Cambridge IGCSE · Chemistry 0620 · Notes

Reversible reactions and equilibrium

Read online at **pastopic.com/cambridge/chemistry-0620/notes/reversible-reactions-and-equilibrium**

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Read first: **Chemical energetics**, **Physical and chemical changes and rate of reaction**

What you need to know

By the end of this topic you should be able to:

1. **State that some reactions are reversible**, shown by the symbol $\rightleftharpoons$: the products can react to give back the reactants.
2. **Describe how changing the conditions reverses a change**, for two salts only, copper(II) sulfate and cobalt(II) chloride: heating the hydrated salt drives off its water, and adding water to the anhydrous salt turns it back into the hydrated salt.
3. **Extended only:** state that a reversible reaction in a **closed system** is at **equilibrium** when the rate of the forward reaction equals the rate of the reverse reaction, and the concentrations of reactants and products are no longer changing.
4. **Extended only:** predict and explain how the **position of equilibrium** moves when you change the **temperature**, the **pressure** or a **concentration**, or add a **catalyst**, using the equation and information the question gives.
5. **Extended only:** state the equation for the **Haber process**, $\mathrm{N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)}$, where its hydrogen (methane) and nitrogen (air) come from, and its typical conditions: $450\ {}^{\circ}\mathrm{C}$, $20\,000\ \mathrm{kPa}$ ($200\ \mathrm{atm}$) and an iron catalyst.
6. **Extended only:** state the equation for the key step of the **Contact process**, $\mathrm{2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)}$, where its sulfur dioxide (burning sulfur or roasting sulfide ores) and oxygen (air) come from, and its typical conditions: $450\ {}^{\circ}\mathrm{C}$, $200\ \mathrm{kPa}$ ($2\ \mathrm{atm}$) and a vanadium(V) oxide catalyst.
7. **Extended only:** explain why those conditions are used, in terms of **rate**, **position of equilibrium**, **safety** and **cost**.

Understand it

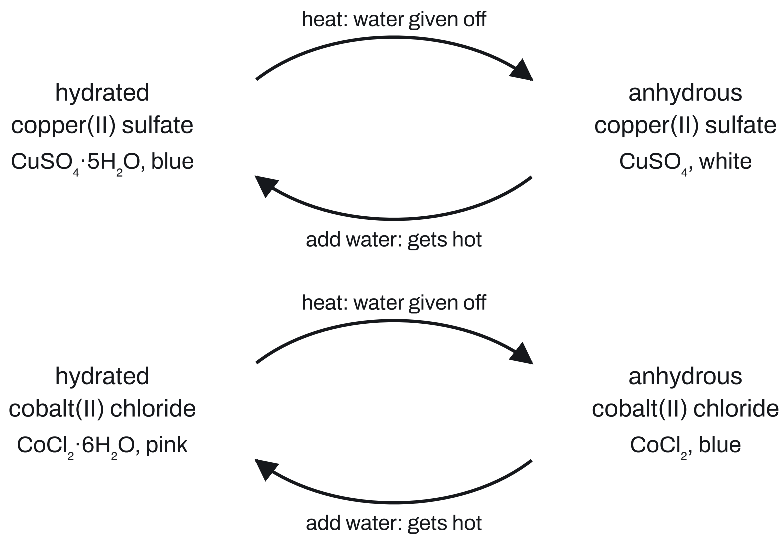
Reactions that can go backwards

Most reactions only go one way: once a candle has burned you cannot turn the carbon dioxide and water back into wax. A **reversible reaction** can go both ways. The **forward reaction** turns reactants (on the left of the equation) into products (on the right); the **reverse reaction** turns the products back into the reactants. The symbol $\rightleftharpoons$ (two half-arrows pointing opposite ways) in an equation means "this reaction is reversible".

Which way it goes depends on the conditions. The clearest examples are two salts that hold water in their crystals.

Hydrated and anhydrous salts (Core)

A **hydrated** salt has water chemically built into its crystals, called **water of crystallisation**. An **anhydrous** salt is the same salt with **no water**. ("Hydrated" means "with water"; "anhydrous" means "without water".)



$$\underset{\text{blue}}{CuSO_4 \cdot 5H_2O} \rightleftharpoons \underset{\text{white}}{CuSO_4} + 5H_2O \qquad \underset{\text{pink}}{CoCl_2 \cdot 6H_2O} \rightleftharpoons \underset{\text{blue}}{CoCl_2} + 6H_2O$$

