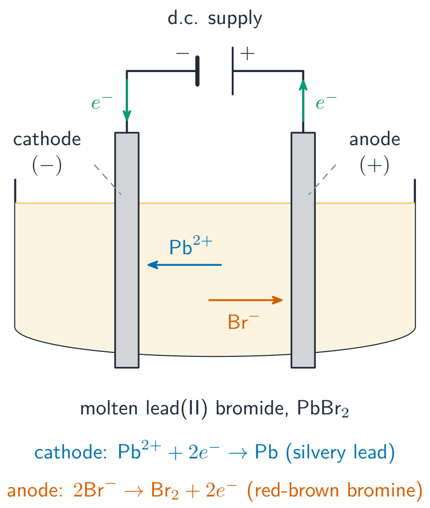
During electrolysis:

- **Electrons** 电子 move through the wires (the **external circuit** 外电路) from the power supply.
- At the cathode, positive ions gain electrons. Gaining electrons is **reduction** 还原.
- At the anode, negative ions lose electrons. Losing electrons is **oxidation** 氧化.
- Inside the electrolyte, the ions move: positive ions go to the cathode and negative ions go to the anode.

You can write a **half-equation** 半反应式 for each electrode. For molten lead(II) bromide:

$$Pb^{2+} + 2e^- \rightarrow Pb \quad \text{(cathode, reduction)}$$

$$2Br^- \rightarrow Br_2 + 2e^- \quad \text{(anode, oxidation)}$$



In molten lead(II) bromide, Pb^{2+} moves to the cathode and Br^- to the anode, where each is discharged

Electrolysis of copper(II) sulfate

The product at the anode depends on the electrode:

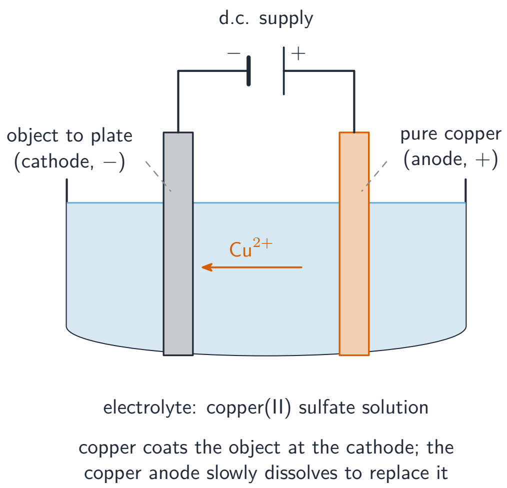
- With **inert** carbon electrodes: **copper** 铜 forms at the cathode and oxygen forms at the anode. The blue colour of the solution slowly fades as copper is removed.
- With copper electrodes: copper forms at the cathode, while the anode itself dissolves into the solution. The blue colour stays the same. This is used to purify copper.

Electroplating

Electroplating 电镀 means covering a metal object with a thin layer of another metal. This improves its appearance and its resistance to **corrosion** 腐蚀 (rusting and wearing away).

To electroplate an object:

- the object to be coated is made the **cathode**;
- the plating metal is made the **anode**;
- the electrolyte is a solution containing ions of the plating metal.

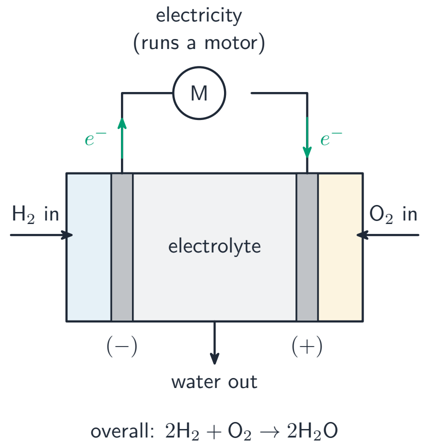


To electroplate, make the object the cathode and the plating metal the anode, in a solution of the plating-metal ions

Hydrogen–oxygen fuel cells

A **fuel cell** 燃料电池 uses hydrogen and oxygen to make electricity directly. The only chemical product is water.

$$2H_2 + O_2 \rightarrow 2H_2O$$



A hydrogen–oxygen fuel cell turns chemical energy straight into electricity, with water as the only product

It is useful to compare a fuel cell with a normal petrol (gasoline) engine in a vehicle.

	Hydrogen–oxygen fuel cell	**Petrol engine**
Main product	water only	carbon dioxide and **pollutants** 污染物
Effect on air	clean	adds to air pollution
Fuel storage	hydrogen is hard and dangerous to store (flammable, needs high pressure)	petrol is easy to store
Source	hydrogen may be made using fossil fuels	made from crude oil

Advantages of the fuel cell: the only product is water, so it does not pollute the air, and it changes chemical energy into electricity efficiently. **Disadvantages**: hydrogen is hard to store and transport safely, and producing the hydrogen can still use energy from fossil fuels.

Exam tips

- At the **cathode** (negative) you get a metal or hydrogen; at the **anode** (positive) you get a non-metal. Positive ions move to the cathode, negative ions to the anode.

- A **molten** compound just gives its two elements. An **aqueous** solution can give something different (concentrated sodium chloride gives hydrogen and chlorine, not sodium).
- **Reduction** is *gain* of electrons (at the cathode); **oxidation** is *loss* of electrons (at the anode). Remember OIL RIG.
- In a **half-equation** the atoms and the charges must balance, with the electrons on the correct side: $Pb^{2+} + 2e^- \to Pb$ (cathode).
- To **electroplate** an object, make it the cathode, make the plating metal the anode, and use a solution containing ions of the plating metal.

Chemical energetics
IGCSE Chemistry

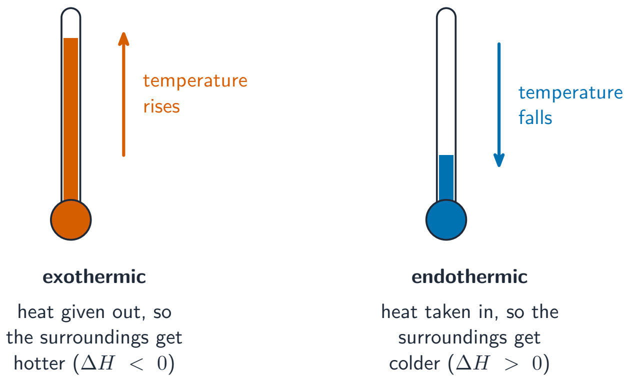
Exothermic and endothermic reactions

Burning wood is exothermic, releasing heat to the surroundings.

In every chemical reaction, energy is transferred. The reaction is either exothermic or endothermic, depending on which way the energy moves.

- An **exothermic reaction** 放热反应 gives out **thermal energy** 热能 to the **surroundings** 环境. So the temperature of the surroundings goes **up**.
- An **endothermic reaction** 吸热反应 takes in thermal energy from the surroundings. So the temperature of the surroundings goes **down**.

Examples of exothermic reactions are **combustion** 燃烧 (burning a fuel) and **neutralisation** 中和 (an acid reacting with an alkali). An example of an endothermic reaction is the thermal **decomposition** 分解 of a compound (breaking it down using heat).

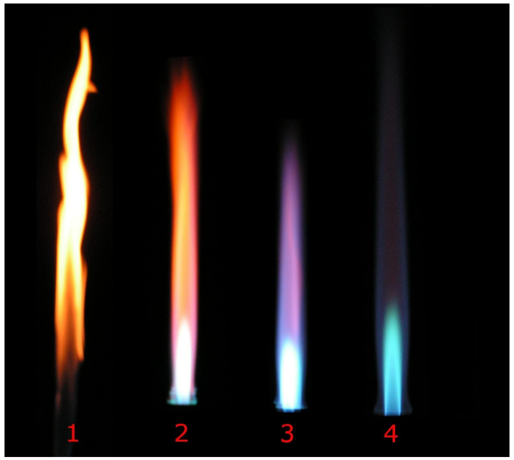


An exothermic reaction warms the surroundings; an endothermic reaction cools them

Enthalpy change, ΔH

The amount of thermal energy transferred in a reaction is called the **enthalpy change** 焓变. It is written as ΔH and has these signs:

- ΔH is **negative** for an exothermic reaction, because energy leaves the chemicals.
- ΔH is **positive** for an endothermic reaction, because energy is taken in.



A Bunsen flame supplies energy: enthalpy change ΔH is the heat transferred at constant pressure

Activation energy

Particles do not react every time they meet. The **activation energy** 活化能 (E_a) is the smallest amount of energy that **colliding** 碰撞 **particles** 粒子 must have before they can react. It is like a hill the particles must get over before the reaction can happen.

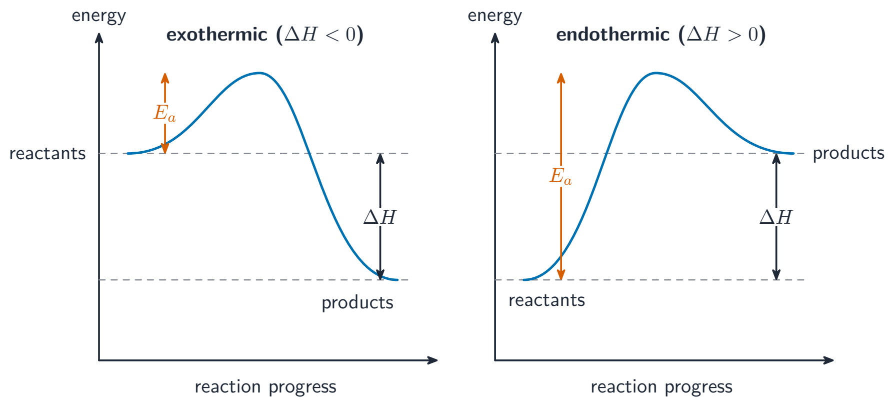
Reaction pathway diagrams

A **reaction pathway diagram** 反应进程图 shows how the energy changes as a reaction happens. Energy is on the vertical axis, and the progress of the reaction is on the horizontal axis.

- The line starts at the energy level of the **reactants** 反应物.
- It rises over a 'hill' — the height of this hill is the activation energy E_a.
- It then falls or rises to the energy level of the **products** 生成物.
- The gap between the reactant level and the product level is the enthalpy change ΔH.

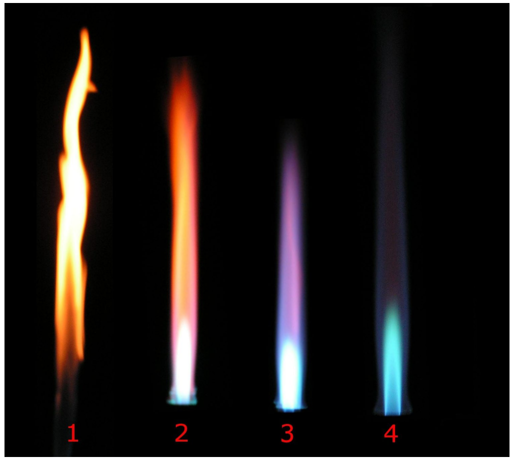
For an **exothermic** reaction, the products are **lower** than the reactants, so energy is given out and ΔH is negative.

For an **endothermic** reaction, the products are **higher** than the reactants, so energy is taken in and ΔH is positive.



Exothermic reactions end lower than they start ($\Delta H < 0$); endothermic reactions end higher ($\Delta H > 0$)

Bonds and energy



Breaking and making bonds transfers energy — the flame supplies it here.

A reaction involves breaking the bonds in the reactants and making new bonds in the products.

- **Bond breaking** 断键 takes in energy, so it is an endothermic step.
- **Bond making** 成键 gives out energy, so it is an exothermic step.

The **bond energy** 键能 is the energy needed to break one mole of a particular bond. You can use bond energies to find the enthalpy change:

$$\Delta H = (\text{energy to break all bonds}) - (\text{energy released making all bonds})$$

If more energy is given out making bonds than is taken in breaking bonds, the reaction is exothermic (ΔH negative). If less energy is given out, it is endothermic (ΔH positive).

