Unit 8

Chemical Reaction

This unit online, with its interactives:
science-playground.com/s/10a8

Pour a few drops of salt water into a test tube of silver nitrate solution. Both liquids are as clear as water, yet the moment they meet, a thick white cloud swirls through the tube and slowly sinks. Pour the white solid onto a piece of filter paper, lay a coin on it and leave it on a sunny windowsill. Within minutes the paper around the coin turns violet-gray, while the patch under the coin stays white. Lift the coin, and its shadow is printed on the paper.

Two reactions happened there, and they have different names. The first made a solid out of two solutions: a **precipitation** reaction. The second was driven by light: a **photochemical** reaction, the same one that made every photograph for a hundred and fifty years. In this unit you will meet seven kinds of reaction by what drives them or what they make (precipitation, hydrolysis, catalytic, photochemical, electrolytic, oxidation and reduction), and then the reactions that join thousands of small molecules into one long chain, the **polymers** of plastic buckets, nylon ropes, rubber, cotton and the rice on your plate.

8.1 Chemical reaction and chemical equation

Introduction

A **chemical reaction** is a change in which one or more substances, the **reactants**, turn into new substances, the **products**, with new properties. In every reaction, bonds between atoms break and new bonds form: the atoms are rearranged, but no atom is made or destroyed. So the products contain exactly the same atoms as the reactants, and their total mass is the same.

How can you tell that a reaction has happened? Look for one or more of these signs:

- **a new color:** an iron nail in copper sulphate solution turns reddish-brown, and the blue solution fades to pale green;
- **a gas given off:** marble fizzes in acid, giving carbon dioxide;
- **a solid formed from two solutions:** the white cloud of silver chloride above;

- **heat or light given out or taken in:** a burning matchstick; the cold of an instant ice pack;
- **a new smell or taste:** milk turning sour, rice turning sweet as you chew it.

None of these signs proves a reaction on its own: a color also changes when a solution is diluted, and bubbles also rise from boiling water. The test is always the one from Grade 9: **has a new substance formed?**

Check 1

Which of these is **not** a chemical reaction?

a a silver spoon slowly turning black in air

b curd setting from warm milk

c ice melting in a glass of water

d a candle burning

Chemical equation

A **chemical equation** is a short way of writing a reaction with symbols and formulas: the reactants on the left, the products on the right, and an arrow between them, read "gives" or "forms". It is **balanced** when every element has the same number of atoms on both sides, which is the law of conservation of mass written in symbols:

$$CaCO_3 + 2HCl \rightarrow CaCl_2 + H_2O + CO_2$$

A bare equation leaves a lot out. Chemists add more to it with a few signs:

Sign	Meaning	Example
(s), (l), (g), (aq)	solid, liquid, gas, dissolved in water	NaCl(aq)
↑ after a product	a gas that escapes	$CO_2\uparrow$
↓ after a product	a precipitate, a solid that forms in a solution	AgCl↓
Δ or "heat" over the arrow	the reactants are heated	$CaCO_3 \xrightarrow{\Delta} CaO + CO_2$
a catalyst over the arrow	it speeds the reaction and is not used up	$2H_2O_2 \xrightarrow{MnO_2} 2H_2O + O_2$
"light" or hν over the arrow	light drives the reaction	$2AgCl \xrightarrow{light} 2Ag + Cl_2$
⇌	a reversible reaction, going both ways	$N_2 + 3H_2 \rightleftharpoons 2NH_3$

With these, the equation for the white cloud says a great deal:

j. **Think:** Rice and a cotton cloth are both made of chains of glucose. You can digest the rice but not the cotton, yet a cow lives on grass, whose cellulose is the same polymer as cotton's. What does this tell you about hydrolysis and enzymes?

5. Numerical problems

a. 3.19 g of copper sulphate in solution is mixed with enough sodium hydroxide solution. a. What mass of copper(II) hydroxide is precipitated? b. What mass of sodium hydroxide is needed for this? (Cu = 63.5, S = 32, O = 16, H = 1, Na = 23)

b. 6.8 g of hydrogen peroxide is decomposed completely with 1 g of manganese dioxide. Find a. the volume of oxygen at STP, b. the mass of water formed, c. the mass of manganese dioxide left. (H = 1, O = 16)

c. How many grams of potassium chlorate must be heated, with manganese dioxide, to give 3.36 L of oxygen at STP? (K = 39, Cl = 35.5, O = 16)

d. A sample of PVC has an average degree of polymerization of 1,600. Find its average molar mass. (C = 12, H = 1, Cl = 35.5)

e. 16.2 g of starch, $(C_6H_{10}O_5)_n$, is hydrolyzed completely to glucose: $(C_6H_{10}O_5)_n + n\ H_2O \rightarrow n\ C_6H_{12}O_6$. What mass of water is used, and what mass of glucose is formed? (C = 12, H = 1, O = 16)

f. A nylon-6,6 chain has a molar mass of 22,600 g/mol, and its repeating unit is $C_{12}H_{22}N_2O_2$. How many repeating units does it have, and about how many water molecules were given off in making it? (C = 12, H = 1, N = 14, O = 16)

Found a mistake? Please tell us.

2. Give reasons

a. An aqueous solution of ammonium chloride turns blue litmus red.

b. A catalyst is written over the arrow of an equation, not among the reactants.

c. Silver bromide is used in photographic films.

d. Oxidation and reduction always take place together.

e. Natural rubber is vulcanized before it is made into tyres.

f. The handle of a pressure cooker is made of Bakelite, not polythene.

3. Differentiate between

i. Oxidation and reduction

ii. Precipitation reaction and hydrolysis reaction

iii. Addition polymerization and condensation polymerization

iv. Natural polymers and synthetic polymers

v. Thermoplastic and thermosetting plastic

4. Answer the following questions

a. What is a precipitation reaction? Write the balanced equations for two precipitation reactions and name the color of each precipitate.

b. What is hydrolysis? Explain, with equations, why a solution of sodium ethanoate is basic and a solution of sodium chloride is neutral.

c. What is a catalyst? Write any four characteristics of a catalyst.

d. Describe an experiment to show a photochemical reaction using a silver compound. Write the equation.

e. Define oxidation and reduction in terms of oxygen, hydrogen and electrons. Identify the substance oxidized and the substance reduced in $Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$.

f. Show, with half-equations, that the reaction of zinc with copper sulphate solution is a redox reaction.

g. What is an electrolytic reaction? Give two examples with equations.

h. Define monomer, polymer and polymerization. Write the equation for the formation of polythene.

i. Write the uses of any four polymers.

$$AgNO_3(aq) + NaCl(aq) \rightarrow AgCl(s)\downarrow + NaNO_3(aq)$$

Ionic equations

In the solutions, silver nitrate, sodium chloride and sodium nitrate are all split into ions (Grade 9 Optional Science showed why). The Na^+ and NO_3^- ions are in the water before the reaction and still in the water after it: they take no part, and are called **spectator ions**. Leave them out, and what is left is the **ionic equation**, the change that really happens:

$$Ag^+(aq) + Cl^-(aq) \rightarrow AgCl(s)$$

It says something the full equation hides: **any** silver salt in solution and **any** chloride in solution give the same white precipitate. That is why silver nitrate is the test for a chloride, whatever the chloride is.

