

Unit 4: Chemical Reactions

Unit 4 is about what happens when substances change. It covers how to tell a chemical change from a physical one, how to write equations in three different forms, the main types of reactions you will see on the exam, and the quantitative tools that go with them: stoichiometry and titrations.

AP Chemistry

Chemical Reactions

About 13 minutes to read

How to use this guide

Read it in order the first time because the topics build on each other. The physical-versus-chemical distinction tells you when a reaction is actually happening, the three equation forms give you the language for describing it, the reaction types give you the patterns to recognize, and stoichiometry and titrations are where the exam turns all of it into numbers.

After the first read, use the trap boxes and the tables to review the distinctions that exam questions test most often. Finish with the practice questions, then complete the recall check on the last page out loud and note any items you cannot explain yet.

What this unit is worth. Chemical Reactions is about 7 to 9 percent of the AP Chemistry exam. It also carries more weight than that number suggests, because net ionic equations, redox, and stoichiometry show up inside later units on equilibrium, acids and bases, and electrochemistry. The equation-writing habits you build here get reused all year.

4.1 Physical Change and Chemical Change

A **physical change** alters a substance's properties without changing its composition. Melting ice, boiling water, and separating a mixture by filtration are physical changes. The molecules themselves are the same before and after; only their arrangement or state has changed.

A **chemical change** produces new substances with different compositions. The evidence is observable: heat or light is produced, a gas forms, a precipitate appears, or the color changes. When iron rusts, the reddish-brown solid that forms is iron(III) oxide, a different substance from the iron and oxygen that made it.

Trap. Color change alone does not prove a chemical change. Dissolving blue copper(II) sulfate in water gives a blue solution, but no new substance formed; that is a physical change. Look for the full picture: new composition, not just a new look.

4.4 Physical Processes and Chemical Processes

The same distinction applies to processes. A **physical process** changes only intermolecular forces, not chemical bonds. Phase changes and the separation of mixtures are physical processes. A **chemical process** involves bond breaking and bond formation, which is what a chemical reaction is.

Salt dissolving in water is the exam's favorite boundary case. The AP framework classifies it as a physical process: the ionic lattice interactions break and ion-dipole interactions form, but the ions themselves are unchanged and no new covalent bonds form. On an FRQ, anchor your answer on "physical" and justify it with what happens at the particle level.

Trap. Dissolving is not automatically a chemical change. Sugar dissolving in water is a physical change: the sugar molecules are intact, just surrounded by water. Reserve "chemical" for cases where the particles themselves are transformed.

4.2 Net Ionic Equations

There are three ways to write the same reaction, and the exam expects you to move between them. The **molecular equation** uses complete neutral formulas: $\text{AgNO}_3(\text{aq}) + \text{NaCl}(\text{aq}) \rightarrow \text{AgCl}(\text{s}) + \text{NaNO}_3(\text{aq})$. The **complete ionic equation** splits every strong electrolyte into its ions: $\text{Ag}^+(\text{aq}) + \text{NO}_3^-(\text{aq}) + \text{Na}^+(\text{aq}) + \text{Cl}^-(\text{aq}) \rightarrow \text{AgCl}(\text{s}) + \text{Na}^+(\text{aq}) + \text{NO}_3^-(\text{aq})$. The **net ionic equation** drops the **spectator ions**, the ones that appear unchanged on both sides, leaving only what actually changed: $\text{Ag}^+(\text{aq}) + \text{Cl}^-(\text{aq}) \rightarrow \text{AgCl}(\text{s})$.

A **balanced chemical equation** conserves atoms and charge on both sides. Check both. In the net ionic equation above, one silver and one chloride on each side, and the charges (+1 and -1) sum to zero on the left to match the neutral solid on the right.

EQUATION FORM	WHAT IT SHOWS
Molecular	Complete neutral formulas for everything. Good for lab work, hides what the ions do.
Complete ionic	Strong electrolytes written as dissociated ions. Shows the spectator ions explicitly.
Net ionic	Only the species that change. The clearest picture of the actual chemistry.