Worked example

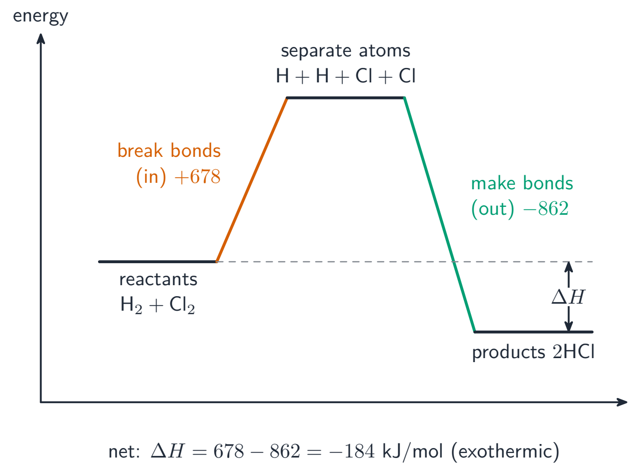
For the reaction $H_2 + Cl_2 \rightarrow 2HCl$, use these bond energies (in kJ/mol): H–H = 436, Cl–Cl = 242, H–Cl = 431.

Bonds broken: one H–H and one Cl–Cl = 436 + 242 = 678.

Bonds made: two H–Cl = 2 × 431 = 862.

$$\Delta H = 678 - 862 = -184 \text{ kJ/mol}$$

The answer is negative, so this reaction is exothermic.



Breaking bonds takes energy in (+678); making bonds gives more out (−862); so $\Delta H = -184$ kJ/mol

Exam tips

- **Exothermic** gives out heat, so the surroundings warm up and ΔH is *negative*; **endothermic** takes in heat, so the surroundings cool and ΔH is *positive*.
- **Bond breaking** takes energy in (endothermic); **bond making** gives energy out (exothermic). Use $\Delta H = (\text{energy to break bonds}) - (\text{energy released making bonds})$.
- If more energy is released making bonds than is used breaking them, the reaction is exothermic. Always check the sign of your final answer.
- On a **reaction pathway diagram**, an exothermic reaction ends *lower* than it starts; an endothermic one ends *higher*. The height of the hill is the **activation energy**.

Chemical reactions

IGCSE Chemistry

Physical and chemical changes

Iron rusting is a chemical change — it forms a new substance.

A **physical change** 物理变化 does not make a new substance. The substance only changes its state or shape, and the change can usually be reversed. Melting ice and dissolving sugar are physical changes.

A **chemical change** 化学变化 (a chemical reaction) makes one or more new substances and is usually hard to reverse. Signs of a chemical change include a colour change, a gas being given off, an energy change, or a **precipitate** 沉淀 (a solid) forming.

Physical change	Chemical change
no new substance made	new substance(s) made
easy to reverse	usually hard to reverse
e.g. melting, boiling, dissolving	e.g. burning, rusting

Rate of reaction

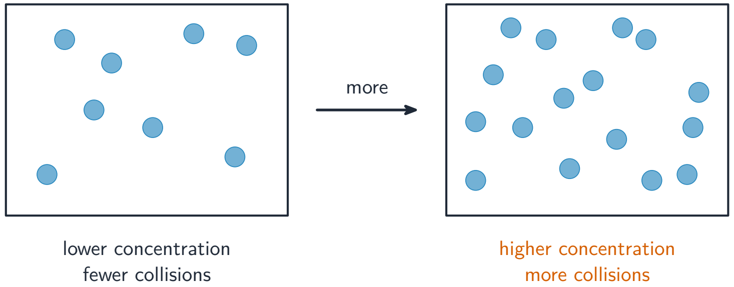
The **rate of reaction** 反应速率 tells you how fast the **reactants** 反应物 change into **products** 生成物.

Collision theory

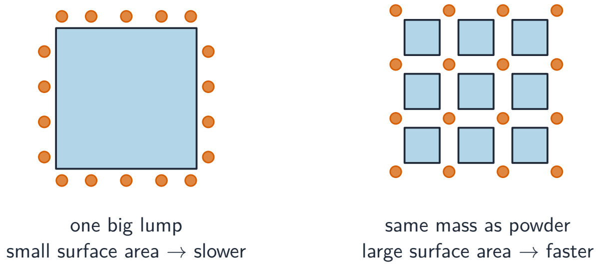
Collision theory 碰撞理论 explains what controls the rate. For a reaction to happen, the **particles** 粒子 must **collide** 碰撞, and they must collide with enough energy. The least energy they need is the **activation energy** 活化能 (E_a). A faster rate happens when the particles have successful collisions more often.

What changes the rate

Change	Effect	Reason (collision theory)
increase **concentration** 浓度 of a solution	faster	more particles in the same volume, so collisions happen more often
increase **pressure** 压强 of gases	faster	particles are pushed closer, so collisions happen more often
increase **surface area** 表面积 of a solid	faster	more particles are exposed, so collisions happen more often
increase temperature	faster	particles gain **kinetic energy** 动能 and move faster, so collisions are more frequent and more of them have enough energy
add a **catalyst** 催化剂	faster	the catalyst lowers the activation energy, so more collisions are successful



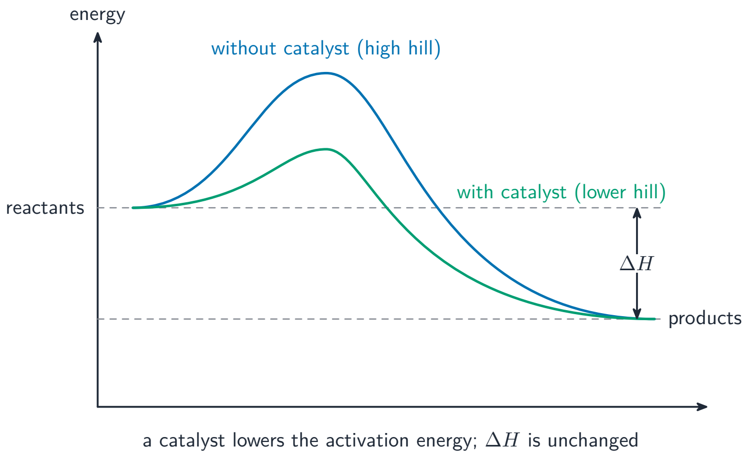
More particles in the same volume collide more often, so the rate is faster



Breaking a solid into a powder exposes much more surface, so the rate is faster

Catalysts

A catalyst speeds up a reaction but is not used up — it is unchanged at the end. It works by lowering the activation energy. **Enzymes** 酶 are biological catalysts (catalysts that work in living things).

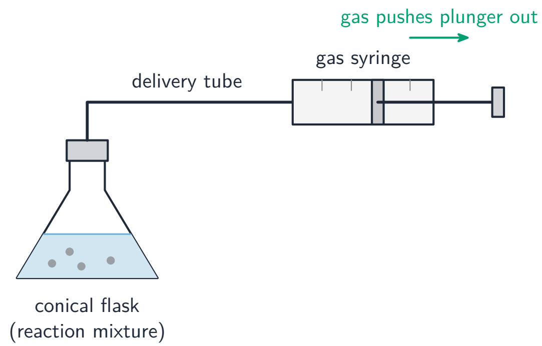


A catalyst gives a lower activation energy so more collisions succeed; ΔH is unchanged

Measuring the rate

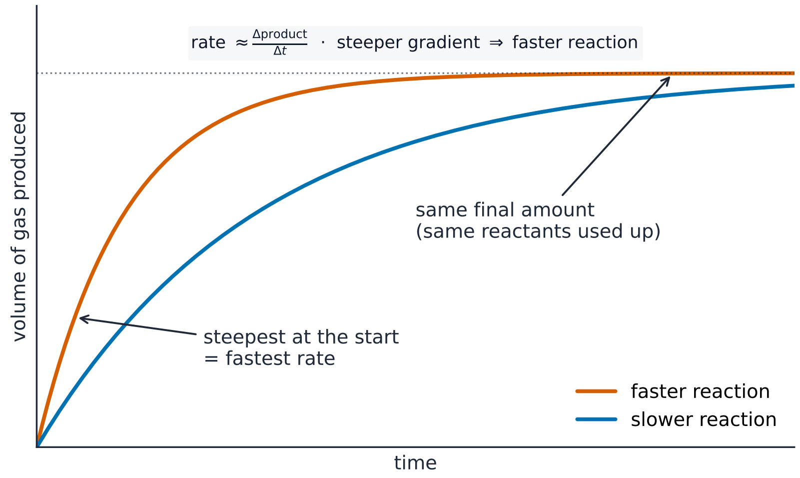
You can follow a reaction over time in these ways:

- **Change in mass**: stand the flask on a balance. If a gas escapes, the mass falls. Record the mass at regular times.
- **Volume of gas**: collect the gas in a gas **syringe** 注射器 and read its volume at regular times.
- **Formation of a precipitate**: in a reaction that turns cloudy, time how long it takes for a mark under the flask to disappear.



A gas syringe collects the gas given off; read its volume at regular times to follow the rate

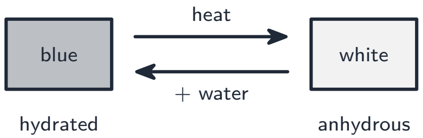
On a graph of product against time, the line is **steepest at the start** (fastest rate), becomes less steep as reactants are used up, and goes **flat** when the reaction has finished.



The rate is fastest at the start (steepest) and the line levels off when the reaction finishes

Reversible reactions and equilibrium

Some reactions are **reversible** 可逆反应: the products can react to form the reactants again. We show this with the symbol $\rightleftharpoons$.



Heating blue copper sulfate drives off water; adding water turns it blue again

Changing the direction

A clear example uses **hydrated** 水合 and **anhydrous** 无水 compounds:

- Blue hydrated copper(II) sulfate, when heated, loses its water to become white anhydrous copper(II) sulfate. Adding water turns it blue again.
- Pink hydrated cobalt(II) chloride loses water when heated to become blue anhydrous cobalt(II) chloride. Adding water turns it pink again.

Adding water to the anhydrous solid (and seeing the colour return) is used as a test for water.

Equilibrium

In a **closed system** 密闭系统 (where nothing enters or leaves), a reversible reaction reaches **equilibrium** 平衡 when:

- the rate of the **forward reaction** 正反应 equals the rate of the **reverse reaction** 逆反应, and
- the concentrations of the reactants and products are no longer changing.

Changing the position of equilibrium

The **position of equilibrium** 平衡位置 tells you whether there are more reactants or more products. You can move it:

- **Temperature**: heating moves the equilibrium in the direction that takes in heat (the **endothermic** 吸热反应 direction); cooling moves it in the direction that gives out heat (the **exothermic** 放热反应 direction).
- **Pressure** (gases): more pressure moves the equilibrium to the side with fewer gas molecules.
- **Concentration**: adding more of a substance moves the equilibrium to the other side, to use it up.
- A **catalyst** does **not** move the position of equilibrium. It only helps the reaction reach equilibrium faster.

The Haber process

The **Haber process** 哈伯法 makes ammonia:

$$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$$

- The **hydrogen** 氢气 comes from **methane** 甲烷 (natural gas); the **nitrogen** 氮气 comes from the air.
- Typical conditions: a temperature of 450 °C, a pressure of about 200 atm (20 000 kPa), and an **iron** 铁 catalyst.

The Contact process

The **Contact process** 接触法 turns sulfur dioxide into sulfur trioxide:

$$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$$

- The sulfur dioxide comes from burning **sulfur** 硫 (or roasting sulfide ores); the **oxygen** 氧气 comes from the air.
- Typical conditions: a temperature of 450 °C, a pressure of about 2 atm (200 kPa), and a **vanadium(V) oxide** 五氧化二钒 catalyst.

Why these conditions are chosen

The conditions are a **compromise** 折中:

- A higher pressure would give more product, but very high pressure is dangerous and expensive, so a medium pressure is used.
- A lower temperature would give more product (both forward reactions are exothermic), but the reaction would be too slow, so a fairly high temperature is used to keep a good rate.
- The catalyst speeds up the reaction without changing the position of equilibrium, which lowers cost.