What a balanced equation tells you, in amounts

The numbers in front of the formulas count particles, so they count moles too (Unit 7, Mole concept). Read the decomposition of hydrogen peroxide in three ways:

	$2H_2O_2$	→	$2H_2O$	+	O_2
molecules	2 molecules		2 molecules		1 molecule
moles	2 mol		2 mol		1 mol
masses (H = 1, O = 16)	$2 \times 34 = 68$ g		$2 \times 18 = 36$ g		32 g
gas volume at STP					22.4 L

68 g of reactant gives 36 g + 32 g = 68 g of products: mass is conserved, as it must be.

WORKED EXAMPLE

Oxygen from hydrogen peroxide

How much oxygen, by mass and by volume at STP, is given off when 1.7 g of hydrogen peroxide decomposes completely? (H = 1, O = 16)

Answer

$M(H_2O_2) = 2 + 32 = 34$ g/mol, so the hydrogen peroxide is $n = \frac{1.7}{34} = 0.05$ mol.

The equation, $2H_2O_2 \rightarrow 2H_2O + O_2$, gives 1 mol O_2 for every 2 mol H_2O_2, so $0.05 \div 2 = 0.025$ mol O_2.

Mass: $0.025 \times 32 =$ **0.8 g of oxygen**. Volume at STP: $0.025 \times 22.4 =$ **0.56 L (560 cm³)**.

What an equation doesn't tell you

Even a balanced equation with every sign says nothing about:

- **whether the reaction happens at all.** $Cu + 2HCl \rightarrow CuCl_2 + H_2$ balances perfectly, but copper doesn't react with dilute hydrochloric acid;
- **how fast it goes:** rusting and an explosion are both written with one arrow;
- **how far it goes:** many reactions stop before the reactants are used up;
- **the concentrations** of the solutions, unless they are written in;
- **how the atoms rearrange**, step by step, on the way from reactants to products.

> CAREFUL
> **Formulas must be right before numbers are**
>
> A balanced equation is only as good as its formulas. Hydrogen is H_2, oxygen O_2, chlorine Cl_2; water is H_2O and never H_2O_2, which is a different substance. Write each formula correctly first, then balance by changing only the numbers in front.

Examples

Reaction	Equation
LPG (propane) burning on the stove	$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$
lime water turning milky with your breath	$Ca(OH)_2 + CO_2 \rightarrow CaCO_3\downarrow + H_2O$
an antacid tablet in the stomach	$Mg(OH)_2 + 2HCl \rightarrow MgCl_2 + 2H_2O$
photosynthesis in a leaf	$6CO_2 + 6H_2O \rightarrow$(light, chlorophyll) $C_6H_{12}O_6 + 6O_2$
respiration in your cells	$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$
yeast making sel roti dough rise	$C_6H_{12}O_6 \rightarrow$(yeast enzymes) $2C_2H_5OH + 2CO_2$

8.2 Introduction to some chemical reactions

Grade 10 Science sorted reactions by how the atoms rearrange: combination, decomposition, displacement and neutralization. Here they are sorted in other ways: by what is formed (a precipitate), by what drives them (light, electricity, a catalyst), by what water does in them, and by what happens to their electrons. So one reaction can

Exercise

1. Choose the correct option

a. Which of these mixtures gives a yellow precipitate?

- **a** silver nitrate and sodium chloride
- **b** copper sulphate and sodium hydroxide
- **c** lead nitrate and potassium iodide
- **d** barium chloride and sodium sulphate

b. An aqueous solution of sodium carbonate is basic because:

- **a** it contains hydroxide ions in its formula
- **b** sodium is a metal
- **c** it is the salt of a weak acid and a strong base, and it hydrolyzes
- **d** it is the salt of a strong acid and a weak base

c. Which reaction is photochemical?

- **a** $2KClO_3 \rightarrow 2KCl + 3O_2$, heated with MnO_2
- **b** $2AgBr \rightarrow 2Ag + Br_2$, in light
- **c** $CuSO_4 + Fe \rightarrow FeSO_4 + Cu$
- **d** $2NaCl \rightarrow 2Na + Cl_2$, molten, with a current

d. In $CuO + H_2 \rightarrow Cu + H_2O$, the oxidizing agent is:

- **a** CuO
- **b** H_2
- **c** Cu
- **d** H_2O

e. The monomer of PVC is:

- **a** ethene
- **b** propene
- **c** chloroethene (vinyl chloride)
- **d** tetrafluoroethene

f. Which is a condensation polymer?

- **a** polythene
- **b** polystyrene
- **c** natural rubber
- **d** nylon

g. Which of these is a natural polymer?

- **a** Bakelite
- **b** cellulose
- **c** PTFE
- **d** polyester

h. A sample of polythene has a molar mass of 42,000 g/mol. Its degree of polymerization is: (C = 12, H = 1)

- **a** 1,000
- **b** 1,500
- **c** 3,000
- **d** 42,000

IN SHORT

- A **chemical reaction** turns reactants into new substances; atoms are rearranged, never made or lost. A **chemical equation** shows it in formulas; state symbols, ↑, ↓, conditions and ⇌ make it say more, and its numbers give the amounts in moles. It doesn't say whether, how fast or how far a reaction goes.
- **Precipitation:** two solutions give an insoluble solid, a precipitate (AgCl white, $BaSO_4$ white, $Cu(OH)_2$ blue, PbI_2 yellow, $Fe(OH)_3$ reddish-brown). Used to test for ions and to soften and clean water.
- **Hydrolysis:** a substance reacts with water, which is split into H and OH. A salt of a strong acid and a weak base gives an acidic solution (NH_4Cl, $CuSO_4$); of a weak acid and a strong base, a basic one (Na_2CO_3, CH_3COONa); of a strong acid and a strong base, a neutral one (NaCl). Esters, fats, sugars, starch and proteins hydrolyze too.
- **Catalytic reaction:** its rate is changed by a catalyst, which is not used up, works in small amounts, is specific, doesn't change the amount of product and can be poisoned or promoted. Enzymes are biocatalysts.
- **Photochemical reaction:** driven by light. Photosynthesis, $2AgCl \rightarrow 2Ag + Cl_2$ (photography), $H_2 + Cl_2 \rightarrow 2HCl$, ozone formation.
- **Electrolytic reaction:** driven by an electric current through an electrolyte: water, molten salt, brine, alumina.
- **Oxidation:** addition of oxygen, removal of hydrogen, **loss of electrons**. **Reduction:** removal of oxygen, addition of hydrogen, **gain of electrons**. They always happen together (**redox**); the oxidizing agent is reduced and the reducing agent is oxidized.
- **Monomers** join into **polymers** by **polymerization**. **Addition** polymerization (monomers with C=C, nothing given off: polythene, PVC, PTFE, rubber); **condensation** polymerization (two reactive groups, water given off at each link: nylon, polyester, proteins, starch, cellulose). Molar mass = n × mass of the repeating unit.
- Polymers are **natural** (starch, cellulose, proteins, rubber, DNA) or **man-made**, synthetic or semi-synthetic (rayon, vulcanized rubber); **thermoplastics** soften on heating, **thermosetting** plastics don't.

have several names. When silver chloride darkens in sunlight, $2AgCl \rightarrow 2Ag + Cl_2$, it is a **decomposition** (one reactant gives two products), a **photochemical** reaction (light drives it), and an **oxidation and reduction** (silver ions gain electrons, chloride ions lose them). An exam asks which name fits what it describes.

Precipitation reaction

A **precipitation reaction** is a reaction in which two solutions react to form an insoluble solid, called a **precipitate**. The precipitate makes the clear liquid cloudy, then slowly settles to the bottom. It is shown by ↓ or (s) after its formula.