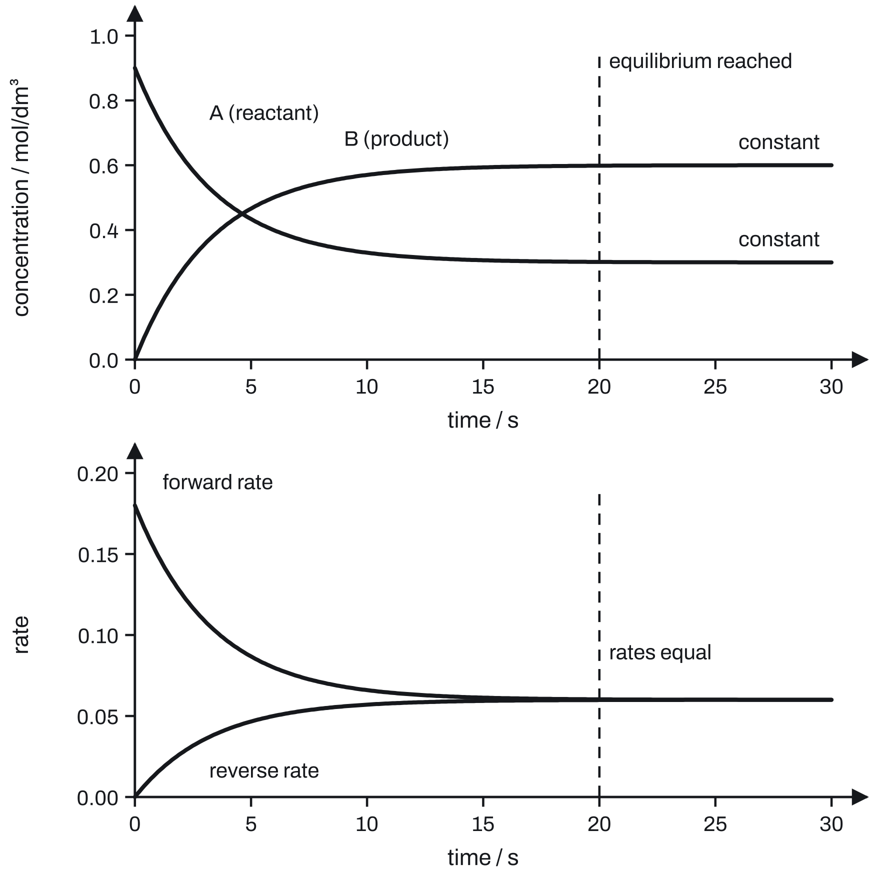
- **Heating** the hydrated salt drives the water off (you see droplets of water condense at the cool top of the tube) and the colour changes: copper(II) sulfate **blue** → **white**, cobalt(II) chloride **pink** → **blue**.
- **Adding water** to the anhydrous salt reverses the change: copper(II) sulfate **white** → **blue**, cobalt(II) chloride **blue** → **pink**. This direction **gives out heat** (it is exothermic), so the solid gets warm. Heating in the other direction takes heat in.
- Left in air, anhydrous copper(II) sulfate slowly soaks up water vapour and turns blue again.

Because the anhydrous forms change colour when water touches them, they are used to **test for water** (the test belongs to another topic; the colours are the same).

Easy way to remember: copper(II) sulfate is **blue with water**; cobalt(II) chloride is **blue without water**.

Equilibrium (Extended)

Put a reversible reaction in a **closed system**, a container that nothing can enter or leave. At first there are only reactants, so the forward reaction is fast and the reverse reaction does not happen at all. As reactants are used up, the forward reaction slows; as products build up, the reverse reaction speeds up. Eventually the two rates become **equal**.



From then on, every second as much A turns into B as B turns back into A. Both reactions are still happening, but nothing seems to change. This is **equilibrium**:

- the **rate of the forward reaction equals the rate of the reverse reaction**, and
- the **concentrations of reactants and products stay constant** (they are no longer changing).

Two things equilibrium does **not** mean: the reactions have **not stopped**, and the concentrations are **not equal to each other** (in the graph, A levels off at 0.30 and B at 0.60). In an **open** container a gas can escape, so equilibrium is never reached.

Moving the position of equilibrium (Extended)

The **position of equilibrium** says how much of the mixture is products. "Shifts to the **right**" means more products form (higher yield); "shifts to the **left**" means more reactants form. When you change a condition, the equilibrium shifts in the direction that **opposes the change**. The four rules:

Change	Position of equilibrium moves	Why
Raise the temperature	In the **endothermic** direction	That direction takes in the extra heat
Lower the temperature	In the **exothermic** direction	That direction gives out heat
Raise the pressure (gases)	To the side with **fewer moles of gas**	Fewer gas molecules take up less space, lowering the pressure

Change	Position of equilibrium moves	Why
Lower the pressure (gases)	To the side with **more moles of gas**	
Add a substance	**Away** from that substance	It is used up
Remove a substance	**Towards** that substance	More of it is made
Add a catalyst	**No change**	It speeds up the forward and reverse reactions equally

Temperature needs the sign of ΔH. If the forward reaction is exothermic (ΔH negative), the reverse reaction is endothermic by the same amount. So raising the temperature shifts an exothermic reaction to the **left**.