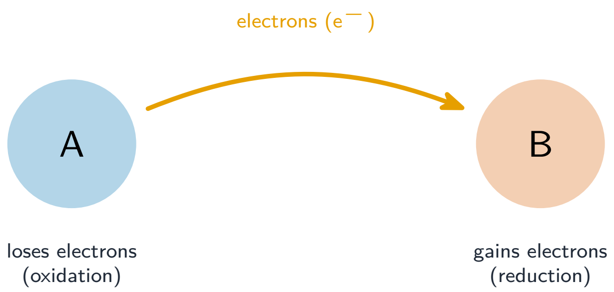
Redox

Oxidation 氧化 and **reduction** 还原 always happen at the same time, in what is called a **redox reaction** 氧化还原反应. ('Redox' is short for reduction–oxidation.)

There are three ways to describe oxidation and reduction:

- **Oxygen**: oxidation is the gain of oxygen; reduction is the loss of oxygen.
- **Electrons** 电子: oxidation is the loss of electrons; reduction is the gain of electrons.
- **Oxidation number** 氧化数: in oxidation the oxidation number goes up; in reduction it goes down.

A useful memory aid is **OIL RIG**: *Oxidation Is Loss, Reduction Is Gain* — of electrons.



Electrons pass from the substance that is oxidised (loses them) to the one that is reduced (gains them) — the two always happen together

Oxidation number rules

The oxidation number is shown by a Roman numeral, as in iron(II) and iron(III). The rules are:

- An element that is not combined has an oxidation number of 0.
- A single-atom ion has an oxidation number equal to its charge (so Na^+ is +1).
- The oxidation numbers in a compound add up to 0.
- The oxidation numbers in an ion add up to the charge on the ion.

Worked example. Find the oxidation number of manganese in the manganate(VII) ion, MnO_4^-. Each oxygen is −2, and there are four of them, giving $4 \times (-2) = -8$. The oxidation numbers in an **ion** must add up to the charge on the ion, which here is −1. So if manganese is x, then $x + (-8) = -1$, giving $x = +7$ - exactly what the

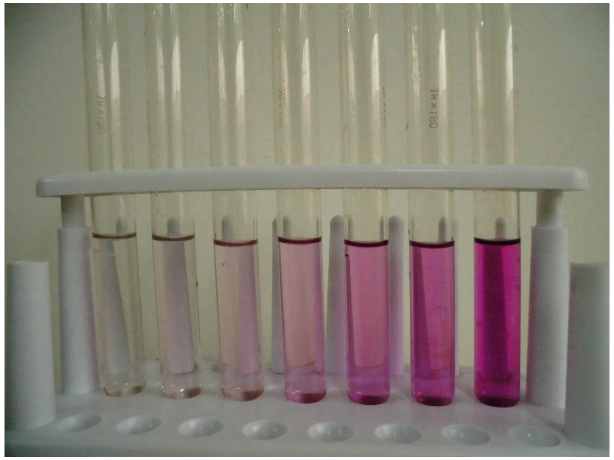
(VII) in the name tells you. Set the total to the **ion's charge**, not to zero: zero is only for a neutral compound.

Oxidising and reducing agents

- An **oxidising agent** 氧化剂 oxidises another substance, and is itself reduced.
- A **reducing agent** 还原剂 reduces another substance, and is itself oxidised.

Some redox reactions show clear colour changes:

- Acidified **potassium manganate(VII)** 高锰酸钾 is purple. When it acts as an oxidising agent it is reduced, and the purple colour fades to colourless.
- **Potassium iodide** 碘化钾 is colourless. When it is oxidised, red-brown **iodine** 碘 is formed.



Potassium manganate(VII) is deep purple; as it is reduced (or diluted) the purple fades to colourless

Exam tips

- Explain a faster rate with **collision theory**: successful collisions happen more often. Concentration, pressure and surface area all raise how often particles collide; a higher temperature does that *and* gives more particles enough energy.
- A **catalyst** lowers the activation energy and speeds the reaction up, but is not used up and does *not* change ΔH or the position of equilibrium.
- At **equilibrium** the forward and reverse rates are equal and the concentrations stop changing — it does *not* mean the amounts of reactant and product are equal.

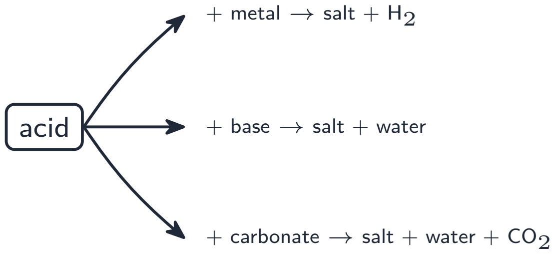
- Use Le Chatelier's principle: raising temperature favours the endothermic direction; raising pressure favours the side with fewer gas molecules; adding a substance shifts the equilibrium away from it.
- **Redox** — OIL RIG: Oxidation Is Loss, Reduction Is Gain of electrons. They always happen together, and an oxidising agent is itself reduced.

Acids, bases and salts

IGCSE Chemistry

Acids

An **acid** 酸 is a substance that forms hydrogen ions (H^+) when dissolved in water. Acids have three typical reactions:



Acids react with metals, bases and carbonates to give different products

- with **metals** 金属: acid + metal → a **salt** 盐 + **hydrogen** 氢气
- with bases: acid + **base** 碱 → a salt + water (this is **neutralisation** 中和)
- with **carbonates** 碳酸盐: acid + carbonate → a salt + water + **carbon dioxide** 二氧化碳

Describing what you see

Naming the products is only half of what the exam wants. “State the observations” asks what you would **see with your eyes**, and it carries its own marks - so learn the words:

You see	Say
bubbles of gas coming off	**effervescence** 泡腾 (also accepted: fizzing, bubbling)
the solid getting smaller and vanishing	the solid **dissolves** / **disappears**
the colour of the solution changing	name the colour, e.g. turns **blue** (copper salts)
bubbling that stops	**no more effervescence** - the acid is used up

So for magnesium added to hydrochloric acid, a full answer is: **effervescence**, and the **solid dissolves** (and the tube gets warm). For copper(II) oxide added to warm sulfuric acid: the black solid **dissolves** and the solution **turns blue**.

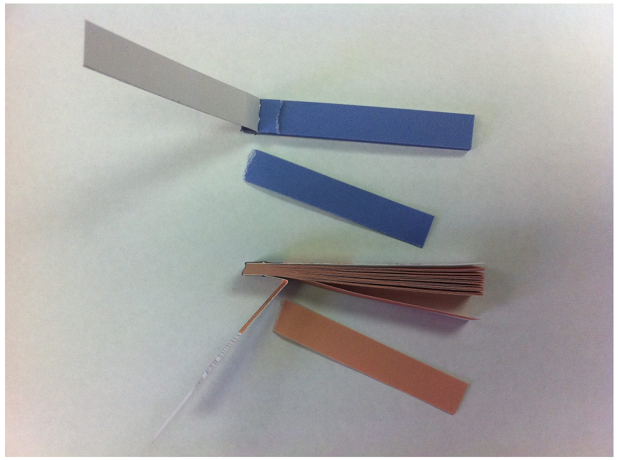
Two rules save most of the lost marks. **Never write “hydrogen is given off” as an observation** - you cannot see hydrogen, you can only see the bubbles, so write *effervescence*. And **do not write a name you cannot see**: “a salt forms” is a conclusion, not an observation.

Indicators

An **indicator** 指示剂 is a dye that changes colour to show whether a solution is acidic or alkaline.

Indicator	In acid	In alkali
litmus 石蕊	red	blue
thymolphthalein 百里酚酞	colourless	blue
methyl orange 甲基橙	red	yellow

Aqueous solutions of acids contain hydrogen **ions** 离子 (H^+). Aqueous solutions of alkalis contain hydroxide ions (OH^-).



Litmus paper: blue litmus turns red in an acid, and red litmus turns blue in an alkali

Bases and alkalis

Bases are **oxides** 氧化物 or **hydroxides** 氢氧化物 of metals. An **alkali** 可溶性碱 is a base that dissolves in water (a soluble base).

Bases have two typical reactions:

- with acids: base + acid → a salt + water (neutralisation again)

- with **ammonium salts** 铵盐: this releases ammonia gas.

pH strips: alkalis turn universal indicator purple or blue (pH > 7)

Strong and weak acids

An acid is a **proton** 质子 donor — it gives away H^+ ions (a hydrogen ion is just a proton). A base is a proton acceptor.

How strong an acid is depends on how much of it splits into ions in water:

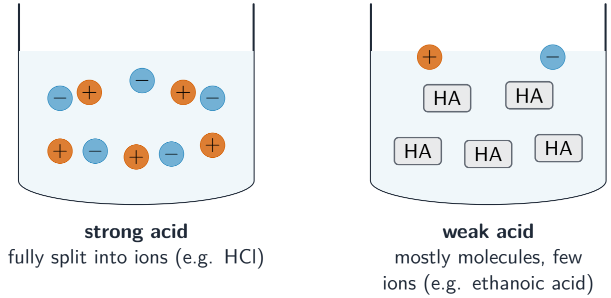
- A **strong acid** 强酸 is completely **dissociated** 电离 (fully split into ions) in water. **Hydrochloric acid** 盐酸 is strong:

$$HCl(aq) \rightarrow H^+(aq) + Cl^-(aq)$$

- A **weak acid** 弱酸 is only partly dissociated. **Ethanoic acid** 乙酸 is weak, so the equation uses the reversible arrow:

$$CH_3COOH(aq) \rightleftharpoons H^+(aq) + CH_3COO^-(aq)$$

Note: 'strong' and 'weak' are about dissociation, not about being dilute or concentrated.



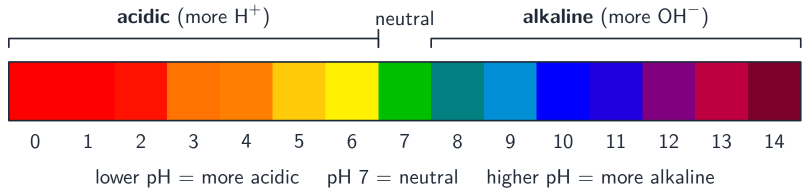
A strong acid is fully split into ions; a weak acid stays mostly as molecules (only partly dissociated)

The pH scale

The pH scale runs from 0 to 14 and tells you how acidic or alkaline a solution is. A higher hydrogen ion concentration means a lower pH.

You can find pH using **universal indicator** 通用指示剂, which turns different colours:

pH	Type	Colour of universal indicator
below 7	**acidic** 酸性	red / orange / yellow
exactly 7	**neutral** 中性	green
above 7	**alkaline** 碱性	blue / purple



Universal indicator turns red in a strong acid, green at neutral (pH 7), and purple in a strong alkali

When an acid and an alkali react, the H^+ and OH^- ions join to make water:

$$H^+(aq) + OH^-(aq) \rightarrow H_2O(l)$$

Oxides

Oxides can be sorted by how they behave:

- **Acidic oxides** are oxides of non-metals, such as SO_2 and CO_2.
- **Basic oxides** are oxides of metals, such as CuO and CaO.
- **Amphoteric** 两性 oxides react with both acids and bases to make a salt and water. Al_2O_3 and ZnO are amphoteric.

So metal oxides tend to be basic and non-metal oxides tend to be acidic.

Limestone is mostly calcium carbonate — a metal carbonate that acts as a base and neutralises acids

Preparing salts

Whether a salt can be made by a certain method depends on whether it is **soluble** 可溶 (dissolves) or **insoluble** 不溶 (does not dissolve).

Solubility rules

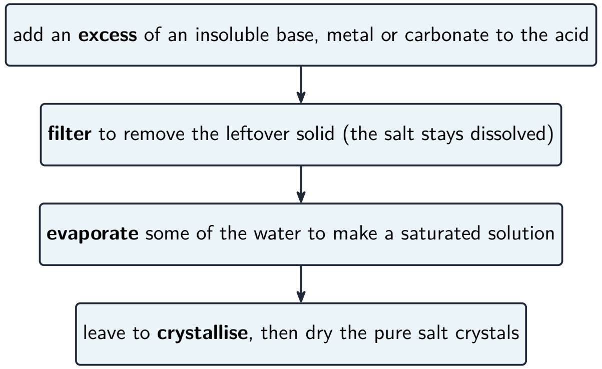
Salt type	Rule
sodium, potassium, ammonium salts	all soluble
nitrates 硝酸盐	all soluble
chlorides 氯化物	soluble, except lead and silver
sulfates 硫酸盐	soluble, except barium, calcium and lead
carbonates	insoluble, except sodium, potassium and ammonium
hydroxides	insoluble, except sodium, potassium, ammonium and (partly) calcium

Making a soluble salt

You react an acid with one of these:

- an **alkali**, using **titration** 滴定 (since both are solutions, you must measure the exact volumes);
- an **excess** 过量 of a metal, an insoluble base, or an insoluble carbonate.