Most precipitation reactions are **double displacement** reactions: the ions of two soluble salts swap partners, and one of the new pairs doesn't dissolve in water. Which ones don't? A few rules cover most cases:

These dissolve in water	Except
all nitrates	none
all salts of sodium, potassium and ammonium	none
most chlorides (and bromides, iodides)	silver and lead(II)
most sulphates	barium and lead(II) (calcium sulphate only slightly)
These don't dissolve	**Except**
most hydroxides	sodium, potassium, ammonium (calcium hydroxide slightly)
most carbonates	sodium, potassium, ammonium

So mixing a solution of any salt with that of another gives a precipitate if the swap makes one of the pairs in the lower half of the table, or one of the exceptions in the upper half.

The four in Figure 8.1, as full equations and as ionic equations:

$$AgNO_3 + NaCl \rightarrow AgCl\downarrow + NaNO_3 \qquad Ag^+ + Cl^- \rightarrow AgCl$$

$$BaCl_2 + Na_2SO_4 \rightarrow BaSO_4\downarrow + 2NaCl \qquad Ba^{2+} + SO_4^{2-} \rightarrow BaSO_4$$

$$CuSO_4 + 2NaOH \rightarrow Cu(OH)_2\downarrow + Na_2SO_4 \qquad Cu^{2+} + 2OH^- \rightarrow Cu(OH)_2$$

$$Pb(NO_3)_2 + 2KI \rightarrow PbI_2\downarrow + 2KNO_3 \qquad Pb^{2+} + 2I^- \rightarrow PbI_2$$

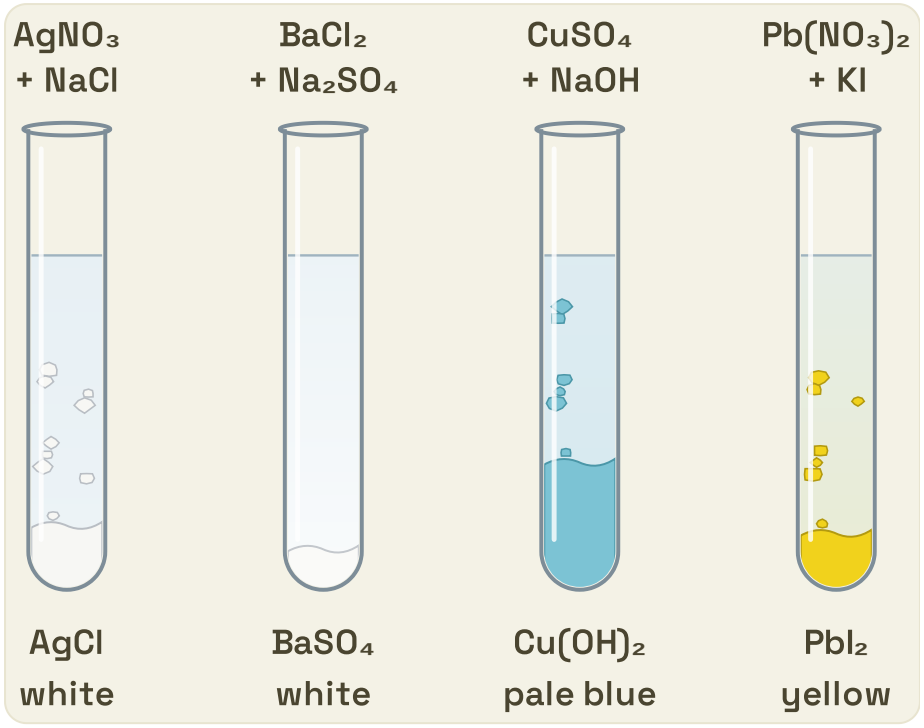


Figure 8.1 *Four precipitates a few minutes after the two solutions were mixed, in their real colors. Silver chloride is white and curdy; barium sulphate is white and so fine that it keeps the liquid milky for a long time; copper(II) hydroxide is a pale blue jelly; lead(II) iodide is bright yellow.*

Two more are worth knowing: iron(III) chloride and sodium hydroxide give a **reddish-brown** precipitate of iron(III) hydroxide, $FeCl_3 + 3NaOH \rightarrow Fe(OH)_3\downarrow + 3NaCl$; and carbon dioxide bubbled through lime water gives the **white** precipitate of calcium carbonate that turns it milky, $Ca(OH)_2 + CO_2 \rightarrow CaCO_3\downarrow + H_2O$. That one is not two solutions mixing, but it is a precipitate all the same.

Uses of precipitation

- **Testing for ions.** Each precipitate's color tells which ion was there: a white precipitate with silver nitrate (and a little dilute nitric acid) means a chloride; a white precipitate with barium chloride means a sulphate; with sodium hydroxide, a blue precipitate means copper(II), a dirty green one iron(II) and a reddish-brown one iron(III). Lime water turning milky is the test for carbon dioxide.
- **Making insoluble salts.** Barium sulphate for X-ray meals is made by precipitation, filtered and washed (Grade 10 Science tells its story: Double displacement reaction).

weighs up what plastic gives and costs, in Nepal too: What plastic gives, and what it costs.

DID YOU KNOW?

The gas cylinder that stayed heavy

In 1938 the American chemist Roy Plunkett opened the valve of a cylinder of tetrafluoroethene gas, and nothing came out, though the cylinder still weighed as much as a full one. He sawed it open and found a slippery white powder: the gas had polymerized by itself inside, into PTFE. It turned out that almost nothing sticks to it and almost no chemical attacks it. Today it coats non-stick pans and the inside of chemical pipes.

Check 11

Electric switches are made of Bakelite rather than polythene because Bakelite:

a is a natural polymer
b conducts electricity
c is a thermosetting plastic that insulates and doesn't soften when it gets hot
d can be melted and remolded easily

Polymer	Property that matters	Uses
polythene	light, flexible, waterproof, cheap	carry bags, milk pouches, black water tanks, pipes
polypropylene	tough, stands boiling water	chairs, buckets, bottle caps, lunch boxes, ropes, sacks
PVC	rigid (or soft with additives), insulates, doesn't rot	water pipes, electric wire coating, raincoats, flooring
polystyrene	rigid, or a light foam (thermocol)	packaging, disposable plates and cups, insulation
PTFE (Teflon)	nothing sticks to it; stands heat and chemicals	non-stick pans and *tawa*, plumbers' tape
acrylic	soft, warm, like wool	sweaters, blankets
nylon	strong, elastic, smooth	ropes, fishing nets, toothbrush bristles, socks, parachutes
polyester (PET)	strong, doesn't crease; clear as a bottle	clothes, soft-drink and water bottles
Bakelite	hard, insulates, doesn't soften when hot	electric switches and plugs, pressure cooker and pan handles
vulcanized rubber	elastic, tough, waterproof	tyres, chappals, gaskets, pipes, balls
natural polymers		cotton and silk clothes, paper, wood; starch and proteins as food

Polymers save lives too: sterile plastic syringes used once and thrown away, blood bags and drips of soft PVC, nylon threads for stitching wounds, and body armor of Kevlar, a polymer whose chains line up into fibers stronger, for their weight, than steel wire.

Their strength is also their problem. The world made about 400 million tonnes of plastic in 2022, and most synthetic polymers don't rot: a polythene bag or a PET bottle thrown away stays in the soil or a river for centuries, breaking into smaller and smaller **microplastics** that are now found in fish, drinking water and people. Burning plastic in the open is worse: PVC gives off hydrogen chloride gas and poisonous dioxins. The answers are to use less, reuse, collect plastics for recycling (thermoplastics can be melted and remolded), and develop polymers that bacteria can digest, such as polylactic acid, made from the starch of maize. Going Further 6–8

- **Softening hard water.** Washing soda precipitates the calcium and magnesium ions that stop soap from lathering: $CaCl_2 + Na_2CO_3 \rightarrow CaCO_3\downarrow + 2NaCl$ 🕮 Grade 10.
- **Cleaning water.** Water works add chemicals that make a fluffy precipitate, which sweeps mud and germs down with it as it settles (alum, in the next section).