Trap. Do not split solids, liquids, gases, or weak electrolytes into ions. Only strong electrolytes dissociate. Writing $\text{AgCl}(\text{s})$ as $\text{Ag}^+ + \text{Cl}^-$ is the most common error in this topic, and it defeats the whole point of the net ionic equation.

4.3 Representations of Reactions

Particulate representations translate between a symbolic equation and a particle-level diagram. The diagram shows atoms and ions as individual particles rearranging during the reaction. To read one, count each type of particle before and after, and match the counts to the coefficients in the balanced equation.

Suppose a diagram shows 3 Ag^+ and 3 Cl^- particles on the left, and 2 AgCl solid units plus 1 leftover Ag^+ and 1 leftover Cl^- on the right. The balanced equation is still $\text{Ag}^+ + \text{Cl}^- \rightarrow \text{AgCl(s)}$; the leftovers just tell you the reactants were not in exact stoichiometric amounts. The diagram and the equation describe the same event at different scales.

Trap. In a particulate diagram, leftover particles do not change the balanced equation. They tell you about limiting and excess reactants, not about the reaction's stoichiometry. Write the equation from the reaction itself, then use the leftovers to figure out which reactant ran out.

4.7 Types of Chemical Reactions

Most exam reactions fall into a few patterns. An **acid-base reaction** transfers a proton (H^+) from an acid to a base. A **precipitation reaction** mixes ion solutions to form an insoluble ionic compound; salts of Na^+ , K^+ , NH_4^+ , and NO_3^- are always soluble, so they never form the precipitate. An **oxidation-reduction (redox) reaction** transfers electrons, which changes the oxidation numbers of some species. A **combustion reaction** is a subclass of redox in which a species reacts with oxygen; hydrocarbons burn completely to CO_2 and H_2O .

REACTION TYPE	WHAT MOVES	EXAMPLE
Acid-base	A proton (H^+) from acid to base	$\text{HCl(aq)} + \text{NaOH(aq)} \rightarrow \text{NaCl(aq)} + \text{H}_2\text{O(l)}$
Precipitation	Ions combine into an insoluble solid	$\text{Ag}^+(\text{aq}) + \text{Cl}^-(\text{aq}) \rightarrow \text{AgCl(s)}$
Redox	Electrons; oxidation numbers change	$\text{Zn(s)} + \text{Cu}^{2+}(\text{aq}) \rightarrow \text{Zn}^{2+}(\text{aq}) + \text{Cu(s)}$
Combustion	Reaction with O_2 ; a redox subclass	$\text{CH}_4(\text{g}) + 2\text{O}_2(\text{g}) \rightarrow \text{CO}_2(\text{g}) + 2\text{H}_2\text{O(l)}$

Trap. Acid-base and redox are not mutually exclusive categories. A reaction can be both, like the reaction of zinc metal with hydrochloric acid: protons transfer to make H_2 gas, and zinc is oxidized while H^+ is reduced. Classify by what actually happens, not by picking one label.

4.8 Brønsted-Lowry Acids and Bases

A **Brønsted-Lowry acid** is a proton (H^+) donor, and a **Brønsted-Lowry base** is a proton (H^+) acceptor. The definition is about the role in a specific reaction, not about the substance in isolation. In $\text{HCl(aq)} + \text{H}_2\text{O(l)} \rightarrow \text{H}_3\text{O}^+(\text{aq}) + \text{Cl}^-(\text{aq})$, HCl donates the proton so it is the acid, and water accepts it so water is the base.

A **conjugate acid-base pair** is an acid and a base that differ by exactly one proton. When HCl donates its proton, it becomes Cl^- ; those two form a conjugate pair. When water accepts the proton, it becomes H_3O^+ ; those two form the other conjugate pair. **Water** is amphiprotic: in aqueous solutions it can accept protons from dissolved species and donate protons to them, so it plays an active role in many acid-base reactions rather than sitting out as a spectator.