When you use an excess of a solid, you then **filter** 过滤 to remove the leftover solid. Finally you **evaporate** 蒸发 some water and let the solution **crystallise** 结晶 to get the salt.



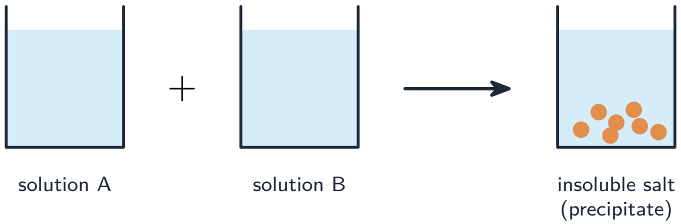
Making a soluble salt from an insoluble solid: react with excess, filter off the excess, evaporate, then crystallise

Letting the solution crystallise slowly gives well-shaped crystals — here, the blue crystals of copper(II) sulfate

Worked example. Which method would you use to prepare (a) copper(II) sulfate and (b) barium sulfate? Check the solubility rules first. (a) Copper(II) sulfate is **soluble** (only barium, calcium and lead sulfates are not), so make it from an insoluble solid and an acid: add **excess** copper(II) oxide to warm dilute sulfuric acid, **filter** off the leftover solid, then evaporate some water and crystallise. (b) Barium sulfate is **insoluble**, so make it by **precipitation**: mix two solutions that each carry one of the needed ions, then filter, wash and dry the solid. The solubility of the salt you want is what decides the method - consult the rules before you choose.

Making an insoluble salt

An insoluble salt is made by **precipitation** 沉淀: mix two solutions that each contain one of the needed ions, and the insoluble salt forms as a solid. You then filter, wash and dry it.



Mixing two solutions that each carry one of the needed ions makes the insoluble salt appear as a solid precipitate, which you then filter off

Water in salts

- A **hydrated** 水合 substance is chemically joined with water.
- An **anhydrous** 无水 substance contains no water.

The water molecules inside hydrated crystals are called the **water of crystallisation** 结晶水. For example, $CuSO_4 \bullet 5H_2O$ has five water molecules for each formula unit.

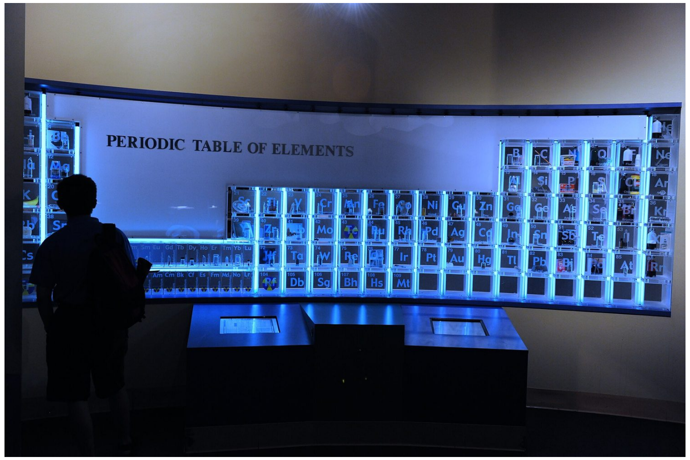
Exam tips

- Learn the three acid reactions: acid + metal → salt + hydrogen; acid + base → salt + water (neutralisation); acid + carbonate → salt + water + carbon dioxide.
- **Strong** and **weak** describe how much the acid splits into ions (dissociation), *not* how concentrated it is. A strong acid is fully dissociated; a weak acid only partly.
- A lower **pH** means a higher hydrogen-ion concentration. pH 7 is neutral, below 7 is acidic, above 7 is alkaline.
- Choose the salt method by solubility: a **soluble** salt is made from an acid + excess solid (then filter, evaporate, crystallise), or by titration with an alkali; an **insoluble** salt is made by precipitation (mix two solutions, then filter).
- Learn the solubility rules — all sodium, potassium, ammonium and nitrate salts are soluble.

The Periodic Table

IGCSE Chemistry

Arrangement of the elements



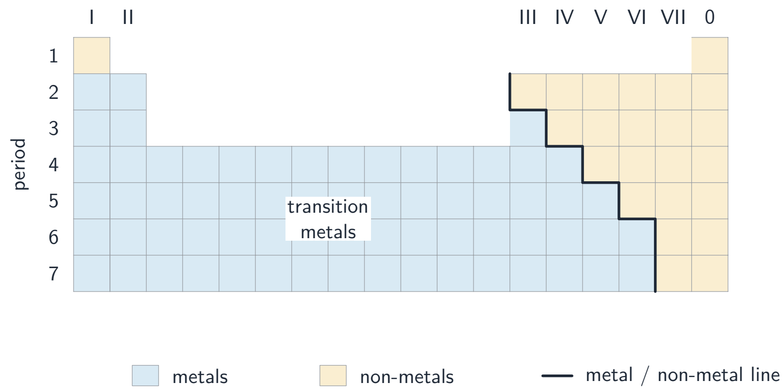
The periodic table arranges the elements in order of atomic number.

The **Periodic Table** 周期表 arranges all the **elements** 元素 in order of increasing **proton number** 质子数 (the **atomic number** 原子序数). The horizontal rows are called **periods** 周期 and the vertical columns are called **groups** 族.

A few key patterns:

- Across a period, the elements change from **metals** 金属 on the left to **non-metals** 非金属 on the right.
- The group number tells you the charge of the **ions** 离子 that the elements form. Group I forms +1 ions, Group II forms +2 ions, and Group VII forms −1 ions.
- Elements in the same group have similar chemical properties. This is because they have the same number of outer-shell **electrons** 电子 (the same outer **electronic configuration** 电子排布).

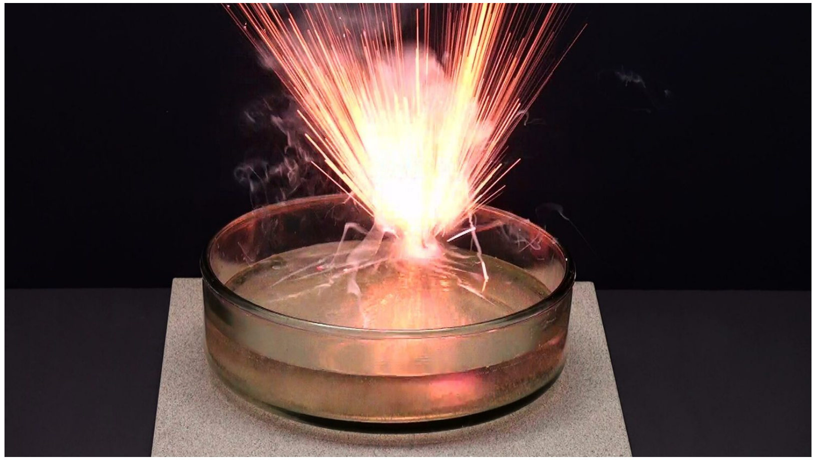
Because of these patterns, you can use an element's position to predict its properties.



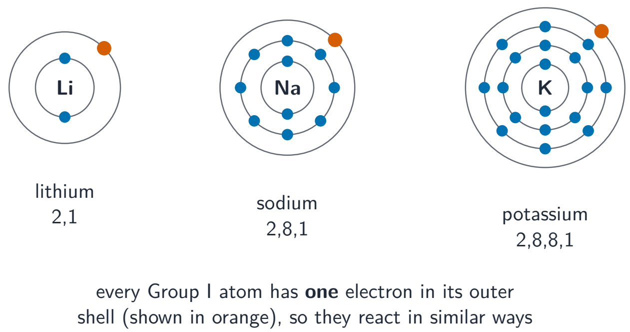
Groups are the columns and periods are the rows; metals lie to the left of the staircase, non-metals to the right

Group I — the alkali metals

Group I elements are the **alkali metals** 碱金属: **lithium** 锂, **sodium** 钠 and **potassium** 钾. They are **soft** 柔软 metals (you can cut them with a knife).



Potassium reacts violently with water, giving off hydrogen that burns with a lilac flame — reactivity increases down Group I



Every Group I atom has one electron in its outer shell, which is why they react in similar ways

Going down the group, there are clear **trends** 趋势:

Property	Trend going down the group
melting point 熔点	decreases
density 密度	increases
reactivity 活泼性	increases

You can use these trends to predict the properties of other Group I elements. For example, rubidium (below potassium) would be even more reactive and have an even lower melting point.

Reaction with water, and what you see

This is the reaction the exam asks about most. Every Group I metal reacts with water to give an **alkali** (the metal hydroxide) plus **hydrogen** - which is exactly why they are called the alkali metals:

$$2Na + 2H_2O \rightarrow 2NaOH + H_2$$

"Describe what you see" is worth marks of its own, so learn the list for **sodium on water**:

- it **floats** - the metal is less dense than water.
- it **melts into a ball** - the reaction gives out heat, and the metal's melting point is low.
- it **moves about** on the surface - the hydrogen jetting off pushes it around.
- there is **effervescence** 泡腾 (fizzing) - the hydrogen gas escaping.
- it **gets smaller and disappears** as it is used up.

- the solution turns **alkaline**, so universal indicator goes **purple** (it is now NaOH).

The trend shows up in how violent this is: **lithium** fizzes steadily but does not melt; **sodium** melts into a ball and darts around; **potassium** is fast enough to ignite its own hydrogen, burning with a **lilac flame**. Two answers to avoid: "hydrogen is given off" is not an observation (you cannot see it - say **effervescence**), and the metal melts because the **reaction is exothermic**, not because "water is hot".

Group VII — the halogens

Group VII elements are the **halogens** 卤素: **chlorine** 氯气, **bromine** 溴 and **iodine** 碘. They are **diatomic** 双原子 non-metals (each molecule is made of two atoms, such as Cl_2).

Their appearance at room temperature and pressure:

Halogen	Appearance
chlorine	a pale yellow-green gas
bromine	a red-brown liquid
iodine	a grey-black solid

Going down the group, the density increases but the reactivity **decreases** (the opposite trend to Group I).

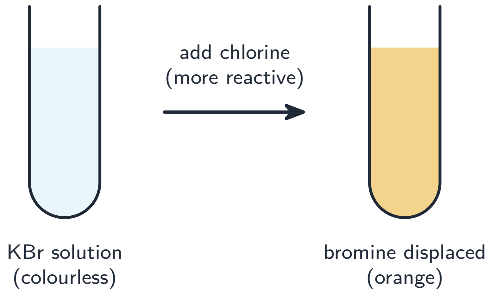
Group I gets more reactive down the group, while Group VII gets less reactive down — opposite trends

Displacement reactions

A more reactive halogen pushes out (displaces) a less reactive **halide** 卤化物 ion from its solution. This is a **displacement reaction** 置换反应.

For example, chlorine is more reactive than bromine, so chlorine displaces bromine from potassium bromide:

$$Cl_2 + 2KBr \rightarrow 2KCl + Br_2$$



Chlorine is more reactive, so it displaces bromine from the solution; the released bromine turns the colourless solution orange

Worked example. Aqueous chlorine is added to potassium iodide solution; then aqueous iodine is added to potassium bromide solution. What happens in each? Reactivity falls **down** Group VII: chlorine, then bromine, then iodine. (a) Chlorine is above iodine, so it is more reactive and displaces it: $Cl_2 + 2KI \rightarrow 2KCl + I_2$, and the solution turns red-brown as iodine is released. (b) Iodine is **below** bromine, so it is less reactive and cannot displace it - there is **no reaction** and no colour change. "No reaction" is a complete answer worth marks: check the order in the group before you write any equation.