Pressure needs the moles of **gas** on each side, from the balancing numbers. Count only (g) substances. In $\mathrm{N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)}$ there are $1 + 3 = 4$ moles of gas on the left and 2 on the right. If both sides have the same number, as in $\mathrm{H_2(g) + I_2(g) \rightleftharpoons 2HI(g)}$ (2 and 2), pressure has **no effect** on the position.

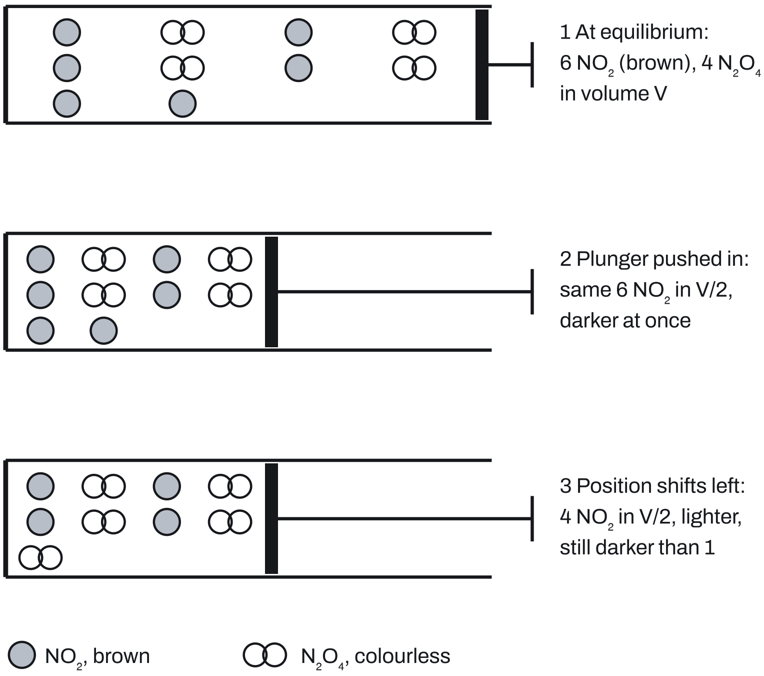
A catalyst gets the mixture to equilibrium faster but does not change the yield.

Position is not the same as rate. Raising the temperature makes **both** the forward and reverse reactions faster (particles collide more often and more collisions have enough energy), even when the position moves left. Raising the pressure of gases also makes both faster (the particles are closer together). The rules above tell you only **where** the equilibrium ends up.

For example, $\mathrm{N_2O_4(g) \rightleftharpoons 2NO_2(g)}$: $\mathrm{N_2O_4}$ is colourless and $\mathrm{NO_2}$ is brown, and the forward reaction is endothermic. Heating the mixture shifts it right, so it turns darker brown; cooling shifts it left, so it turns paler.

Squashing a coloured gas

Pushing in the plunger of a sealed syringe raises the pressure. Two things happen, one after the other.



1. **At once**, the mixture goes **darker**. No reaction has happened yet: the same number of brown $\mathrm{NO_2}$ molecules is squeezed into a smaller volume, so their **concentration** is higher.
2. **Then** the position shifts to the side with fewer gas moles, here the **left** (2 moles of $\mathrm{NO_2}$ become 1 mole of $\mathrm{N_2O_4}$), so some of the brown gas is used up and the colour gets **lighter** again.

When the two sides have equal gas moles (the purple iodine in $2\mathrm{HI} \rightleftharpoons \mathrm{H_2} + \mathrm{I_2}$), only step 1 happens: darker, and it stays darker.

Industrial processes (Extended)

Two important reversible reactions are run in industry. Both forward reactions are **exothermic**, and both have **fewer gas moles on the right**.

The Haber process makes ammonia (used to make fertilisers):

$$\mathrm{N_2(g)} + 3\mathrm{H_2(g)} \rightleftharpoons 2\mathrm{NH_3(g)} \qquad \Delta H = -92\ \mathrm{kJ/mol}$$

- Nitrogen from the **air** (separated from liquid air by fractional distillation); hydrogen from **methane** (natural gas, reacted with steam).
- $450\ ^\circ\mathrm{C}$, $20\,000\ \mathrm{kPa}$ $(200\ \mathrm{atm})$, **iron** catalyst.

The Contact process makes sulfuric acid. Its key step is:

$$2\mathrm{SO_2(g)} + \mathrm{O_2(g)} \rightleftharpoons 2\mathrm{SO_3(g)} \qquad \Delta H\ \text{negative}$$

- Sulfur dioxide from **burning sulfur** or **roasting sulfide ores** (such as iron pyrite, $\mathrm{FeS_2}$); oxygen from the **air**.
- $450\ ^\circ\mathrm{C}$, $200\ \mathrm{kPa}$ $(2\ \mathrm{atm})$, **vanadium(V) oxide** catalyst, $\mathrm{V_2O_5}$.