Hydrolysis reaction

Hydrolysis means "splitting by water" (from Greek *hydro*, water, and *lysis*, loosening). A **hydrolysis reaction** is a reaction in which a substance reacts with water, and the water molecule is split: its H goes to one part of the substance and its OH to the other.

This is more than dissolving. Sugar dissolves in water and stays sugar. In hydrolysis the water itself takes part, and new substances form.

Hydrolysis of salts

Dissolve some salts in water and the solution is neutral; dissolve others and it turns litmus red or blue, though the salt itself contains no H^+ or OH^-. The salt has reacted with water. Every salt is made from an acid and a base, and what its solution does depends on how strong each was (Grade 9 Optional Science explained strong and weak):



Figure 8.2 *Lead(II) iodide forming where a drop of lead nitrate solution meets potassium iodide solution. Its color is so bright that it was once used as a yellow paint pigment; it is poisonous, as lead compounds are.*
Photo: PRHaney, CC BY-SA 3.0



Figure 8.3 *Silver chloride forming where a chloride solution meets silver nitrate solution. The white solid comes out in curdy clumps; in light it slowly turns violet-gray, as you will see in the photochemical reaction.*
Photo: Luisbrudna, CC BY-SA 4.0

WORKED EXAMPLE

How much silver chloride?

1.17 g of sodium chloride is dissolved in water, and silver nitrate solution is added until no more precipitate forms. What mass of silver chloride forms, and what mass of silver nitrate is used? (Na = 23, Cl = 35.5, Ag = 108, N = 14, O = 16)

Answer

$NaCl + AgNO_3 \rightarrow AgCl + NaNO_3$: 1 mol of each reactant gives 1 mol AgCl.
$M(NaCl) = 23 + 35.5 = 58.5$ g/mol, so $n = \frac{1.17}{58.5} = 0.02$ mol.
$M(AgCl) = 108 + 35.5 = 143.5$ g/mol: $0.02 \times 143.5 =$ **2.87 g of silver chloride**.
$M(AgNO_3) = 108 + 14 + 48 = 170$ g/mol: $0.02 \times 170 =$ **3.4 g of silver nitrate**.

Check 2

Which pair of solutions gives a precipitate when mixed?

a sodium chloride and potassium nitrate
b sodium sulphate and potassium chloride
c barium nitrate and sodium sulphate
d ammonium chloride and sodium nitrate

Salt made from	Examples	Hydrolysis?	Its solution
strong acid + strong base	NaCl, KNO_3, Na_2SO_4	no	neutral (pH 7)
strong acid + weak base	NH_4Cl, $CuSO_4$, $FeCl_3$, alum	yes	acidic (turns blue litmus red)
weak acid + strong base	Na_2CO_3, CH_3COONa, $NaHCO_3$	yes	basic (turns red litmus blue)
weak acid + weak base	CH_3COONH_4	yes	close to neutral

Ammonium chloride is the salt of a strong acid (HCl) and a weak base (ammonia). With water it gives back a little of each:

$$NH_4Cl + H_2O \rightleftharpoons NH_4OH + HCl$$

The hydrochloric acid formed is strong, so it is fully split into H^+ and Cl^- ions; the ammonium hydroxide is weak and stays mostly together. So the solution has more H^+ than OH^- ions, and it is **acidic**. Copper sulphate (from strong sulphuric acid and weak copper hydroxide) and iron(III) chloride are acidic for the same reason:

much more slowly. Tyres, chappals, rubber bands and pressure cooker gaskets are vulcanized rubber; with a lot more sulphur (about a third of its mass), rubber becomes hard **ebonite**.

Thermoplastics and thermosetting plastics

Man-made polymers are also sorted by what heat does to them:

Thermoplastic	Thermosetting plastic
softens when heated and hardens again when cooled, again and again	sets hard once, when it is made; heated again, it doesn't soften but chars
its chains are separate, and slide past each other when warm	its chains are cross-linked into one rigid network
can be melted down, remolded and recycled	can't be remolded or melted down for recycling
polythene, PVC, polypropylene, polystyrene, nylon, PET	Bakelite, melamine, epoxy glue

Check 10

Which pair is a natural polymer and a semi-synthetic one, in that order?

a nylon and PVC
b cellulose and rayon
c starch and glucose
d polythene and natural rubber

Application of polymers

Polymers can be made hard or soft, rigid or stretchy, clear or colored, and they are light, waterproof, cheap and resistant to rust and rot. That is why they are everywhere:

Natural polymer	Monomer	Found in
starch	glucose	rice, wheat, maize, potatoes
cellulose	glucose	cotton (almost pure cellulose), wood, paper, jute
proteins	amino acids	silk, wool, hair, nails, muscle, enzymes, casein in milk
natural rubber	isoprene, C_5H_8	the latex (milky sap) of the rubber tree
DNA and RNA	nucleotides	every living cell

Man-made polymers are made by people. Most are **synthetic**, made entirely from small molecules, most of them from oil and natural gas: polythene, polypropylene, PVC, polystyrene, PTFE, acrylic, nylon, polyester, Bakelite, synthetic rubber. Some are **semi-synthetic**, made by changing a natural polymer: **rayon** (viscose, "artificial silk") is cellulose from wood pulp dissolved and spun back into shiny threads, and **vulcanized rubber** is natural rubber cross-linked with sulphur.

Natural rubber

Cut a shallow groove in the bark of a rubber tree, *Hevea brasiliensis*, and a milky white liquid, **latex**, drips out into a cup. It is tiny droplets of rubber in water. Rubber is **polyisoprene**, an addition polymer of isoprene (2-methylbuta-1,3-diene, $CH_2{=}C(CH_3){-}CH{=}CH_2$). Its long chains are coiled and tangled, like a plate of noodles: pull, and they straighten; let go, and they coil back. That is why rubber stretches and springs back.

Raw rubber has two faults: it turns soft and sticky in the heat and hard and brittle in the cold. In 1839 the American inventor Charles Goodyear found the cure, as the story goes, when a mixture of rubber and sulphur he was working with touched a hot stove: it charred at the edges but stayed firm and springy. Heating rubber with a little sulphur makes short chains of sulphur atoms that link the rubber chains to one another at many points. This **vulcanization** keeps the chains from sliding apart, so the rubber stays elastic from cold to heat and wears



Figure 8.7 *Latex dripping from a fresh cut into a collecting cup on a rubber tree. The cut stops just short of the thin growing layer under the bark, so the tree heals and can be tapped again every few days for decades.*

Photo: Vis M, CC BY-SA 4.0

$$CuSO_4 + 2H_2O \rightleftharpoons Cu(OH)_2 + H_2SO_4 \qquad FeCl_3 + 3H_2O \rightleftharpoons Fe(OH)_3 + 3HCl$$

Sodium ethanoate (sodium acetate) is the salt of a weak acid (ethanoic acid) and a strong base (sodium hydroxide):

$$CH_3COONa + H_2O \rightleftharpoons CH_3COOH + NaOH$$

This time the strong one formed is the base, fully split into Na^+ and OH^-; the weak ethanoic acid stays mostly together. The solution has more OH^- than H^+: it is **basic**. **Sodium carbonate** (washing soda) is basic the same way, and strongly so:

$$Na_2CO_3 + 2H_2O \rightleftharpoons 2NaOH + H_2CO_3$$

Sodium chloride comes from a strong acid and a strong base. Any NaOH and HCl formed would split into ions at once and give back exactly what was there, so nothing changes: its solution is neutral, and we say a salt of a strong acid and a strong base doesn't hydrolyze.