Transition elements

The **transition elements** 过渡元素 are the block of metals in the middle of the Periodic Table. Compared with Group I metals, they:

- have high densities;
- have high melting points;
- form **coloured** 有色 **compounds** 化合物;
- often act as catalysts, both as elements and in compounds.

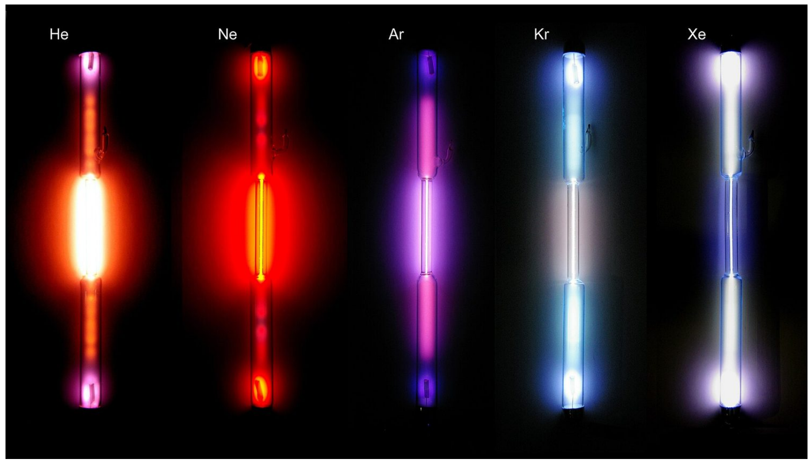
They can also have **variable** 可变 **oxidation numbers** 氧化数. For example, **iron** 铁 forms both iron(II) and iron(III) compounds.

Transition metals form coloured compounds: each of these solutions contains a different transition-metal ion

Group VIII — the noble gases

The Group VIII **noble gases** 稀有气体 are **unreactive** 不活泼, **monatomic** 单原子 gases (they exist as single atoms, not as molecules).

They are unreactive because they already have a full outer shell of electrons. This makes them stable, so they do not need to gain, lose or share electrons.



Passing electricity through each noble gas makes it glow a characteristic colour — this is how neon signs and other lights work

Exam tips

- The Periodic Table is ordered by **proton number**. Elements in the same **group** (column) have the same number of outer electrons, so they react in similar ways; **periods** are the rows.
- **Group I** (alkali metals) get *more* reactive going down; **Group VII** (halogens) get *less* reactive going down — opposite trends.
- A more reactive **halogen displaces** a less reactive one from a solution of its salt — for example chlorine displaces bromine.
- **Noble gases** are unreactive because they have a full outer shell. **Transition elements** are hard and dense, form coloured compounds, act as catalysts and have variable oxidation numbers.

Metals

IGCSE Chemistry

Properties of metals

Physical properties

Metals 金属 and **non-metals** 非金属 behave very differently:

Property	Metals	Non-metals
thermal conductivity 导热性 (conducting heat)	good	poor
electrical conductivity 导电性	good	poor (except graphite)
malleability 展性 and **ductility** 延性	malleable and ductile	**brittle** 易碎 (they snap)
melting point 熔点 and **boiling point** 沸点	usually high	usually low

Chemical properties

Metals react in three main ways:

- with dilute **acids** 酸 → a **salt** 盐 + **hydrogen** 氢气
- with cold water or **steam** 蒸汽 → a metal hydroxide (or oxide) + hydrogen
- with **oxygen** 氧气 → a metal **oxide** 氧化物

Native copper: metals are shiny, dense, malleable conductors of heat and electricity

Uses of metals

A metal is chosen for a job because of its physical properties.

- **Aluminium** 铝 is used to make aircraft because of its low **density** 密度 (it is light).
- Aluminium is used for overhead electrical cables because of its low density and good electrical conductivity.
- Aluminium is used for food containers because it resists **corrosion** 腐蚀.
- **Copper** 铜 is used for electrical wiring because of its good electrical conductivity and its ductility (it can be drawn into wires).

Aircraft bodies use a lot of aluminium: it is strong but has a low density, so the plane stays light

Alloys

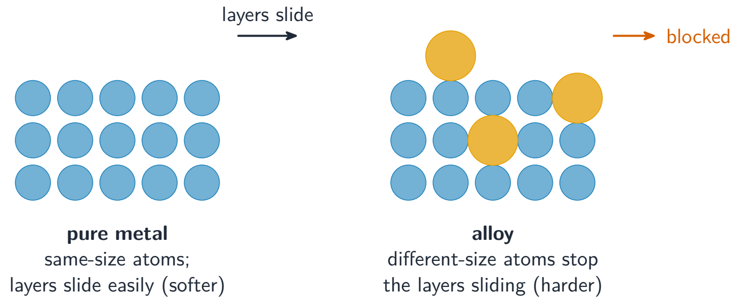
An **alloy** 合金 is a **mixture** 混合物 of a metal with one or more other elements.

- **Brass** 黄铜 is a mixture of copper and **zinc** 锌.
- **Stainless steel** 不锈钢 is a mixture of **iron** 铁 with other elements such as **chromium** 铬, **nickel** 镍 and **carbon** 碳.

Alloys are usually harder and stronger than the pure metals, which makes them more useful. For example, stainless steel is used for cutlery because it is hard and does not rust.

Why alloys are harder. In a pure metal, the **atoms** 原子 are all the same size, so

the **layers** 层 can slide over each other easily. In an alloy, the different-sized atoms stop the layers from sliding, so the alloy is harder and stronger.



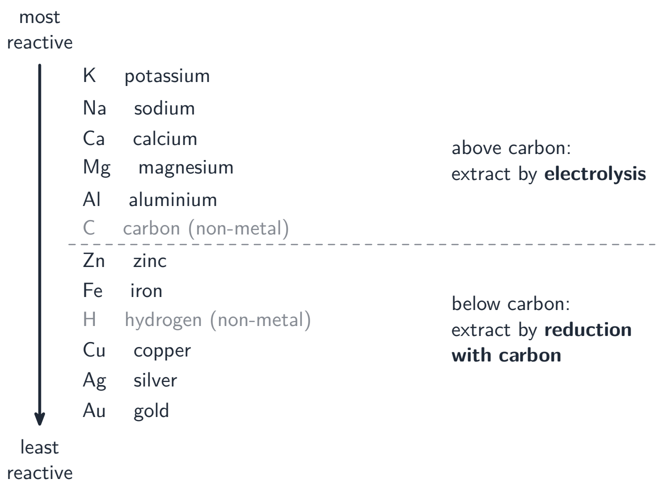
In an alloy, different-sized atoms stop the layers sliding past each other, so the alloy is harder than the pure metal

The reactivity series

The **reactivity series** 金属活动性顺序 lists metals in order of how reactive they are. Carbon and hydrogen are included for comparison:

> **potassium** 钾, **sodium** 钠, **calcium** 钙, **magnesium** 镁, aluminium, carbon, zinc, iron, hydrogen, copper, silver, gold

(most reactive at the top, least reactive at the bottom)



Metals above carbon are extracted by electrolysis; those below carbon can be extracted by heating with carbon

The higher a metal is, the more easily it forms positive **ions** 离子. This explains its reactions:

- potassium, sodium and calcium react with cold water.
- magnesium reacts with steam (but only very slowly with cold water).
- magnesium, zinc and iron react with dilute hydrochloric acid; copper, silver and gold do not.

Displacement reactions

A more reactive metal will displace a less reactive metal from a solution of its ions (a **displacement reaction** 置换反应). For example, zinc displaces copper from copper(II) sulfate solution, because zinc is more reactive than copper:

$$\mathrm{Zn + CuSO_4 \rightarrow ZnSO_4 + Cu}$$

Be ready to say what you would **see**, because those are separate marks:

- the **blue** colour of the solution **fades** - the blue Cu^{2+} ions are being used up (zinc sulfate is colourless).
- a **pink-brown solid** coats the zinc - that is the displaced copper.
- the grey zinc **dissolves** and gets smaller.
- the mixture **warms up** - displacement is exothermic.

Metal-and-acid reactions have their own list: **effervescence** 泡腾 (the hydrogen escaping) and the **solid dissolves**. With copper(II) oxide or carbonate and acid, add that the solution **turns blue**. Never write “hydrogen is given off” as an observation - you cannot see the gas, only the bubbles, so write **effervescence**.

Worked example. Zinc and aluminium are both found as oxides. Which can be extracted by heating with carbon, and why? Find each metal’s place relative to **carbon** in the reactivity series. Zinc sits **below** carbon, so carbon is the more reactive of the two and can take the oxygen away from it: zinc oxide is reduced by heating with carbon. Aluminium sits **above** carbon, so carbon is not reactive enough to displace it, and aluminium must be extracted by **electrolysis** instead - which is why aluminium costs far more to extract. The line in the series that decides the method is carbon’s, not the top of the list.

The special case of aluminium

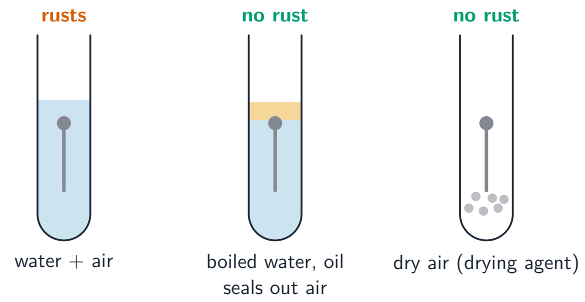
Aluminium seems less reactive than its position suggests. This is because it is covered by a thin, strong **oxide layer** 氧化层 that stops other substances reaching the metal underneath.

Corrosion of metals

Corrosion slowly eats away unprotected metal.

Rusting 生锈 is the corrosion of iron and steel. Two things are needed for rusting: **oxygen** (from the air) and water. The **rust** 铁锈 formed is hydrated iron(III) oxide.

Sea water and air have badly rusted this iron chain — the rust is hydrated iron(III) oxide



Rusting needs both water and oxygen — the nail only rusts in the tube that has both

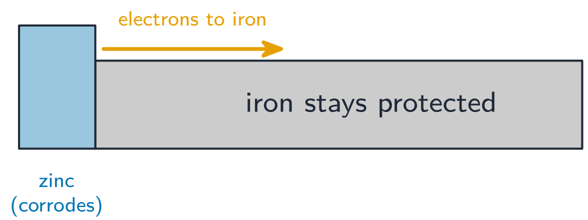
Stopping rust

Barrier methods 隔离法 keep oxygen and water away from the iron:

- painting, **greasing** (covering with oil), and coating with plastic.

Galvanising 镀锌 means coating iron with a layer of zinc. This works in two ways:

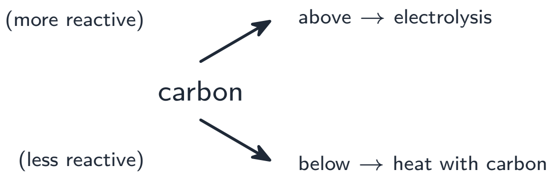
- it is a barrier (the zinc keeps out air and water);
- it gives **sacrificial protection** 牺牲保护. Because zinc is more reactive than iron, the zinc loses **electrons** 电子 and corrodes instead of the iron — even if the surface is scratched.



The more reactive zinc corrodes and gives its electrons to the iron, so the iron is protected even where the surface is scratched

Extraction of metals

How a metal is taken from its **ore** 矿石 depends on its place in the reactivity series. Metals below carbon can be extracted by heating with carbon (which removes the oxygen). Metals above carbon are too reactive for this and must be extracted by **electrolysis** 电解.

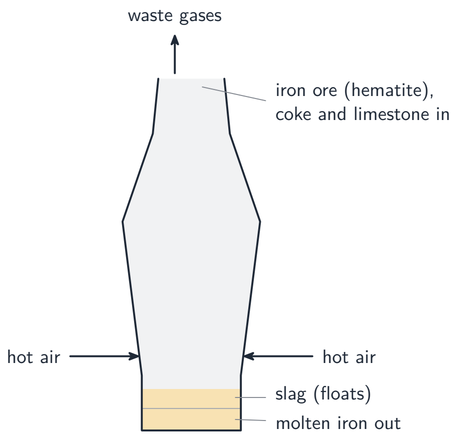


Metals above carbon need electrolysis; those below are heated with carbon

Iron from the blast furnace

Iron is extracted from its ore **hematite** 赤铁矿 (iron(III) oxide) in a **blast furnace** 高炉:

- Carbon (coke) burns in hot air to give carbon dioxide and lots of heat.
- This **carbon dioxide** 二氧化碳 reacts with more carbon to form **carbon monoxide** 一氧化碳.
- The carbon monoxide **reduces** the iron(III) oxide to iron (this is **reduction** 还原).
- **Limestone** 石灰石 (calcium carbonate) breaks down in the heat to form **calcium oxide** 氧化钙.
- The calcium oxide reacts with sandy impurities to form **slag** 炉渣, which is removed.