Same temperature, very different pressures and catalysts: that is exactly what questions test.

Why these conditions? The best conditions for yield and the best for rate pull in different directions, so industry picks a **compromise**:

- **Temperature.** The forward reaction is exothermic, so a **low** temperature gives a **higher yield**, but the reaction would be **too slow**. A **high** temperature is fast but gives a **lower yield** (and uses more energy). $450\ ^\circ\mathrm{C}$ gives a fast enough rate with a reasonable yield.
- **Pressure.** There are fewer gas moles on the right, so a **high** pressure gives a **higher yield** and a **faster rate**. But high pressure needs thick, strong pipes and a lot of energy for compressors, so it is **expensive** and more **dangerous** (risk of explosion). The Haber process uses $200\ \mathrm{atm}$ as a balance of yield, cost and safety. In the Contact process the position is already far to the right at just $2\ \mathrm{atm}$, so a higher pressure would add cost for very little extra sulfur trioxide.
- **Catalyst.** It increases the rate, so the lower-than-ideal temperature is still fast enough. It does **not** change the yield.
- Unreacted gases are recycled, so none is wasted.

Catalysts are transition elements

Iron, vanadium (in $\mathrm{V_2O_5}$), cobalt, copper, nickel and platinum are **transition elements**, and transition elements and their compounds often act as catalysts. If a question lists elements and asks which is most likely to catalyse a reaction, choose the transition element and give "it is a transition element" as the reason.

Key facts and formulas

"Given" means the exam paper prints it. "Learn it" means you must remember it. Chemistry 0620 has no formula sheet, so everything here must be learned.

Formula	Status
$\rightleftharpoons$ means a reversible reaction	Learn it
$\mathrm{CuSO_4 \cdot 5H_2O}$ (blue) $\rightleftharpoons$ $\mathrm{CuSO_4}$ (white) $+5\mathrm{H_2O}$; heat drives water off; adding water turns it blue and gives out heat	Learn it
$\mathrm{CoCl_2 \cdot 6H_2O}$ (pink) $\rightleftharpoons$ $\mathrm{CoCl_2}$ (blue) $+6\mathrm{H_2O}$; heat drives water off; adding water turns it pink and gives out heat	Learn it
Extended only: equilibrium (closed system): rate forward $=$ rate reverse; concentrations no longer change	Learn it
Extended only: higher temperature → endothermic direction; lower → exothermic direction	Learn it
Extended only: higher pressure → side with fewer gas moles; equal gas moles → no effect	Learn it

Formula	Status
Extended only: add a substance → shifts away from it; remove → shifts towards it; catalyst → no change	Learn it
Extended only: Haber: $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$; $450\ ^\circ C$, $20\,000\ kPa$ / $200\ atm$, iron; H_2 from methane, N_2 from air	Learn it
Extended only: Contact: $2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$; $450\ ^\circ C$, $200\ kPa$ / $2\ atm$, vanadium(V) oxide; SO_2 from burning sulfur or roasting sulfide ores, O_2 from air	Learn it
Extended only: the forward reactions in both processes are exothermic	Learn it

How to do it

In the questions we have tagged for this topic (160 questions, 2021–2025), the types came up this often. 22 of the 160 questions mix types, so the counts add up to 204.

Question type	Questions
Recall Haber and Contact process conditions, catalysts, sources and equations	51
Predict (and explain) the effect of a change on the position of equilibrium or the yield	50
Hydrated and anhydrous copper(II) sulfate and cobalt(II) chloride	42
State the features of an equilibrium or a closed system	20
Meaning of the symbol $\rightleftharpoons$ / pick the reversible reaction	15
Explain the choice of industrial conditions	11
Deduce exothermic or endothermic (or the gas moles) from an observed shift	6
Choose a suitable catalyst and give a reason	5
Explain the colour change when a coloured gas mixture is compressed	4

1. Recall Haber and Contact process conditions, catalysts, sources and equations (51 questions)

1. **Name the process** from the product: ammonia → **Haber**; sulfur trioxide or sulfuric acid → **Contact**. Spell Haber correctly.
2. **Write the equation** with $\rightleftharpoons$ (not $\rightarrow$) and state symbols if asked.
3. **Give the conditions with units**: temperature in $^\circ C$, pressure in the unit asked for (kPa or atm), and the catalyst's name.
4. **Give the sources** if asked: Haber: N_2 from air, H_2 from methane. Contact: SO_2 from burning sulfur or roasting sulfide ores, O_2 from air.