The rule in one line: **the solution takes the side of the stronger partner.** The ⇌ in each equation shows that only a small part of the salt reacts; the rest stays as it is.

CAREFUL

What really reacts with water

Equations like those above are the ones written in exams, and they give the right answer, acidic or basic. Chemists write them with ions, because only the ion of the weak partner reacts. In ammonium chloride it is the ammonium ion, which gives an H^+ to a water molecule: $NH_4^+ + H_2O \rightleftharpoons NH_3 + H_3O^+$. (There is in fact no molecule of "NH_4OH": the name ammonium hydroxide is kept for ammonia dissolved in water.) In sodium carbonate it is the carbonate ion, which takes an H^+ from water and leaves OH^- behind: $CO_3^{2-} + H_2O \rightleftharpoons HCO_3^- + OH^-$, stopping mostly at the hydrogencarbonate ion rather than going on to carbonic acid. If an exam asks for the hydrolysis of a salt, the molecular equation is accepted; the ionic one shows you understand why.

Hydrolysis of other compounds

Water splits many other compounds, often with an acid, a base or an enzyme as a catalyst:

- **Esters** split into an acid and an alcohol. Ethyl ethanoate, the fruity-smelling liquid in some nail-polish removers: $CH_3COOC_2H_5 + H_2O \rightleftharpoons CH_3COOH + C_2H_5OH$.

DID YOU KNOW?

Wood ash and fitkiri

Before soap was cheap, pots in Nepal's villages were scrubbed with wood ash, *kharani*. Ash contains potassium carbonate, a salt of a weak acid and a strong base: in water it hydrolyzes and the water turns basic, slippery to touch, and it attacks grease Grade 10. And a lump of alum, *fitkiri*, stirred into muddy water clears it within an hour. Alum's aluminium ions hydrolyze into aluminium hydroxide, $Al^{3+} + 3H_2O \rightleftharpoons Al(OH)_3 + 3H^+$, a fluffy, jelly-like precipitate that traps the fine mud as it sinks. (Clear water is not yet safe water: it must still be boiled or treated to kill germs.)

- **Fats and oils** heated with sodium hydroxide split into soap and glycerol. This hydrolysis by a base is called **saponification**, "soap-making" Grade 10.
- **Sugar** (sucrose) splits into two simpler sugars, glucose and fructose: $C_{12}H_{22}O_{11} + H_2O \rightarrow C_6H_{12}O_6 + C_6H_{12}O_6$. Honey is mostly these two, made from the sucrose of nectar by an enzyme of the bees.
- **Calcium carbide** gives ethyne gas (acetylene): $CaC_2 + 2H_2O \rightarrow C_2H_2 + Ca(OH)_2$. This is the gas that some traders use, unsafely, to ripen fruit Grade 10.
- **Food** in your gut. Digestion is hydrolysis: enzymes split the starch of rice into sugars, proteins into amino acids and fats into fatty acids and glycerol, each step taking in water. You will see in 8.3 that this is polymer-making run backward.

Check 3

Which of these salts gives a **basic** solution in water?

a potassium nitrate, KNO_3
b ammonium chloride, NH_4Cl
c sodium ethanoate, CH_3COONa
d sodium sulphate, Na_2SO_4

Catalytic reaction

A **catalytic reaction** is a reaction whose rate is changed by a catalyst. A **catalyst** is a substance that changes the rate of a chemical reaction without itself undergoing any permanent chemical change. It is written over the arrow, not among the reactants.

Grade 10 Science showed what a catalyst does to the rate, and why: it gives the reaction a path with a lower **activation energy**, so more collisions succeed Grade 10. Grade 9 Optional Science had you prove it, by recovering the manganese dioxide unchanged after it made hydrogen peroxide froth Grade 9. Here are the catalytic reactions you will meet most often:

Addition polymerization	Condensation polymerization
Monomers have a double bond (C=C).	Monomers have two reactive groups (–OH, –COOH, $–NH_2$).
Nothing is given off.	A small molecule (usually water) is given off at each link.
The repeating unit has the same formula as the monomer.	The repeating unit has fewer atoms than the monomers.
The chain grows quickly, one unit at a time, at its end.	Monomers and short chains join anywhere, step by step.
Polythene, PVC, polypropylene, PTFE, natural rubber	Nylon, polyester, Bakelite, proteins, starch, cellulose

WORKED EXAMPLE

Water from a protein chain

Glycine, $H_2N–CH_2–COOH$, has a molar mass of 75 g/mol. a. How many water molecules are given off when 50 glycine molecules join into one chain? b. What is the molar mass of the chain? ($H_2O = 18$)

Answer

a. Each new link gives off one water molecule. 50 units in a row have 49 links, so **49 water molecules** are given off.
b. Molar mass of the chain $= 50 \times 75 - 49 \times 18 = 3{,}750 - 882 =$ **2,868 g/mol**.

(Check with the widget: 4 glycines give off 3 waters and make a chain of $4 \times 75 - 3 \times 18 = 246$ g/mol.)

Check 9

A polymer is formed from monomers with no double bond, and water is given off at every link. It is formed by:

a addition polymerization
b condensation polymerization
c hydrolysis
d photochemical reaction

Types of polymers: natural and man-made

Natural polymers are made by living things:

- **Proteins** are chains of **amino acids**. The –COOH of one amino acid and the –NH_2 of the next join into a **peptide bond**, –CO–NH–, the same link as nylon's, giving off water. The widget above builds a chain of glycine, the simplest amino acid; your body uses twenty different ones.
- **Starch** and **cellulose** are chains of **glucose** units, joined through oxygen atoms, each link giving off a water molecule: n $C_6H_{12}O_6$ → $(C_6H_{10}O_5)_n$ + n H_2O. They differ in the way the links are turned, which is why you can digest the starch of rice but not the cellulose of its husk.
- **DNA** and **RNA** are chains of nucleotides, joined by condensation too Grade 10.



Figure 8.6 *The "nylon rope trick": two solutions, one floating on the other, each holding one of the two monomers of a nylon. Where the two liquids meet, nylon forms at once as a film, and it can be pulled out as a continuous thread and wound onto a rod. (A demonstration for a fume cupboard: the monomers are corrosive.)*

Photo: Thctamm, CC BY-SA 3.0

CAREFUL

Condensation and hydrolysis are the same link, made and broken

Condensation polymerization joins two units and gives off water. Hydrolysis (8.2) takes in water and splits the link again. When you digest rice, enzymes hydrolyze its starch back into glucose, $(C_6H_{10}O_5)_n + n\,H_2O \rightarrow n\,C_6H_{12}O_6$; proteins are hydrolyzed into their amino acids the same way. Polymers made by addition can't be split by water like this: polythene has no link that water can open. That is one reason a polythene bag lasts for centuries, while a cotton bag rots.