$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$$
(carbon monoxide reduces the ore)

In the blast furnace, carbon monoxide reduces the iron ore, and limestone removes sandy impurities as slag

Aluminium by electrolysis

Aluminium is extracted from its ore **bauxite** 铝土矿 (purified to aluminium oxide) by electrolysis:

- The aluminium oxide is dissolved in molten **cryolite** 冰晶石 to lower its melting point and save energy.

- At the **cathode** 阴极, aluminium ions gain electrons to form aluminium metal.
- At the **anode** 阳极, oxygen is formed. This oxygen reacts with the hot carbon anodes and burns them away, so they must be replaced regularly.

Exam tips

- Learn the **reactivity series** (potassium → gold). A more reactive metal displaces a less reactive one from a solution of its ions.
- Metals *above* carbon are extracted by **electrolysis**; those *below* carbon (like iron) can be extracted by heating with carbon.
- **Rusting** needs *both* water and oxygen. Barrier methods (paint, oil) keep them out; **galvanising** also gives sacrificial protection, because the more reactive zinc corrodes instead of the iron.
- **Alloys** are harder than pure metals because the different-sized atoms stop the layers of ions sliding over each other.

Chemistry of the environment

IGCSE Chemistry

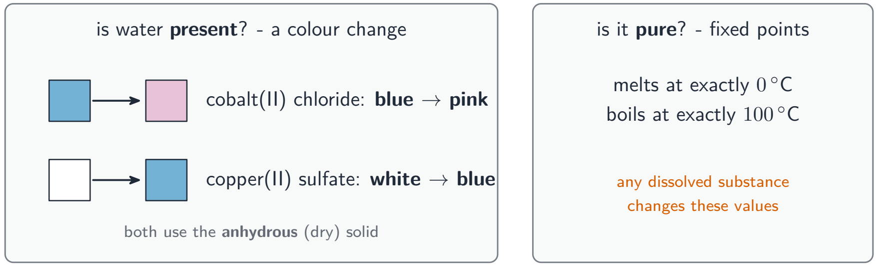
Water

Testing for water

Two chemical tests show that water is **present**:

- **Anhydrous** 无水 cobalt(II) chloride turns from blue to pink when water is added.
- Anhydrous copper(II) sulfate turns from white to blue when water is added.

These tests only show that water is there. To show that water is **pure**, you test its **melting point** 熔点 and **boiling point** 沸点: pure water melts at exactly 0 °C and boils at exactly 100 °C. Any dissolved substance changes these values.



Colour-change tests show water is present; fixed melting and boiling points show it is pure

This is why **distilled water** 蒸馏水 is used in chemistry instead of tap water — it has far fewer chemical **impurities** 杂质.

What is in natural water

Water from rivers, lakes and the sea is not pure. It may contain dissolved **oxygen** 氧气, metal compounds, plastics, **sewage** 污水, harmful **microbes** 微生物, and **nitrates** 硝酸盐 and **phosphates** 磷酸盐 (which come from fertilisers and detergents).

Some of these are helpful:

- dissolved oxygen lets **aquatic life** 水生生物 (fish and plants) breathe;
- some metal compounds give essential **minerals** 矿物质.

Others are harmful:

- some metal compounds are **toxic** 有毒 (poisonous);
- some plastics harm aquatic life;
- sewage carries microbes that cause disease;
- nitrates and phosphates cause **deoxygenation** 缺氧 (loss of oxygen) in the water, which harms aquatic life.

Treating drinking water

To make water safe to drink, the water supply is treated in steps:

- **sedimentation** 沉降 and **filtration** 过滤 remove solid bits;
- passing it through **carbon** 碳 removes bad tastes and smells;
- **chlorination** 氯消毒 (adding chlorine) kills harmful microbes.

sedimentation — large bits settle to the bottom
↓
filtration — remove the remaining solid bits
↓
pass through **carbon** — removes bad tastes and smells
↓
chlorination — chlorine kills harmful microbes
↓
safe drinking water

Water is made safe to drink in steps: settle out big bits, filter, remove tastes with carbon, then chlorinate

Fertilisers

Fertilisers 肥料 are added to soil to help plants grow. Ammonium salts and nitrates are common fertilisers.

NPK fertilisers contain the three elements plants need most: **nitrogen** 氮气, **phosphorus** 磷 and **potassium** 钾.

N	P	K
nitrogen	**phosphorus**	**potassium**
leaf and stem growth	strong roots	flowers and fruit

NPK fertilisers contain all three - ammonium salts and nitrates supply the nitrogen

NPK fertilisers supply the three elements plants need most: nitrogen, phosphorus and potassium

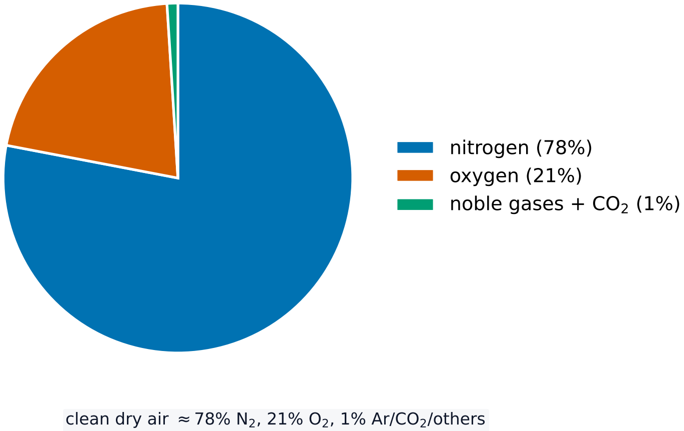
Air quality and climate

Burning fossil fuels pollutes the air and changes the climate.

Clean, dry air is approximately:

- 78% nitrogen (N_2)
- 21% oxygen (O_2)

- the rest is a mixture of **noble gases** 稀有气体 and carbon dioxide (CO_2).



Clean, dry air is about 78% nitrogen, 21% oxygen, and 1% other gases (noble gases and carbon dioxide)

Air pollutants and their sources

Pollutant	Main source
carbon dioxide (CO_2)	**complete combustion** 完全燃烧 of carbon-containing fuels
carbon monoxide 一氧化碳 and **particulates** 颗粒物	**incomplete combustion** 不完全燃烧 of carbon-containing fuels
methane 甲烷	rotting plants and waste gases from animal digestion
oxides of nitrogen 氮氧化物	car engines
sulfur dioxide	burning **fossil fuels** 化石燃料 that contain **sulfur** 硫

Effects of these pollutants

- **Carbon dioxide** 二氧化碳 and methane are **greenhouse gases** 温室气体: more of them causes **global warming** 全球变暖, which leads to **climate change** 气候变化.
- Carbon monoxide is a toxic gas.
- Particulates increase the risk of **respiratory** 呼吸 (breathing) problems and **cancer** 癌症.
- Oxides of nitrogen cause **acid rain** 酸雨, **photochemical smog** 光化学烟雾 and breathing problems.
- Sulfur dioxide causes acid rain.

Worked example. A power station burns coal containing sulfur, and a lake downwind slowly turns acidic. Name the pollutant, explain the link, and give one way to stop it. Burning a fossil fuel that contains sulfur releases **sulfur dioxide**, which causes **acid rain**, so the rain falling on the lake is acidic. To stop it at the source, use **flue gas desulfurisation**, where calcium oxide removes the sulfur dioxide from the waste gases before they leave the chimney, or switch to a low-sulfur fuel. Match the fix to the pollutant: a **catalytic converter** treats a car's oxides of nitrogen and would do nothing about a coal-fired power station's sulfur dioxide.

Reducing these problems

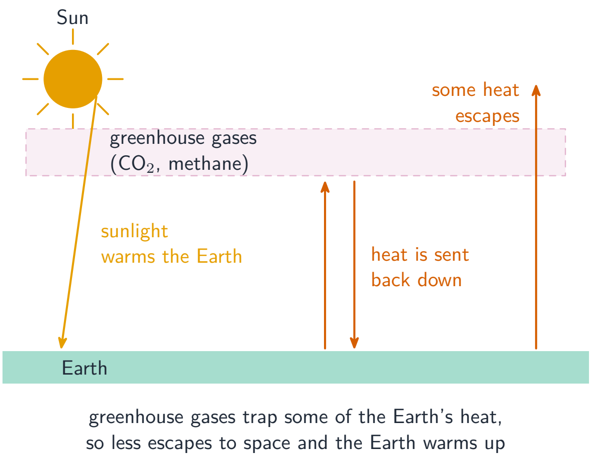
To slow **climate change**: plant trees, farm fewer animals, burn fewer fossil fuels, and use more hydrogen and **renewable energy** 可再生能源 such as wind and solar power.

To reduce **acid rain**: fit **catalytic converters** 催化转化器 in cars, use low-sulfur fuels, and use **flue gas desulfurisation** 烟气脱硫 with **calcium oxide** 氧化钙 to remove sulfur dioxide from waste gases.

Inside a catalytic converter is a honeycomb coated with catalyst metals; the many tiny channels give a huge surface area

How greenhouse gases warm the Earth

Greenhouse gases such as carbon dioxide and methane let sunlight through, but they **absorb** the **thermal energy** 热能 given off by the warm Earth, and send some of it back down. This reduces the thermal energy lost to space, so the Earth gets warmer.



Greenhouse gases let sunlight through but trap some of the heat the Earth gives off, so the Earth warms up

In a car engine, the high temperature makes nitrogen and oxygen from the air react to form oxides of nitrogen. A **catalytic converter** removes them, for example:

$$2CO + 2NO \rightarrow 2CO_2 + N_2$$

Photosynthesis

Photosynthesis 光合作用 is the opposite of combustion — it removes carbon dioxide from the air. Plants use light energy and **chlorophyll** 叶绿素 to turn carbon dioxide and water into **glucose** 葡萄糖 and oxygen:

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$$

Exam tips

- Two tests show water is *present* (cobalt(II) chloride blue → pink; copper(II) sulfate white → blue), but only fixed melting and boiling points (0 °C and 100 °C) show it is *pure*.
- Clean, dry air is about **78% nitrogen, 21% oxygen** and 1% other gases (mostly noble gases and carbon dioxide).
- Match each pollutant to its source and effect: **carbon monoxide** (incomplete combustion; toxic); **sulfur dioxide** and **oxides of nitrogen** (acid rain); **carbon dioxide** and **methane** (greenhouse gases → global warming).
- Greenhouse gases let sunlight through but absorb the heat the warm Earth gives off and send some back down, so the Earth warms up.

Organic chemistry

IGCSE Chemistry

Organic chemistry is the chemistry of carbon compounds. Carbon is special because it can join to other carbon atoms to make long chains and rings.

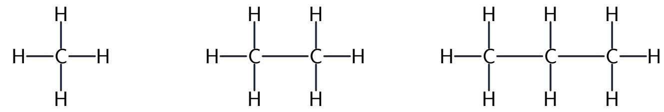
Formulae and key words

There are several ways to write an organic molecule:

- The **molecular formula** 分子式 shows how many of each atom there are, for example C_2H_6.
- The **displayed formula** 结构式 shows every atom and every bond drawn out in full.
- The **structural formula** 结构简式 shows how the atoms are arranged without drawing every bond, for example CH_3CH_2OH.
- The **general formula** 通式 works for a whole family, for example C_nH_{2n+2} for alkanes.

A **homologous series** 同系物 is a family of compounds with the same **functional group** 官能团 — the atom or group of atoms that gives the family its chemical properties. Members of a series have the same general formula, differ by a CH_2 unit each step, and have similar chemical properties with a gradual change in physical properties.