Variations you will meet:

- **Multiple choice rows** of pressure, temperature and catalyst. Check all three: the usual traps are swapping iron and vanadium(V) oxide, or the two pressures ($200\ \mathrm{kPa}$ is the Contact process; $20\,000\ \mathrm{kPa}$ is the Haber process).
- **"Using numbers only"**, for example the Contact process temperature: write just 450.
- **Which stage uses a catalyst?** In sulfuric acid manufacture only the $SO_2 \rightarrow SO_3$ step does. Questions sometimes describe the later stages (sulfur trioxide absorbed into concentrated sulfuric acid to make oleum, $H_2S_2O_7$, then water added); the question gives you those details, so build the equation from them.
- **Which is a raw material?** Sulfur, air, methane, water. Vanadium(V) oxide and iron are catalysts, not raw materials.

2. Predict (and explain) the effect of a change on the position of equilibrium or the yield (50 questions)

1. **Read the information:** the equation with state symbols, and the sign of ΔH (or "the forward reaction is exothermic").
2. **Count gas moles** on each side from the balancing numbers.
3. **Apply the rule** for the change (the table in "Understand it"), and say where the position moves: **left**, **right** or **no change**.
4. **Turn that into what is asked:** shift right → more product, yield and product concentration **increase**, reactant concentrations **decrease**; shift left → the opposite.
5. **For "explain", add the reason:** "the forward reaction is exothermic", "fewer moles of gas on the right", "a catalyst does not affect the position of equilibrium".

For example, $C_2H_4(g) + H_2O(g) \rightleftharpoons C_2H_5OH(g)$, forward exothermic, 2 gas moles → 1. Lowering the temperature: shifts right, yield of ethanol increases. Raising the pressure: shifts right (fewer gas moles), yield increases. Lowering the pressure: shifts left, yield decreases.

Variations you will meet:

- **A table to fill in with "increases", "decreases" or "no change"**, often with a second column for the **rate** of the forward or reverse reaction. Use only those words. For rate: higher temperature, higher pressure (gases), higher concentration or a catalyst → **increases** (both forward and reverse); the opposite changes → **decreases**. Adding a catalyst: position no change, rate increases.
- **Equal gas moles on both sides**, such as $H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$: pressure has **no effect**, because there are the same number of gas moles on each side.
- **Adding or removing one substance.** For $P(g) + Q(g) + R(g) \rightleftharpoons S(g) + T(g)$, adding more T shifts the position left: P, Q and R increase and S decreases.
- **Coloured mixtures.** Work out the shift, then which coloured substance increases. For $Fe^{3+}(aq)$ (yellow) $+ SCN^{-}(aq)$ (colourless) $\rightleftharpoons FeSCN^{2+}(aq)$ (red), adding more SCN^{-} shifts right, so the mixture becomes more red.

- **Multiple choice about colour and pressure** for $N_2O_4 \rightleftharpoons 2NO_2$: judge by the shift. Raising the pressure shifts it left, so "a darker brown colour is seen" counts as **not correct**. Only when a question describes pushing in a syringe plunger and asks about the **immediate** change do you use type 9.
- **Unfamiliar reactions** (in solution, or with a solid): the same rules apply, using the information given.

3. Hydrated and anhydrous copper(II) sulfate and cobalt(II) chloride (42 questions)

1. **Identify the salt from the colours:**
   - blue → white on heating, white → blue with water: **copper(II) sulfate**;
   - pink → blue on heating, blue → pink with water: **cobalt(II) chloride**.
2. **Say which form:** the form with water is **hydrated** (blue $CuSO_4 \cdot 5H_2O$, pink $CoCl_2 \cdot 6H_2O$); the form without is **anhydrous** (white $CuSO_4$, blue $CoCl_2$).
3. **Say how to reverse it:** heat to remove water; add water to put it back.
4. **Energy:** adding water to the anhydrous salt **gives out heat**; heating the hydrated salt takes heat in.

Variations you will meet:

- **"Which word describes the reaction?"**: reversible (not neutralisation, oxidation or reduction).
- **"Which reaction produces a white substance?"**: heating hydrated copper(II) sulfate.
- **Colour change asked for in order**, "from ... to ...": both colours, in the right order, for example "white to blue".
- **"State the meaning of hydrated"**: containing water of crystallisation (not just "wet" or "dissolved in water").
- **An observation on heating**: colour change, and droplets of (colourless) liquid forming at the top of the tube. "Water is formed" is a conclusion, not an observation.

4. State the features of an equilibrium or a closed system (20 questions)

1. **Feature 1:** the rate of the forward reaction **equals** the rate of the reverse reaction. Write the word "rate".
2. **Feature 2:** the concentrations of reactants and products are **no longer changing** (constant).
3. **Closed system:** nothing (no substance) can enter or leave. An open beaker is not closed: a gas can escape.