Trap. Conjugate pairs differ by one H^+ , not by one H atom. The conjugate base of H_2CO_3 is HCO_3^- , formed by removing H^+ . If you remove a neutral H atom instead, the charges will not work out.

4.9 Oxidation-Reduction: Half-Reactions

Oxidation is loss of electrons and **reduction** is gain of electrons. The **oxidation number** is a bookkeeping number assigned to each atom so you can track which species is oxidized and which is reduced. In $\text{Zn(s)} + \text{Cu}^{2+}(\text{aq}) \rightarrow \text{Zn}^{2+}(\text{aq}) + \text{Cu(s)}$, zinc goes from 0 to +2, so it loses electrons and is oxidized. Copper goes from +2 to 0, so it gains electrons and is reduced.

A **half-reaction** writes the oxidation and reduction parts separately. For the zinc-copper reaction: $\text{Zn(s)} \rightarrow \text{Zn}^{2+}(\text{aq}) + 2\text{e}^{-}$ is the oxidation half-reaction, and $\text{Cu}^{2+}(\text{aq}) + 2\text{e}^{-} \rightarrow \text{Cu(s)}$ is the reduction half-reaction. A balanced redox equation is built by combining the two half-reactions so the electrons cancel.

Trap. The species that is oxidized is the reducing agent, and the species that is reduced is the oxidizing agent. Zinc is oxidized, so zinc metal is the reducing agent: it causes copper(II) to be reduced. Students flip these labels constantly. Track the electrons first, then assign the labels.

TERM	WHAT HAPPENS TO IT	ITS ROLE
Oxidized species	Loses electrons; oxidation number increases	Reducing agent
Reduced species	Gains electrons; oxidation number decreases	Oxidizing agent

4.5 Stoichiometry

Stoichiometry uses the mole ratios from a balanced equation to calculate how much product forms or how much reactant is needed. The coefficients are the conversion factors. For $2\text{H}_2(\text{g}) + \text{O}_2(\text{g}) \rightarrow 2\text{H}_2\text{O}(\text{l})$, 2 moles of H_2 react with 1 mole of O_2 to make 2 moles of H_2O .

The **limiting reactant** is the one consumed first, and it determines the maximum product. Suppose you mix 4.0 mol H_2 with 1.5 mol O_2 . The 4.0 mol H_2 would need 2.0 mol O_2 ($4.0 \times 1/2$), but only 1.5 mol is available, so O_2 is limiting. The product is set by the limiting reactant: $1.5 \text{ mol } \text{O}_2 \times (2 \text{ mol } \text{H}_2\text{O} / 1 \text{ mol } \text{O}_2) = 3.0 \text{ mol } \text{H}_2\text{O}$. The leftover 1.0 mol H_2 simply does not react.

Trap. The limiting reactant is not the one with the smallest number of moles. It is the one that runs out first relative to what the balanced equation demands. Always divide each reactant's moles by its coefficient and compare those ratios; the smallest ratio wins.

4.6 Titrations

A **titration** determines the amount of an **analyte**, the substance being measured, by reacting it with a **titrant**, a solution of known concentration. The **equivalence point** is the moment the analyte has been completely consumed by the titrant. The **endpoint** is the observable color change of an indicator, which signals that the equivalence point has been reached.

The standard calculation: 25.00 mL of $\text{HCl}(\text{aq})$ is titrated with 0.100 M $\text{NaOH}(\text{aq})$, and the endpoint arrives after 32.50 mL of titrant. At the equivalence point, moles of acid equal moles of base for this 1:1 reaction: $(0.100 \text{ mol/L})(0.03250 \text{ L}) = 0.00325 \text{ mol } \text{NaOH} = 0.00325 \text{ mol } \text{HCl}$. The acid's concentration is $0.00325 \text{ mol} / 0.02500 \text{ L} = 0.130 \text{ M}$.

Trap. The equivalence point and the endpoint are not the same thing. The equivalence point is the theoretical moment of complete reaction; the endpoint is what you see. A good titration picks an indicator whose color change lands as close to the equivalence point as possible, but they are defined differently and exam questions test the distinction.