Series	Functional group	General formula
alkanes	C–C single bonds only	C_nH_{2n+2}
alkenes	C=C double bond	C_nH_{2n}
alcohols	–OH	$C_nH_{2n+1}OH$
carboxylic acids	–COOH	$C_nH_{2n+1}COOH$

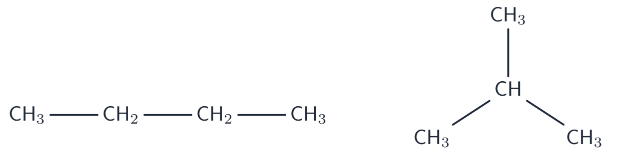


The alkanes are a homologous series: each member has one more CH_2 unit (general formula C_nH_{2n+2})

A **saturated** 饱和 compound has only single carbon–carbon bonds. An **unsaturated** 不饱和 compound has one or more carbon–carbon bonds that are not single (such as a C=C double bond).

A saturated compound has only single C–C bonds; an unsaturated one has a C=C double bond

Structural isomers 同分异构体 are compounds with the same molecular formula but different structural formulae. For example, C_4H_{10} can be a straight chain or a branched chain.



butane (straight chain)

2-methylpropane (branched)

both have the formula C_4H_{10}: same formula, different structure (structural isomers)

Structural isomers: butane and 2-methylpropane share the formula C_4H_{10} but have different structures

Naming organic compounds

The end of the name tells you the family:

Ending	Family	Example
-ane	alkane	methane, ethane
-ene	alkene	ethene
-ol	alcohol	ethanol
-oic acid	carboxylic acid	ethanoic acid

The start of the name tells you the number of carbon atoms: *meth-* = 1, *eth-* = 2, *prop-* = 3, *but-* = 4. For longer alkenes and alcohols, a number shows where the functional group is, for example but-1-ene and but-2-ene, or propan-1-ol and propan-2-ol.

Fuels

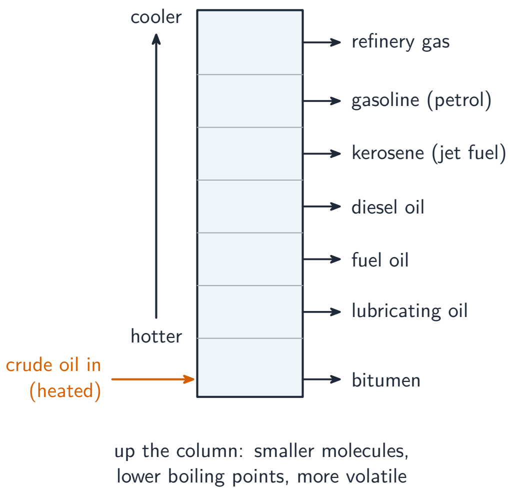
An oil refinery separates crude oil into useful fuels by fractional distillation.

The three **fossil fuels** 化石燃料 are **coal** 煤, **natural gas** 天然气 and **petroleum** 石油 (crude oil). **Methane** 甲烷 is the main part of natural gas.

A **hydrocarbon** 碳氢化合物 is a compound made of hydrogen and carbon only. Petroleum is a mixture of many different hydrocarbons.

Fractional distillation

Petroleum is separated into useful **fractions** 馏分 by **fractional distillation** 分馏. The mixture is heated, and the different hydrocarbons turn to gas and rise up a tall **fractionating column** 分馏塔. The column is hot at the bottom and cool at the top, so each fraction turns back to liquid at a different height.



Fractions separate by boiling point: small molecules leave the cool top, thick bitumen stays at the hot bottom

Going from the bottom to the top of the column, the fractions have:

- shorter **chain length** 链长 (smaller molecules);
- higher **volatility** 挥发性 (they turn to gas more easily);
- lower boiling points;
- lower **viscosity** 黏度 (they flow more easily).

Fraction	Use
refinery gas	gas for heating and cooking
gasoline / petrol	fuel for cars
naphtha	raw material for making chemicals
kerosene / paraffin	jet fuel
diesel oil	fuel for diesel engines
fuel oil	fuel for ships and home heating
lubricating oil	lubricants, waxes and polishes
bitumen 沥青	making roads

Alkanes

Alkanes 烷烃 have only single covalent bonds, so they are saturated hydrocarbons. They are generally unreactive. Their two important reactions are:

- **Combustion** 燃烧: they burn in plenty of oxygen to give carbon dioxide and water.
- **Substitution** with chlorine.

In a **substitution reaction** 取代反应, one atom (or group of atoms) is replaced by another. Alkanes react with chlorine only in **ultraviolet light** 紫外线 — this is a **photochemical reaction** 光化学反应, where the light provides the **activation energy** 活化能. For example:

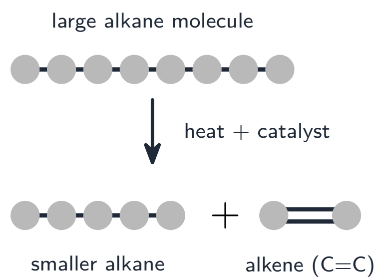
$$CH_4 + Cl_2 \rightarrow CH_3Cl + HCl$$

Alkenes

Alkenes 烯烃 have a carbon–carbon double bond (C=C), so they are unsaturated hydrocarbons.

Cracking

Large alkane molecules are not very useful. **Cracking** 裂化 breaks them into smaller, more useful molecules — smaller alkanes and alkenes — using a high temperature and a **catalyst** 催化剂. Cracking also makes **hydrogen** 氢气 and provides alkenes for making plastics.



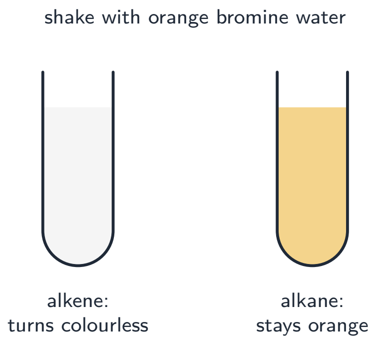
Cracking breaks one large alkane into a smaller alkane plus an alkene (with a C=C), using heat and a catalyst

Worked example. Cracking one molecule of decane, $C_{10}H_{22}$, gives octane, C_8H_{18}, and one other product. Identify it, and say how you would tell the two products apart. Atoms are conserved, so subtract: carbon $10-8=2$, hydrogen $22-18=4$. The other product is C_2H_4, ethene - an **alkene**, because it fits C_nH_{2n}. To tell them apart, shake each with orange **bromine water**: ethene has a C=C, so it decolourises the bromine water, while octane is saturated and leaves it orange. Balance a cracking equation by counting atoms on each side; the alkene is whatever is left over.

Reactions of alkenes

The C=C double bond makes alkenes reactive. They take part in **addition reactions** 加成反应, where two molecules join to form a single product.

- **Test for unsaturation**: shake the compound with **bromine** 溴 water (which is orange). An alkene turns the bromine water colourless; an alkane does not change it.

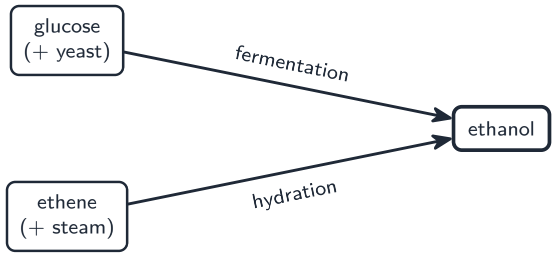


The bromine water test: an alkene decolourises the orange bromine water (its C=C reacts), while an alkane leaves it orange

- With hydrogen and a **nickel** 镍 catalyst, an alkene becomes an alkane.
- With **steam** 蒸汽 and an acid catalyst, an alkene becomes an alcohol.

Alcohols

Alcohols 醇 contain the –OH functional group. The most important one is **ethanol** 乙醇. There are two ways to make ethanol.



Two routes to ethanol: fermentation, and hydration of ethene

Method	Conditions	Notes
fermentation 发酵 of glucose	yeast, 25–35 °C, no oxygen	uses renewable sugar, but slow and gives impure ethanol
addition of steam to **ethene** 乙烯	300 °C, 60 atm, acid catalyst	fast and pure, but uses petroleum (non-renewable)

In **fermentation**, **yeast** 酵母 turns **glucose** 葡萄糖 into ethanol and carbon dioxide.

Ethanol burns well (combustion), so it is used as a **fuel**. It also dissolves many substances, so it is used as a **solvent** 溶剂.

Carboxylic acids

Carboxylic acids 羧酸 contain the –COOH functional group. **Ethanoic acid** 乙酸 is the one to know. Like other acids, it reacts with:

A carboxylic acid and an alcohol react to make an ester and water

- **metals** 金属 → a salt + hydrogen;
- **bases** 碱 → a **salt** 盐 + water;
- **carbonates** 碳酸盐 → a salt + water + carbon dioxide.

The salts formed are called ethanoates.

Ethanoic acid can be made by the **oxidation** 氧化 of ethanol, either using acidified **potassium manganate(VII)** 高锰酸钾, or by bacteria during the making of **vinegar** 醋.

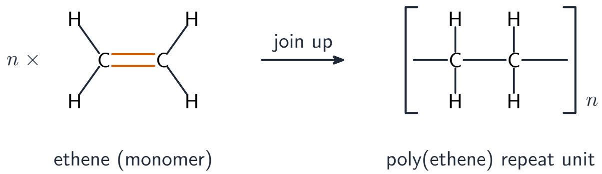
When a carboxylic acid reacts with an alcohol (using an acid catalyst), it forms an **ester** 酯. For example, **ethanol + ethanoic acid → ethyl ethanoate + water**. The ester's functional group is −COO−, and you name it from its two parents: the alcohol gives the first part with an **-yl** ending (*ethyl*), the acid gives the second part with an **-oate** ending (*ethanoate*). Its displayed formula is CH_3-COO-CH_2-CH_3.

Polymers

A **polymer** 聚合物 is a very large molecule built from many small molecules called **monomers** 单体.

Addition polymerisation

In **addition polymerisation** 加聚, many unsaturated monomers join together with no other product. For example, many ethene monomers join to make poly(ethene). The small part that repeats along the chain is the **repeat unit** 重复单元.



In addition polymerisation the C=C bonds open up and many ethene monomers join into a long poly(ethene) chain

Condensation polymerisation

In **condensation polymerisation** 缩聚, monomers join and a small molecule (usually water) is lost each time a bond forms. This makes two important types:

- **Polyamides** 聚酰胺 are made from a dicarboxylic acid and a diamine. **Nylon** 尼龙 is a polyamide.
- **Polyesters** 聚酯 are made from a dicarboxylic acid and a diol. PET is a polyester, and it can be broken back into its monomers and re-made.

The new bond joining the monomers is the **linkage**: an **amide linkage** 酰胺键 (written −CO-NH−) in a polyamide such as nylon, and an **ester linkage** 酯键 (written −CO-O−) in a polyester such as PET. A repeat unit is drawn in brackets, e.g. nylon as −[CO-$(CH_2)_4$-CO-NH-$(CH_2)_6$-NH]−; in an exam you may be asked to circle the linkage in a drawn repeat unit.

Plastics and the environment

Plastics 塑料 are made from polymers. Because many plastics do not break down, getting rid of them is a problem:

- they build up in **landfill** 填埋 sites;
- they collect in the oceans and harm sea life;
- burning them can make toxic gases.

Most plastics are non-biodegradable, so waste plastic collects on beaches and in the oceans for hundreds of years

Proteins

Proteins 蛋白质 are natural polyamides. They are made from **amino acid** 氨基酸 monomers joined in long chains.

Exam tips

- Learn each **homologous series** by its functional group and general formula: alkanes C_nH_{2n+2}, alkenes C_nH_{2n}, alcohols −OH, carboxylic acids −COOH.
- The **bromine water test** for unsaturation: an alkene (with its C=C) turns orange bromine water colourless; an alkane leaves it orange.

- **Cracking** breaks large, less useful alkanes into smaller alkanes and alkenes, using heat and a catalyst.
- Two routes to **ethanol**: fermentation of glucose (renewable but slow and impure) and adding steam to ethene (fast and pure, but from petroleum).
- **Addition** polymerisation joins unsaturated monomers with no other product; **condensation** polymerisation joins monomers and loses a small molecule (usually water) each time.