Reaction	Catalyst	Where
$2KClO_3 \rightarrow 2KCl + 3O_2$	manganese dioxide, MnO_2	oxygen in the laboratory
$2H_2O_2 \rightarrow 2H_2O + O_2$	manganese dioxide, MnO_2	oxygen without heating
$N_2 + 3H_2 \rightleftharpoons 2NH_3$	iron, Fe	the Haber process: ammonia for fertilizers
$2SO_2 + O_2 \rightleftharpoons 2SO_3$	vanadium pentoxide, V_2O_5	the contact process: sulphuric acid
$4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O$	platinum, Pt	the first step to nitric acid
vegetable oil + H_2 → vanaspati ghee	nickel, Ni	hydrogenation of oils
$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$	enzymes of yeast	fermentation: dough, *jand*, ethanol
starch + water → maltose	amylase in saliva	digestion

The catalysts of living things are proteins called **enzymes**, or **biocatalysts**. Every reaction in your body has its own.

Characteristics of a catalyst

1. **It is not used up.** At the end of the reaction it has the same mass and the same chemical composition as at the start, so it can be recovered and used again. (It may change physically: lumps of manganese dioxide can crumble to powder.)
2. **A small amount is enough.** A pinch of manganese dioxide decomposes a whole bottle of hydrogen peroxide; one molecule of an enzyme can handle millions of reactant molecules a minute.
3. **It doesn't start a reaction that can't happen.** It only speeds up a reaction that would go anyway, however slowly. No catalyst makes copper react with dilute hydrochloric acid.
4. **It doesn't change how much product forms.** With or without manganese dioxide, a bottle of hydrogen peroxide gives the same volume of oxygen in the end: the catalyst only gets there sooner. In a reversible reaction it speeds up the forward and the backward reactions equally.
5. **It is specific.** A catalyst works for one reaction or a few. Amylase splits starch but not protein; iron works for ammonia, vanadium pentoxide for sulphur trioxide.

6. **It works best at a certain temperature.** Enzymes work best at about body temperature, 37 °C, and are destroyed by boiling; industrial catalysts each have their own range.
7. **It can be poisoned or helped.** Small amounts of some substances, **poisons**, stop a catalyst working (arsenic poisons platinum; lead poisons a car's catalytic converter). Others, **promoters**, make it work better (a little molybdenum or potassium oxide improves the iron of the Haber process).

A catalyst that speeds a reaction up is a **positive catalyst**; one that slows a reaction down is a **negative catalyst**, or **inhibitor** (Grade 10 Science explains the difference). The phosphoric acid added to hydrogen peroxide, and the antioxidants in packed food and in oil, are inhibitors.

WORKED EXAMPLE

The catalyst changes the time, not the amount

24.5 g of potassium chlorate is heated with 2 g of manganese dioxide until no more gas comes off. a. What volume of oxygen at STP is given off? b. What mass of manganese dioxide is left? c. What would change if no manganese dioxide were added? (K = 39, Cl = 35.5, O = 16)

Answer

a. $2KClO_3 \rightarrow 2KCl + 3O_2$. $M(KClO_3) = 39 + 35.5 + 48 = 122.5$ g/mol, so $n = \frac{24.5}{122.5} = 0.2$ mol. 2 mol $KClO_3$ give 3 mol O_2, so 0.2 mol gives 0.3 mol O_2: $0.3 \times 22.4 =$ **6.72 L at STP**.

b. **2 g.** The catalyst is not used up.

c. **The same 6.72 L**, but only after much stronger heating: alone, potassium chlorate gives oxygen only when heated above about 400 °C, and slowly; with manganese dioxide it gives it briskly at a much lower temperature.

DID YOU KNOW?

The catalyst under every car

A car's exhaust carries poisonous carbon monoxide, unburnt fuel and nitrogen oxides. In its **catalytic converter**, a honeycomb coated with a few grams of platinum, palladium and rhodium, they react to give carbon dioxide, water and nitrogen before they leave the pipe. Lead from leaded petrol poisoned these catalysts, which is one reason the whole world gave up leaded petrol: the last country stopped selling it for cars in 2021.

Monomer	Polymer	Equation
ethene	polythene (polyethylene)	n $CH_2{=}CH_2$ → $[–CH_2–CH_2–]_n$
propene	polypropylene	n $CH_2{=}CH–CH_3$ → $[–CH_2–CH(CH_3)–]_n$
chloroethene (vinyl chloride)	polyvinyl chloride, PVC	n $CH_2{=}CHCl$ → $[–CH_2–CHCl–]_n$
tetrafluoroethene	polytetrafluoroethene, PTFE (Teflon)	n $CF_2{=}CF_2$ → $[–CF_2–CF_2–]_n$
phenylethene (styrene)	polystyrene	n $CH_2{=}CH–C_6H_5$ → $[–CH_2–CH(C_6H_5)–]_n$
propenenitrile (acrylonitrile)	polyacrylonitrile (acrylic)	n $CH_2{=}CH–CN$ → $[–CH_2–CH(CN)–]_n$

Condensation polymerization

In **condensation polymerization**, each monomer has **two reactive groups**, one at each end. The group at the end of one monomer reacts with the group at the end of the next, and at every new link a **small molecule is given off**, usually water (sometimes hydrogen chloride or methanol). So the polymer has fewer atoms than the monomers that made it.

Nylon-6,6 is made from two monomers, hexane-1,6-diamine, with an $–NH_2$ group at each end, and hexanedioic acid (adipic acid), with a –COOH group at each end. An $–NH_2$ and a –COOH join into an **amide link**, –CO–NH–, and a molecule of water leaves:

$$n\,H_2N(CH_2)_6NH_2 + n\,HOOC(CH_2)_4COOH \longrightarrow [–NH(CH_2)_6NH–CO(CH_2)_4CO–]_n +$$

(Each of its two monomers has six carbon atoms, hence the name 6,6. Strictly, a chain of n repeating units gives off 2n − 1 water molecules, as the chain keeps an end group at each end; for a long chain that is 2n.)

Polyester (PET, or terylene) is made the same way from a diol and a dicarboxylic acid, ethane-1,2-diol and benzene-1,4-dicarboxylic acid, which join through **ester links**, –CO–O–, giving off water. It is the plastic of soft-drink bottles and the polyester of clothes. **Bakelite** is made from phenol and methanal (formaldehyde), giving off water; its chains are joined to one another in every direction into one hard network.

Nature makes its polymers by condensation:

WORKED EXAMPLE

How long is the chain?

A sample of polythene has an average molar mass of 56,000 g/mol. Find its degree of polymerization. (C = 12, H = 1)

Answer

The repeating unit, –CH_2–CH_2–, has the same atoms as ethene, C_2H_4: $2 \times 12 + 4 \times 1 = 28$ g/mol.

$$n = \frac{\text{molar mass of polymer}}{\text{molar mass of repeating unit}} = \frac{56{,}000}{28} = 2{,}000$$

n = 2,000: each chain is made of about 2,000 ethene units, 4,000 carbon atoms in a row.

A STORY FROM SCIENCE

“Big molecules”, the idea nobody believed

In the 1910s, chemists thought rubber, starch and cellulose were small molecules clumped together by some weak force, the way soap molecules gather in water. In 1920 the German chemist Hermann Staudinger said they were wrong: these were single, giant molecules, thousands of atoms long, held together by ordinary covalent bonds. Leading chemists told him no molecule could be that big. He spent the next twenty years proving it, measuring how the length of the chains changed the way their solutions flowed. He called them **macromolecules**, and in 1953 he received the Nobel Prize in Chemistry. By then nylon, PVC and polythene were being made in factories, all designed with his idea.

Examples: two ways to make a polymer

Monomers join in two different ways.