Variations you will meet:

- **Multiple choice misconceptions**: "the reactions have stopped" (wrong: both continue), "the concentrations of reactants and products are equal" (wrong: constant, not equal), "all the reactants are turned into products" (wrong: a reversible reaction never goes to completion).
- **"What happens to the concentration of the product at equilibrium? Explain."**: it stays constant, because it is made as fast as it is used up (forward and reverse rates are equal).

5. Meaning of the symbol $\rightleftharpoons$ / pick the reversible reaction (15 questions)

1. **The symbol** $\rightleftharpoons$ means the reaction is **reversible**. If asked to draw it, draw two half-arrows pointing opposite ways.
2. **To pick the reversible reaction**, look for $\rightleftharpoons$, or a change that is undone by changing the conditions: hydrating anhydrous copper(II) sulfate, making an ester from an acid and an alcohol, $N_2O_4 \rightleftharpoons 2NO_2$ on heating and cooling, the Haber and Contact reactions. Burning, rusting, and an acid reacting with a metal or carbonate are **not** reversible.

6. Explain the choice of industrial conditions (11 questions)

1. **Temperature lower than used:** the rate would be **too slow** (even though the yield would be higher).
2. **Temperature higher than used:** the **yield would be lower**, because the forward reaction is exothermic (and the energy costs more).
3. **Pressure lower than used:** the **rate** would be lower **and** the **yield** would be lower (fewer gas moles on the right).
4. **Pressure higher than used:** it would cost more (stronger equipment, more energy) and be less safe.
5. **The catalyst** increases the rate; it has no effect on the yield.

Variations you will meet:

- **"Give reasons that do not involve cost"**: use rate and yield only. For a reaction with **more** gas moles on the right, such as $4NH_3(g) + 5O_2(g) \rightleftharpoons 4NO(g) + 6H_2O(g)$ $(9 \rightarrow 10)$, a higher pressure is avoided because it would **lower the yield**.
- **Both a high yield and a high rate are needed**: say which one each extreme of temperature spoils, for example "below $300\ ^\circ C$ the rate is too slow; above $300\ ^\circ C$ the yield decreases".
- **True or false statements** about the Haber process: high temperature is used because the reaction is slow at room temperature (true); high temperature increases the yield (false).

7. Deduce exothermic or endothermic (or the gas moles) from an observed shift (6 questions)

1. **Find the direction** the position moved when the temperature changed: less product (or the colour of a reactant getting stronger) → it moved **left**.
2. **Raising the temperature favours the endothermic direction.** So if heating shifts it left, the reverse reaction is endothermic and the **forward reaction is exothermic**. If heating shifts it right, the forward reaction is endothermic. When the temperature was **lowered**, flip the logic.
3. **For pressure:** if raising the pressure increases the product, the product side has **fewer** gas moles.

For example, "raising the temperature decreases the yield of methanol" → the forward reaction is **exothermic**.

8. Choose a suitable catalyst and give a reason (5 questions)

1. From the list, choose the **transition element** (for example cobalt, copper, nickel, platinum, iron), not a Group I or II metal or a non-metal.
2. **Reason:** it is a transition element (transition elements often act as catalysts).

9. Explain the colour change when a coloured gas mixture is compressed (4 questions)

1. **Immediately darker:** the same number of molecules of the coloured gas are in a **smaller volume**, so their **concentration increases** (the molecules are closer together). Name the coloured gas. Do **not** talk about the equilibrium shifting for this part.
2. **Then**, if the question says the colour changes again, explain the shift: towards the side with fewer gas moles.
3. **If the position does not change**, explain: the **same number of moles of gas** on each side.

Worked examples

The bold codes show where marks are earned, as in Cambridge mark schemes. The number is how many marks.

- **B1** mark for a correct result on its own, with no method needed.

Example 1

Pink crystals of hydrated cobalt(II) chloride are heated in a test tube.

(a) State the colour of the solid at the end of the heating, and one other observation. **[2]**

(b) The solid is cooled and a few drops of water are added. State two observations. **[2]**

(c) What does this show about the reaction? **[1]**

(a) The solid turns **blue** (anhydrous cobalt(II) chloride). **B1** Droplets of colourless liquid (water) form at the cooler top of the tube. **B1**

(b) The solid turns from **blue to pink**. **B1** The tube gets **warm** (heat is given out). **B1**

(c) The reaction is **reversible**: heating drives the water off, and adding water reverses the change. **B1**

Example 2

Nitrogen monoxide reacts with oxygen in a closed container and reaches equilibrium.

$$2\mathrm{NO(g)} + \mathrm{O_2(g)} \rightleftharpoons 2\mathrm{NO_2(g)} \qquad \Delta H = -114\ \mathrm{kJ/mol}$$

(a) Copy and complete the table using only the words **increases**, **decreases** or **no change**. **[8]**

Change	Effect on the equilibrium concentration of NO_2	Effect on the rate of the forward reaction
The temperature is increased		
The pressure is increased		
Some O_2 is removed		
A catalyst is added		

(b) Explain your answer for the effect of increasing the temperature on the concentration of NO_2. **[2]**

(a) Gas moles: $2 + 1 = 3$ on the left, 2 on the right. Forward reaction exothermic.