Experimental techniques and chemical analysis

IGCSE Chemistry

Experimental design

Apparatus

You should know which piece of apparatus to use for each measurement:

Measurement	Apparatus
time	**stop-watch** 秒表
temperature	**thermometer** 温度计
mass	**balance** 天平
volume (accurate)	**burette** 滴定管 or **volumetric pipette** 移液管
volume (rough)	**measuring cylinder** 量筒
volume of a gas	**gas syringe** 注射器

Key words

These words are used throughout practical chemistry:

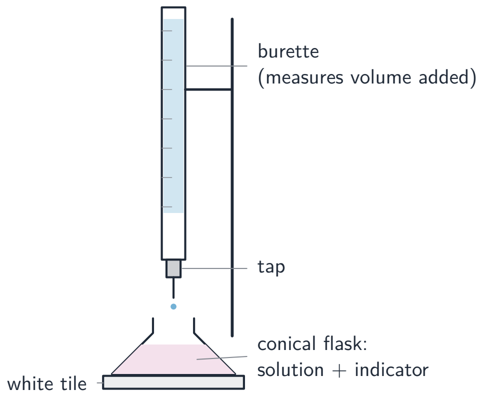
- A **solvent** 溶剂 is a substance that dissolves a solute.
- A **solute** 溶质 is the substance that dissolves in the solvent.
- A **solution** 溶液 is a mixture of one or more solutes dissolved in a solvent.
- A **saturated solution** 饱和溶液 holds the maximum amount of solute that will dissolve at a given temperature.
- A **residue** 残渣 is the substance left behind after evaporation, distillation or filtration.
- A **filtrate** 滤液 is the liquid that has passed through a filter.

Acid–base titrations

A **titration** 滴定 finds the exact volume of one solution that reacts with another.

- Use a **volumetric pipette** to measure a fixed volume of one solution into a flask.
- Add a few drops of a suitable **indicator** 指示剂.
- Add the other solution from a **burette**, slowly, until the colour just changes.

The **end-point** 终点 is the moment the indicator changes colour, which shows the reaction is exactly complete. You read the burette to find the volume added.

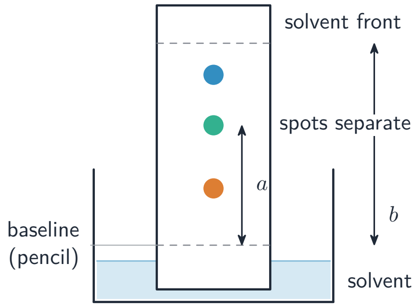


Solution is run from the burette into the flask until the indicator just changes colour (the end-point)

A real titration: solution from the burette is added to the flask, where the indicator has turned orange

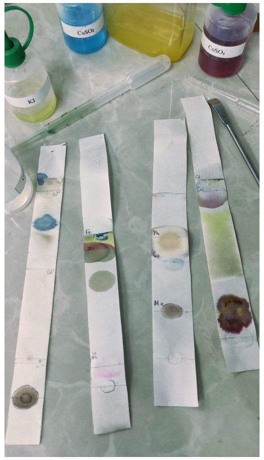
Chromatography

Paper chromatography 纸色谱法 separates a mixture of soluble substances. You put a spot of the mixture near the bottom of the paper, then stand the paper in a solvent. As the solvent rises up the paper, the substances move different distances, so they separate.



$$R_f = \frac{a}{b} = \frac{\text{spot}}{\text{solvent}}$$

As the solvent rises, the substances travel different distances and separate; R_f is the spot distance (a) divided by the solvent distance (b)



On real chromatograms, each substance in the mixture rises a different distance, leaving a separate coloured spot

- For **coloured** substances you can see the spots directly.
- For **colourless** substances you must spray a **locating agent** 显色剂 to make the spots show up.

The finished paper is a **chromatogram** 色谱图. You can use it to:

- identify an unknown substance by comparing it with known substances;
- tell if a substance is pure (a pure substance gives only one spot).

You can also calculate the R_f value of a spot:

$$R_f = \frac{\text{distance moved by the substance}}{\text{distance moved by the solvent}}$$

Worked example. On a chromatogram the solvent front has risen 8.0 cm from the baseline, and a spot has moved 6.0 cm. Find its R_f value.

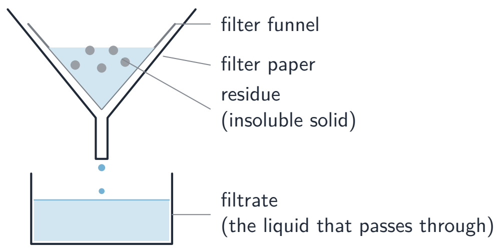
$$R_f = \frac{6.0}{8.0} = 0.75$$

Both distances are measured from the **baseline** (the pencil line), and the spot's distance is taken to the **centre** of the spot. An R_f has no unit, and it is always **less than 1**, because a spot can never travel further than the solvent carrying it - an answer above 1 means the two distances have been divided the wrong way round.

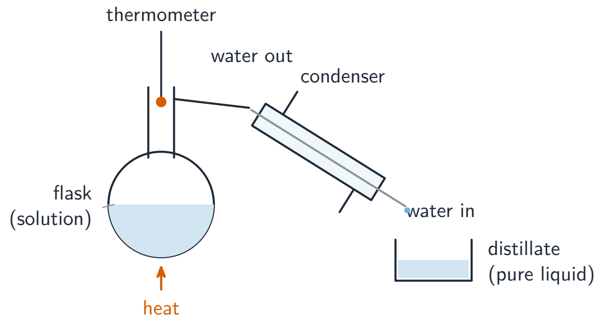
Separation and purification

You choose a method based on the mixture:

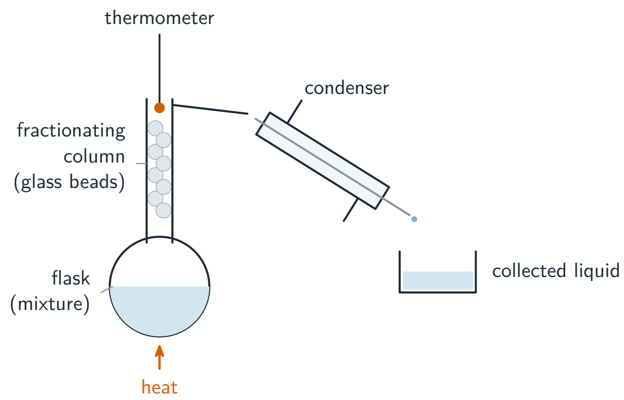
Method	Used to separate
dissolving in a suitable solvent, then **filtration** 过滤	an insoluble solid from a liquid
crystallisation 结晶	a soluble solid from its solution
simple distillation 蒸馏	a solvent (the liquid) from a solution
fractional distillation 分馏	two or more liquids with different boiling points



Filtration: the insoluble solid stays on the filter paper (residue) and the liquid passes through (filtrate)



Simple distillation: the solvent boils off, the condenser cools it back to a liquid, and the pure distillate is collected



Fractional distillation adds a fractionating column, so liquids with different boiling points separate cleanly

You can check the purity of a substance using its **melting point** 熔点 and **boiling point** 沸点: a pure substance melts and boils at sharp, fixed temperatures, while impurities lower the melting point and raise the boiling point.

Identifying ions and gases

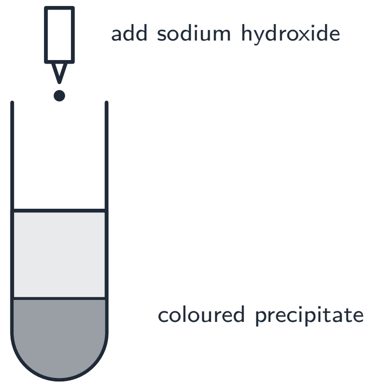
Tests for anions

An **anion** 阴离子 is a negative ion.

Anion	Test	Result
carbonate 碳酸盐 (CO_3^{2-})	add dilute acid	fizzes; the gas turns limewater milky (**carbon dioxide** 二氧化碳)
chloride 氯化物 (Cl^-)	add dilute **nitric acid** 硝酸, then **silver nitrate** 硝酸银	white precipitate
bromide 溴化物 (Br^-)	add dilute nitric acid, then silver nitrate	cream precipitate
iodide 碘化物 (I^-)	add dilute nitric acid, then silver nitrate	yellow precipitate
nitrate 硝酸盐 (NO_3^-)	add **aluminium** 铝 foil and **sodium hydroxide** 氢氧化钠, warm	**ammonia** 氨气 gas given off
sulfate 硫酸盐 (SO_4^{2-})	add dilute nitric acid, then **barium nitrate** 硝酸钡	white precipitate
sulfite 亚硫酸盐 (SO_3^{2-})	add acidified **potassium manganate(VII)** 高锰酸钾	purple colour fades

Tests for cations

A **cation** 阳离子 is a positive ion. Add aqueous sodium hydroxide, or aqueous ammonia, and look at the **precipitate** 沉淀 formed.



Adding sodium hydroxide forms a coloured precipitate for some metal ions

Cation	With sodium hydroxide	With aqueous ammonia
aluminium (Al^{3+})	white, dissolves in excess	white, stays
ammonium 铵 (NH_4^+)	ammonia gas when warmed	—
calcium 钙 (Ca^{2+})	white, stays	no precipitate
chromium(III) 铬 (Cr^{3+})	green, dissolves in excess	green, stays
copper(II) 铜 (Cu^{2+})	light blue, stays	light blue, dissolves to deep blue
iron(II) 铁 (Fe^{2+})	green, stays	green, stays
iron(III) (Fe^{3+})	red-brown, stays	red-brown, stays
zinc 锌 (Zn^{2+})	white, dissolves in excess	white, dissolves in excess

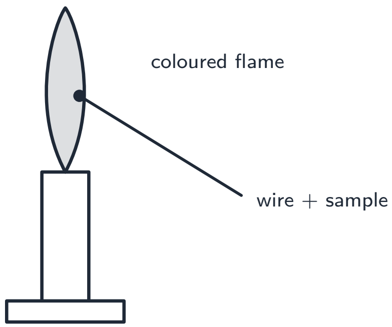
Tests for gases

Gas	Test	Result
ammonia (NH_3)	damp red **litmus** 石蕊 paper	turns blue
carbon dioxide (CO_2)	bubble through **limewater** 石灰水	turns milky
chlorine 氯气 (Cl_2)	damp litmus paper	bleached white
hydrogen 氢气 (H_2)	a lighted splint	burns with a squeaky pop
oxygen 氧气 (O_2)	a glowing splint	relights
sulfur dioxide (SO_2)	acidified potassium manganate(VII)	purple colour fades

Testing gases: hydrogen pops, oxygen relights a glowing splint

Flame tests

A **flame test** 焰色试验 identifies some metal cations by the colour they give to a flame:



A flame test: the metal ion gives the flame a colour

Cation	Flame colour
lithium 锂 (Li^+)	red
sodium 钠 (Na^+)	yellow
potassium 钾 (K^+)	lilac (purple)
calcium (Ca^{2+})	orange-red
barium 钡 (Ba^{2+})	light green
copper(II) (Cu^{2+})	blue-green

Exam tips

- Pick apparatus by the measurement: a **burette** or **pipette** for accurate volumes, a measuring cylinder for a rough volume, a gas syringe for a gas volume, a balance for mass.
- $R_f = \dfrac{\text{distance moved by the substance}}{\text{distance moved by the solvent}}$, so it is always less than 1. A pure substance gives a single spot.
- Learn the anion tests: a **carbonate** fizzes and the gas turns limewater milky; halides with silver nitrate give a chloride *white*, bromide *cream*, iodide *yellow* precipitate; a **sulfate** gives a white precipitate with barium nitrate.
- Learn the gas tests: **hydrogen** gives a squeaky pop, **oxygen** relights a glowing splint, **carbon dioxide** turns limewater milky, **chlorine** bleaches damp litmus, **ammonia** turns damp red litmus blue.
- For cations, add sodium hydroxide and read the precipitate colour: copper(II) light blue, iron(II) green, iron(III) red-brown.