Addition polymerization

In **addition polymerization**, monomers with a double bond (C=C) add on to one another. The second bond of each double bond opens, and the freed electrons form the bonds to the neighbors on either side. **Nothing is given off**: the polymer contains every atom of the monomers, so its repeating unit has the same formula as the monomer.

It is the addition reaction of Unit 9 Grade 10, done thousands of times in a row, usually at high pressure or with a catalyst.

Check 4

Which statement about a catalyst is **wrong**?

a it is left unchanged in mass and composition at the end of the reaction

b a small amount of it is enough

c it increases the amount of product formed

d it is specific to one reaction or a few

Photochemical reaction

A **photochemical reaction** is a reaction that is started or driven by light. A molecule absorbs light, and the energy of the light breaks one of its bonds, so the reaction can go. Each needs light of the right color, often violet or ultraviolet, whose energy is greatest (sunlight has both; photosynthesis uses red light as well as blue); in the dark the same reactants hardly react at all.

The most important photochemical reaction on Earth is **photosynthesis**, in which green plants use the energy of light, absorbed by chlorophyll, to make glucose:

$$6CO_2 + 6H_2O \xrightarrow[\text{chlorophyll}]{\text{light}} C_6H_{12}O_6 + 6O_2$$

Silver chloride and silver bromide decompose in light into silver and the halogen. The silver forms in grains so fine that they look not shiny but violet-gray or black:

$$2AgCl \xrightarrow{\text{light}} 2Ag + Cl_2 \qquad 2AgBr \xrightarrow{\text{light}} 2Ag + Br_2$$

Hydrogen and chlorine don’t react in the dark. In diffused light they combine steadily; in bright sunlight the mixture explodes:

$$H_2 + Cl_2 \xrightarrow{\text{light}} 2HCl$$

Methane and chlorine react the same way in diffused sunlight, a substitution you will meet in Unit 9 Grade 10.

Ozone is made in the stratosphere by sunlight. Ultraviolet light splits oxygen molecules into atoms, and each atom joins an oxygen molecule:

$$O_2 \xrightarrow{\text{UV light}} 2O \qquad O + O_2 \rightarrow O_3$$

Others you have met: hydrogen peroxide and silver nitrate decompose in light, which is why they are sold in brown bottles Grade 10; concentrated nitric acid turns yellow in light, as a little of it breaks down into brown nitrogen dioxide; colors of clothes and posters fade in the sun; and your skin makes vitamin D when sunlight’s ultraviolet falls on it.

Electrolytic reaction

An **electrolytic reaction** is a reaction brought about by passing an electric current through an electrolyte, molten or in solution. Electrical energy is turned into chemical energy, and the electrolyte decomposes at the electrodes. Grade 9 Optional Science explained how it works, with the ions moving to the electrodes and the rules for which ions are discharged Grade 9. Some important electrolytic reactions:

$2H_2O \xrightarrow{\text{electricity}} 2H_2 + O_2$ (water with a

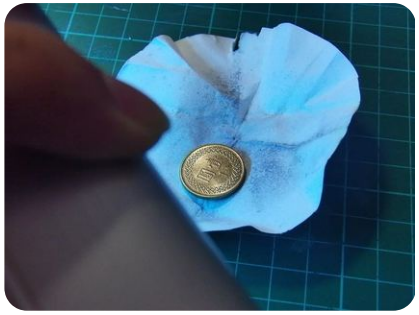


Figure 8.4 *The practical done with a lamp giving ultraviolet light instead of sunlight: silver chloride on filter paper, with a coin laid on it. Around the coin, the silver chloride has turned gray-violet.*
Photo: GOKLuLe 盧樂, CC BY-SA 3.0

CAREFUL

Is the chlorine really given off?

$2AgCl \rightarrow 2Ag + Cl_2$ is the equation every exam expects, and it is right. In a real precipitate, only the surface darkens, because the silver formed there blocks the light from the solid beneath; and much of the chlorine stays trapped in the solid or reacts with the water around it, rather than escaping as a gas. The darkening, finely divided silver, is what you see.

A STORY FROM SCIENCE

Pictures drawn by light

In 1838, in Paris, Louis Daguerre pointed his camera at the Boulevard du Temple. His plate was a sheet of silver-coated copper, made sensitive by iodine vapor, which covered it with silver iodide. Light falling on the plate made changes too small to see; mercury vapor then brought the picture out. The exposure took several minutes, so the carts and people moving along the street left no trace. But a man stood still at a corner, having his boots polished, and he is the first person ever photographed. In England, Henry Fox Talbot was making pictures on paper soaked in salt and silver nitrate, the silver chloride of the practical above. From then until digital cameras took over in the 2000s, almost every photograph was made by light breaking down silver halides.

The third is how most of the world's sodium hydroxide and chlorine are made; the fourth is how every aluminium can and window frame begins. Copper is purified, and

Check 8

Which of these is **not** a redox reaction?

a $2Mg + O_2 \rightarrow 2MgO$
b $Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$
c $NaOH + HCl \rightarrow NaCl + H_2O$
d $2Na + Cl_2 \rightarrow 2NaCl$

8.3 Monomer, polymer, and polymerization

Introduction

Going Further 6–8 showed how ethene molecules from oil join end to end into polythene, the plastic of bags and water tanks (From oil to a plastic bucket). Here are the words for it, exactly:

- A **monomer** ("one part") is a small molecule that can join with others of its kind, or of another kind, into a long chain.
- A **polymer** ("many parts") is a very large molecule, a **macromolecule**, made of many monomer units joined by covalent bonds, one after another.
- **Polymerization** is the chemical reaction in which monomers join to form a polymer.

The part that repeats along the chain is the **repeating unit**, and the number of repeating units in one chain is the **degree of polymerization**, n. A polymer is written as its repeating unit in brackets with n after it:

$$n\,CH_2{=}CH_2 \longrightarrow -[CH_2{-}CH_2]_n-$$

Here n is a few thousand or more, so the molar mass of the polymer is enormous: n times the mass of the repeating unit. (The ends of the chain differ a little, but in a chain thousands of units long they make no difference you could measure.) A real sample is a mixture of chains of different lengths, so its n and its molar mass are averages.

	Oxidation	Reduction
oxygen	added	removed
hydrogen	removed	added
electronegative element	added	removed
electropositive element	removed	added
electrons	lost	gained
in electrolysis, at the	anode	cathode
the substance this happens to is the	reducing agent	oxidizing agent

Not every reaction is a redox reaction. In a precipitation such as $Ag^+ + Cl^- \rightarrow AgCl$, or a neutralization such as $H^+ + OH^- \rightarrow H_2O$, ions only join; no electrons pass from one to another.

WORKED EXAMPLE

Who is oxidized?

In each reaction, name the substance oxidized, the substance reduced, the oxidizing agent and the reducing agent.

a. $ZnO + C \rightarrow Zn + CO$

b. $2Na + Cl_2 \rightarrow 2NaCl$

c. $H_2S + Cl_2 \rightarrow 2HCl + S$

Answer

a. Zinc oxide loses oxygen: **reduced**. Carbon gains oxygen: **oxidized**. Oxidizing agent: **ZnO**. Reducing agent: **C**.

b. Each sodium atom loses an electron, $Na \rightarrow Na^+ + e^-$: sodium is **oxidized**. Each chlorine atom gains one, $Cl_2 + 2e^- \rightarrow 2Cl^-$: chlorine is **reduced**. Oxidizing agent: **Cl_2**. Reducing agent: **Na**.

c. Hydrogen sulphide loses hydrogen: **oxidized** (to sulphur). Chlorine gains hydrogen: **reduced** (to HCl). Oxidizing agent: **Cl_2**. Reducing agent: **H_2S**.