Change	Concentration of NO_2	Rate of forward reaction
Temperature increased	decreases	increases
Pressure increased	increases	increases
Some O_2 removed	decreases	decreases
Catalyst added	no change	increases

B1 for each correct cell. Removing O_2 shifts the position towards the O_2 (left), and there is less O_2 to collide with, so the forward rate falls.

(b) The position of equilibrium shifts to the **left**. **B1** Because the forward reaction is **exothermic** (so the reverse, endothermic, direction is favoured at a higher temperature). **B1**

Example 3

Sulfuric acid is made by the Contact process. In one step, sulfur dioxide reacts with oxygen. The forward reaction is exothermic.

(a) Write the symbol equation, with state symbols, for this step. **[2]**

(b) State one source of sulfur dioxide and the source of oxygen. **[2]**

(c) State the typical temperature, pressure and catalyst used. **[3]**

(d) Explain why a temperature of $450\ ^\circ\mathrm{C}$ is used, rather than a lower or a higher one. **[2]**

(e) A higher pressure would increase the yield of sulfur trioxide. Suggest why it is not used. **[1]**

(a) $2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$ **B1** for the correct balanced formulae, **B1** for $\rightleftharpoons$ and state symbols.

(b) Burning sulfur (or roasting sulfide ores). **B1** Air. **B1**

(c) $450\ ^\circ\mathrm{C}$ **B1**; $200\ \mathrm{kPa}$ (or $2\ \mathrm{atm}$) **B1**; vanadium(V) oxide **B1**.

(d) A lower temperature would give a higher yield, but the **rate would be too slow**. **B1** A higher temperature would be faster, but the **yield would be lower** because the forward reaction is exothermic. **B1**

(e) The yield is already high at $2\ \mathrm{atm}$, so a higher pressure would add cost (stronger equipment, more energy) for little extra product. **B1** (Safety: a high pressure also has a risk of explosion.)

Example 4

Hydrogen reacts with bromine gas. The reaction is reversible.

$$\underset{\text{colourless}}{\mathrm{H_2(g)}} + \underset{\text{red-brown}}{\mathrm{Br_2(g)}} \rightleftharpoons \underset{\text{colourless}}{\mathrm{2HBr(g)}}$$

A mixture of the three gases reaches equilibrium in a sealed gas syringe. It is pale red-brown.

(a) State two features of the mixture at equilibrium. **[2]**

(b) The plunger is pushed in. The temperature does not change. The mixture turns darker at once and the position of equilibrium does not change.

(i) Explain why the mixture turns darker. **[1]**

(ii) Explain why the position of equilibrium does not change. **[1]**

(c) The syringe is heated. The mixture turns darker. State what this shows about the forward reaction, and explain. **[2]**

(d) State the effect of increasing the temperature on the rate of the forward reaction and on the rate of the reverse reaction. **[2]**

(a) The rate of the forward reaction equals the rate of the reverse reaction. **B1** The concentrations of $\mathrm{H_2}$, $\mathrm{Br_2}$ and HBr are no longer changing. **B1**

(b)(i) The same number of $\mathrm{Br_2}$ molecules is in a smaller volume, so the **concentration of bromine increases**. **B1**

(b)(ii) There are the **same number of moles of gas** on each side ($1 + 1 = 2$ on the left, 2 on the right). **B1**

(c) Darker means more $\mathrm{Br_2}$, so the position shifted **left** on heating. Heating favours the endothermic direction, so the reverse reaction is endothermic and the **forward reaction is exothermic**. **B1 B1**

(d) Forward rate **increases**; reverse rate **increases**. **B1 B1** (Heating speeds up both reactions; only the position depends on which is endothermic.)