Practice Questions

Original questions written for this guide in the style of the AP exam. Answers and explanations are on the next page, so complete the questions before checking them.

1. Which of the following is a chemical change?

- A. Ice melting in a glass of water
- B. Iron nails developing a reddish-brown coating in moist air
- C. Sugar dissolving in hot tea
- D. Water boiling in a kettle

2. When aqueous AgNO_3 and aqueous NaCl are mixed, a white solid forms. The net ionic equation is

- A. $\text{AgNO}_3(\text{aq}) + \text{NaCl}(\text{aq}) \rightarrow \text{AgCl}(\text{s}) + \text{NaNO}_3(\text{aq})$
- B. $\text{Ag}^+(\text{aq}) + \text{NO}_3^-(\text{aq}) + \text{Na}^+(\text{aq}) + \text{Cl}^-(\text{aq}) \rightarrow \text{AgCl}(\text{s}) + \text{Na}^+(\text{aq}) + \text{NO}_3^-(\text{aq})$
- C. $\text{Ag}^+(\text{aq}) + \text{Cl}^-(\text{aq}) \rightarrow \text{AgCl}(\text{s})$
- D. $\text{Na}^+(\text{aq}) + \text{NO}_3^-(\text{aq}) \rightarrow \text{NaNO}_3(\text{aq})$

3. What is the oxidation number of sulfur in H_2SO_4 ?

- A. +2
- B. +4
- C. +6
- D. -2

4. In the reaction $\text{Zn}(\text{s}) + \text{Cu}^{2+}(\text{aq}) \rightarrow \text{Zn}^{2+}(\text{aq}) + \text{Cu}(\text{s})$, which species is oxidized?

- A. $\text{Zn}(\text{s})$
- B. $\text{Cu}^{2+}(\text{aq})$
- C. $\text{Zn}^{2+}(\text{aq})$
- D. $\text{Cu}(\text{s})$

5. A mixture contains 4.0 mol H_2 and 1.5 mol O_2 . For the reaction $2\text{H}_2(\text{g}) + \text{O}_2(\text{g}) \rightarrow 2\text{H}_2\text{O}(\text{l})$, what is the maximum amount of H_2O that can form?
- A. 1.5 mol
 - B. 3.0 mol
 - C. 4.0 mol
 - D. 5.5 mol
6. In a titration, the equivalence point is best described as the point at which
- A. the indicator changes color
 - B. the analyte has been completely consumed by the titrant
 - C. equal volumes of analyte and titrant have been mixed
 - D. the pH of the solution equals 7
7. The conjugate base of H_2CO_3 is
- A. H_3CO_3^+
 - B. HCO_3^-
 - C. CO_3^{2-}
 - D. H_2O
8. 25.00 mL of $\text{HCl}(\text{aq})$ requires 32.50 mL of 0.100 M $\text{NaOH}(\text{aq})$ to reach the endpoint. What is the concentration of the HCl ?
- A. 0.0770 M
 - B. 0.100 M
 - C. 0.130 M
 - D. 0.325 M