Check 7

In $Cu^{2+} + Zn \rightarrow Cu + Zn^{2+}$, which is the reducing agent?

a Cu^{2+} b Zn

c Cu d Zn^{2+}

spoons and ornaments are silver- or gold-plated, by electrolysis too.

At the cathode, ions **gain** electrons ($Na^+ + e^- \rightarrow Na$); at the anode, ions **lose** electrons ($2Cl^- \rightarrow Cl_2 + 2e^-$). Gaining and losing electrons are exactly what the next two kinds of reaction are about. A cell or battery runs the other way: in the lead-acid cell a chemical reaction pushes electrons round the circuit, turning chemical energy into electrical energy, and charging it is an electrolytic reaction Grade 10.



Figure 8.5 *Daguerre's Boulevard du Temple, 1838. The street was busy, but the traffic moved too fast to show. On the pavement at the lower left, a man stands with one foot up on a shoeshiner's box.*

Photo: Louis Daguerre, Public domain

DID YOU KNOW?

Glasses that darken in the sun

Some spectacle lenses turn dark outdoors and clear again indoors. The first such lenses, made of glass from the 1960s, had tiny crystals of silver chloride or bromide spread through the glass: sunlight's ultraviolet split them into silver and the halogen, which darkened the lens, but trapped in the glass the two couldn't drift apart, and they joined up again indoors. Most such lenses today are plastic, and work with dyes whose molecules change shape in ultraviolet light, but the idea is the same: a photochemical reaction that runs backward in the dark.

Check 5

Why does silver nitrate solution come in brown bottles?

a brown glass is stronger than clear glass

b light decomposes silver nitrate, and brown glass keeps most of it out

c silver nitrate reacts with clear glass

d the brown color is a catalyst for its storage

Check 6

Which of these is an electrolytic reaction?

a $2H_2O_2 \rightarrow 2H_2O + O_2$, with manganese dioxide

b $2AgBr \rightarrow 2Ag + Br_2$, in sunlight

c $2H_2O \rightarrow 2H_2 + O_2$, with a current passed through acidified water

d $CaCO_3 \rightarrow CaO + CO_2$, on heating

Oxidation reaction

The word comes from oxygen, and its first meaning was just that. In the older (classical) sense, **oxidation** is:

- **the addition of oxygen** to a substance: $2Mg + O_2 \rightarrow 2MgO$; $C + O_2 \rightarrow CO_2$; $2SO_2 + O_2 \rightarrow 2SO_3$;
- **the removal of hydrogen** from a substance: in $H_2S + Cl_2 \rightarrow 2HCl + S$, hydrogen sulphide loses its hydrogen and is oxidized to sulphur;
- by extension, **the addition of an electronegative element** (such as chlorine) or **the removal of an electropositive element** (such as a metal): $2FeCl_2 + Cl_2 \rightarrow 2FeCl_3$, where iron(II) chloride gains chlorine and is oxidized.

These all have one thing in common, which is the modern meaning. When magnesium burns, each magnesium atom gives two electrons to an oxygen atom and becomes an Mg^{2+} ion. When iron(II) chloride takes more chlorine, each Fe^{2+} ion gives one more electron away and becomes Fe^{3+}. So in the electronic sense:

Oxidation is the loss of electrons by an atom, ion or molecule.

$$Mg \rightarrow Mg^{2+} + 2e^- \qquad Fe^{2+} \rightarrow Fe^{3+} + e^- \qquad 2Cl^- \rightarrow Cl_2 + 2e^-$$

The electronic meaning is wider: it covers reactions with no oxygen at all. When sodium burns in chlorine, $2Na + Cl_2 \rightarrow 2NaCl$, each sodium atom loses an electron to a chlorine atom, $Na \rightarrow Na^+ + e^-$, and sodium is oxidized.

A substance that oxidizes another, by giving it oxygen, taking its hydrogen, or taking its electrons, is an **oxidizing agent**. Oxygen, chlorine, hydrogen peroxide, potassium permanganate and concentrated nitric acid are strong oxidizing agents.

Oxidation is all around you: burning of fuels, the rusting of iron ($4Fe + 3O_2 + 2xH_2O \rightarrow 2Fe_2O_3{\cdot}xH_2O$), the respiration in your cells that oxidizes glucose to carbon dioxide and water, the browning of a cut apple, and **rancidity**, the stale smell and taste of oily food left in air. Packets of chips are filled with nitrogen, not air, for this reason: with no oxygen inside, the oil in the chips can't go rancid.

Reduction reaction

Reduction is the opposite of oxidation. In the classical sense, it is:

- **the removal of oxygen** from a substance: $CuO + H_2 \rightarrow Cu + H_2O$, in which copper oxide loses its oxygen and is reduced to copper; $ZnO + C \rightarrow Zn + CO$;
- **the addition of hydrogen** to a substance: $H_2 + Cl_2 \rightarrow 2HCl$, in which chlorine gains hydrogen and is reduced;
- by extension, **the removal of an electronegative element** or **the addition of an electropositive element**: $2FeCl_3 + SnCl_2 \rightarrow 2FeCl_2 + SnCl_4$, where iron(III) chloride loses chlorine and is reduced.

In the electronic sense:

Reduction is the gain of electrons by an atom, ion or molecule.

$$Cu^{2+} + 2e^- \rightarrow Cu \qquad Fe^{3+} + e^- \rightarrow Fe^{2+} \qquad Cl_2 + 2e^- \rightarrow 2Cl^-$$

A substance that reduces another, by taking its oxygen, giving it hydrogen, or giving it electrons, is a **reducing agent**. Hydrogen, carbon, carbon monoxide, hydrogen sulphide and reactive metals such as zinc and sodium are reducing agents. Getting metals from their ores is mostly reduction: in a blast furnace, carbon monoxide reduces iron oxide, $Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$ (Reduction; Unit 10 goes through the furnace step by step).

> CAREFUL
> **Remember it as OIL RIG**
>
> **O**xidation **I**s **L**oss, **R**eduction **I**s **G**ain (of electrons). And in electrolysis: oxidation happens at the anode, reduction at the cathode. ("An ox", "red cat": **an**ode **ox**idation, **red**uction **cat**hode.)

Oxidation and reduction go together: redox

Electrons don't vanish, and oxygen doesn't either. Whatever one substance loses, another must gain. So **oxidation and reduction always happen together**, in the same reaction, and such a reaction is called a **redox reaction** (*red*uction + *ox*idation).

Take hydrogen passed over hot copper(II) oxide:

$$CuO + H_2 \rightarrow Cu + H_2O$$

Copper oxide loses oxygen: it is **reduced**. Hydrogen gains oxygen: it is **oxidized**. Copper oxide gives the oxygen, so it is the **oxidizing agent**; hydrogen takes it, so it is the **reducing agent**. The oxidizing agent is itself reduced, and the reducing agent is itself oxidized.

Or take the iron nail in copper sulphate solution from Grade 10 Science:

$$Fe + CuSO_4 \rightarrow FeSO_4 + Cu \qquad \text{or, as ions,} \qquad Fe + Cu^{2+} \rightarrow Fe^{2+} + Cu$$

Split it into two **half-equations**: $Fe \rightarrow Fe^{2+} + 2e^-$ (iron loses electrons: oxidized) and $Cu^{2+} + 2e^- \rightarrow Cu$ (copper ions gain them: reduced). The two electrons that one iron atom loses are exactly the two that one copper ion gains. The sulphate ions take no part.