Common mistakes

- **Mixing up the colours of the two salts.** Examiners see guessing on these every year, and cobalt(II) chloride confused with copper(II) sulfate. Learn the pairs: copper(II) sulfate blue (hydrated) / white (anhydrous); cobalt(II) chloride pink (hydrated) / blue (anhydrous).
- **Vague meanings of "hydrated".** "Contains water", "wet" or "dissolved in water" do not score; say it contains **water of crystallisation**.
- **Leaving "rate" out of the equilibrium definition.** "The forward reaction equals the reverse reaction" earns nothing. So does "the rates are constant" (they are **equal**) and "the concentrations are equal" (they are **constant**, no longer changing).
- **Saying the reaction shifts, or describing the result vaguely.** It is the **position of equilibrium** that shifts. When asked what happens to it, say "shifts to the left", "shifts to the right" or "no change"; phrases such as "more product forms" or "shifts to the endothermic side" are ignored. There is no "endothermic side", only an endothermic **direction**.
- **Contradicting yourself**, such as "shifts towards the reactants, so more product forms". Decide left or right first, then write one clear statement.
- **Giving a principle instead of a reason.** "To oppose the change" or "to restore the balance" is not enough; give the specific reason: "fewer moles of gas on the left", "the forward reaction is exothermic".
- **Mixing up position and rate.** Higher temperature makes both the forward and the reverse reactions faster, even when the position moves left. Don't be afraid to give the same answer ("increases") for both rates.
- **Forgetting units or mixing up the processes' conditions.** 200 without atm, or $200\,000\ \mathrm{kPa}$ and $0.2\ \mathrm{kPa}$, lose the mark; so do the Contact values given for the Haber process. The Haber catalyst is iron; the Contact catalyst is vanadium(V) oxide.
- **Not knowing methane is the source of hydrogen** for the Haber process (air, for nitrogen, is well known).
- **Explaining a darker colour on compression by a shift.** The immediate change is caused by the higher concentration of the coloured gas: name the gas and say "concentration increases" or "molecules closer together".

How to get the marks

- **Use the question's words.** If told to use only "increases", "decreases" or "no change", write exactly those. Each cell of such a table is usually 1 mark.
- **"State the effect on the position of equilibrium"**: left, right or no change. **"Explain"** adds a second mark for the reason (exothermic or endothermic forward reaction, gas moles on each side, a catalyst not affecting the position).
- **Always look for the sign of ΔH and the state symbols** before answering: they decide the temperature and pressure answers.
- **Conditions need numbers and units**: $450\ ^\circ\mathrm{C}$, $200\ \mathrm{atm}$ or $20\,000\ \mathrm{kPa}$ for the Haber process; $450\ ^\circ\mathrm{C}$, $2\ \mathrm{atm}$ or $200\ \mathrm{kPa}$ for the Contact process. Give one value, not a range. Name the catalyst in full.
- **Equations for the two processes need $\rightleftharpoons$.**
- **Two features of equilibrium = two marks**: rates equal, concentrations no longer changing.

- **"Explain why this condition is used"**: mention both **rate** and **yield** (and cost or safety for pressure), and link each to the direction of the change.
- **"Suggest"** (a catalyst, an unfamiliar reaction): apply the rules to the information given; the answer will not be in your notes word for word.
- **Colour changes**: give both colours in order, "from blue to pink".

Quick check

1. Water is added to white anhydrous copper(II) sulfate. State the colour change and whether heat is given out or taken in. How can the change be reversed?
2. A pink solid turns blue when it is heated gently, and droplets of water form at the top of the tube. Name the pink solid.
3. **Extended.** $\mathrm{N_2(g) + O_2(g) \rightleftharpoons 2NO(g)}$, $\Delta H = +181\ \mathrm{kJ/mol}$. State and explain the effect on the equilibrium yield of NO of (a) increasing the temperature, (b) increasing the pressure, (c) adding a catalyst.
4. **Extended.** For the gas reaction $a\mathrm{G(g)} \rightleftharpoons b\mathrm{J(g)}$, raising the temperature decreases the equilibrium concentration of J, and raising the pressure increases it. What can you deduce?
5. **Extended.** Give the equation, the three typical conditions and the sources of both raw materials for the Haber process. Why is a temperature of $1000\ ^\circ\mathrm{C}$ not used?

Answers

1. White to blue; heat is **given out** (it gets warm). Reverse it by **heating** the blue solid to drive the water off.
2. Hydrated cobalt(II) chloride ($CoCl_2 \cdot 6H_2O$).
3. (a) Yield **increases**: the forward reaction is endothermic, and a higher temperature favours the endothermic direction, so the position shifts right. (b) **No change**: there are 2 moles of gas on each side. (c) **No change**: a catalyst speeds up the forward and reverse reactions equally, so it does not affect the position.
4. Raising the temperature shifts the position left, so the reverse reaction is endothermic and the **forward reaction is exothermic**. Raising the pressure shifts it right, so the right has fewer gas moles: b **is less than** a.
5. $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$; $450\ ^\circ C$, $200\ \mathrm{atm}$ ($20\,000\ \mathrm{kPa}$), iron catalyst; nitrogen from air, hydrogen from methane. At $1000\ ^\circ C$ the yield of ammonia would be much lower, because the forward reaction is exothermic (and heating to that temperature costs more energy).

Past questions to try

- **0620/41/M/J/21 Q4**: equilibrium features, squashing N_2O_4 and NO_2 in a syringe, and the effect of temperature.
- **0620/43/M/J/23 Q6**: Haber process sources and conditions, then explaining another process's conditions without cost.
- **0620/22/F/M/23 Q17**: adding a product to an equilibrium mixture.
- **0620/41/O/N/21 Q2**: hydrated copper(II) sulfate and water of crystallisation.