Answer Key

- 1. B.** Rusting forms iron(III) oxide, a new substance with a different composition. That is the definition of a chemical change. A is a phase change, C is sugar molecules dispersing intact in water, and D is a phase change. All three are physical changes.
- 2. C.** The net ionic equation includes only the species that change: Ag^+ and Cl^- combine into the solid. A is the molecular equation. B is the complete ionic equation, which still shows the spectator ions Na^+ and NO_3^- . D describes the spectator ions combining, which does not happen; NaNO_3 stays dissolved.
- 3. C.** Assign H as +1 (two of them: +2 total) and O as -2 (four of them: -8 total). The molecule is neutral, so $+2 + S + (-8) = 0$, giving $S = +6$. A and B come from miscounting the oxygens. D is the oxidation number of sulfur in H_2S , a different compound.
- 4. A.** Zn goes from oxidation number 0 to +2, which is a loss of electrons: oxidation. B is reduced (Cu^{2+} gains electrons to become Cu). C and D are products; the question asks which reactant is oxidized.
- 5. B.** The 4.0 mol H_2 would need 2.0 mol O_2 , but only 1.5 mol is present, so O_2 limits. Product follows the limiting reactant: $1.5 \times (2/1) = 3.0$ mol H_2O . A uses the limiting reactant's moles as the answer without applying the mole ratio. C assumes H_2 limits. D adds the reactant amounts, which is never the move.
- 6. B.** The equivalence point is the theoretical moment of complete reaction. A describes the endpoint, the observable signal. C is wrong because equal volumes mean nothing without concentrations. D is only true for a strong acid with a strong base; a weak-acid titration reaches equivalence at pH above 7.
- 7. B.** A conjugate base forms by removing one proton (H^+) from the acid: H_2CO_3 minus H^+ is HCO_3^- . A adds a proton instead. C removes two protons, which gives the conjugate base of HCO_3^- , not of H_2CO_3 .
- 8. C.** Moles of $\text{NaOH} = (0.100 \text{ mol/L})(0.03250 \text{ L}) = 0.00325 \text{ mol}$, which equals moles of HCl in this 1:1 reaction. Concentration = $0.00325 \text{ mol} / 0.02500 \text{ L} = 0.130 \text{ M}$. A inverts the volume ratio. B assumes the concentrations match because the reaction is 1:1, ignoring the different volumes. D multiplies instead of dividing by the acid volume.

One-Page Recall Check

- State the evidence that tells you a chemical change occurred rather than a physical one.
- Explain why dissolving salt in water can be argued as either a physical or a chemical process.
- Write the molecular, complete ionic, and net ionic equations for $\text{AgNO}_3(\text{aq}) + \text{NaCl}(\text{aq})$.
- Name the species you must never split into ions when writing a net ionic equation.
- Explain how to read a particulate diagram and what leftover particles tell you.
- Classify each of these as acid-base, precipitation, redox, or combustion: $\text{HCl} + \text{NaOH}$; $\text{Ag}^+ + \text{Cl}^-$; $\text{Zn} + \text{Cu}^{2+}$; $\text{CH}_4 + \text{O}_2$.
- Identify the conjugate acid-base pairs in $\text{HCl}(\text{aq}) + \text{H}_2\text{O}(\text{l}) \rightarrow \text{H}_3\text{O}^+(\text{aq}) + \text{Cl}^-(\text{aq})$.
- Explain what makes water amphiprotic in acid-base reactions.
- State what oxidation and reduction mean in terms of electrons, and assign oxidation numbers in $\text{Zn} + \text{Cu}^{2+} \rightarrow \text{Zn}^{2+} + \text{Cu}$.
- Write the two half-reactions for the zinc-copper redox reaction.
- Explain the difference between the species oxidized and the reducing agent.
- Find the limiting reactant and maximum product for 4.0 mol H_2 with 1.5 mol O_2 .
- Distinguish the equivalence point from the endpoint in a titration.
- Calculate an unknown acid concentration from a titration volume and a known titrant.

Study this unit in Rycal. Open the Chemical Reactions deck under AP Chemistry at rycal.web.app/apchem. The deck covers the terms in this guide, and its practice questions target the same traps named here. If you have a test date, add it in the Test Planner. You can also start your next review with a Brain Dump, then check what you missed against this guide.

Key terms for this unit

Physical change, Chemical change, Balanced chemical equation, Molecular equation, Complete ionic equation, Net ionic equation, Particulate representations of reactions, Chemical process, Physical process, Salt dissolution: physical or chemical process, Stoichiometry, Limiting reactant, Titration, Analyte, Titrant, Equivalence point (titration), Endpoint, Acid-base reaction, Oxidation-reduction (redox) reaction, Oxidation, Reduction, Oxidation number, Precipitation reaction, Combustion reaction, Brønsted-Lowry acid, Brønsted-Lowry base, Conjugate acid-base pair, Water in acid-base reactions, Half-reaction

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