Structure 2.4 · From models to materials

International Baccalaureate · IB Diploma · Chemistry · HL

Scope and prerequisites

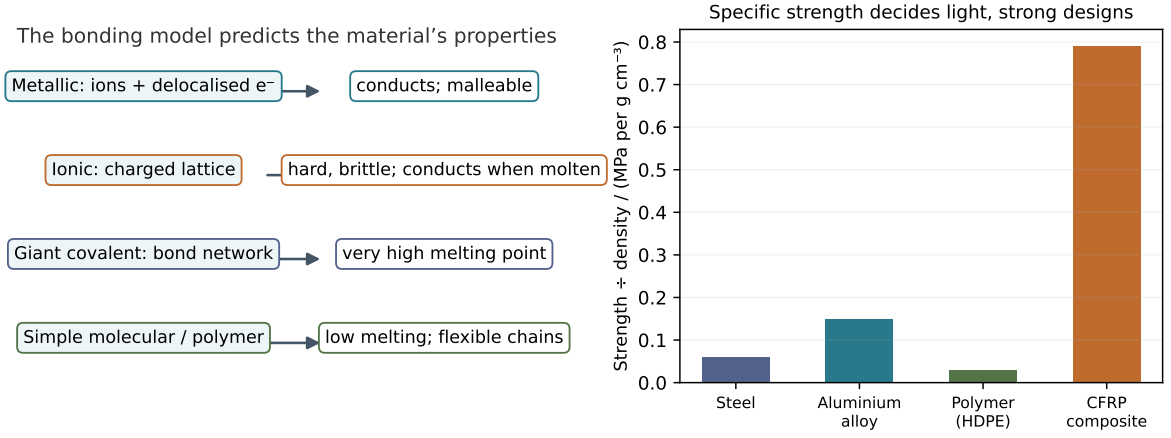
This handout teaches Structure 2.4, From models to materials, for the course first assessed in 2025. Sections marked **AHL** are for Higher Level only.

Prerequisites: the ionic, covalent and metallic models from Structures 2.1 to 2.3, and electronegativity values from the data booklet. You will draw structural formulas of simple organic molecules.

Bonding is a continuum

■ Why is a bicycle frame made of carbon fibre?

A racing bicycle frame must be strong, stiff and light. Steel is strong but heavy. Aluminium alloy is lighter. Carbon-fibre composite, long chains of covalently bonded carbon held in a polymer, is stronger than steel for its mass. Choosing a **material** means choosing a type of bonding, because the bonding decides the properties.



The bonding model predicts properties; strength per unit density decides light, strong designs

■ Three models, one continuum

Ionic, covalent and metallic bonding are models: ideal cases. Real substances often sit between them.

- **Ionic** bonding needs a large difference in electronegativity: one atom takes electrons from the other.
- **Covalent** bonding happens between atoms that both have high electronegativity: they share electrons.

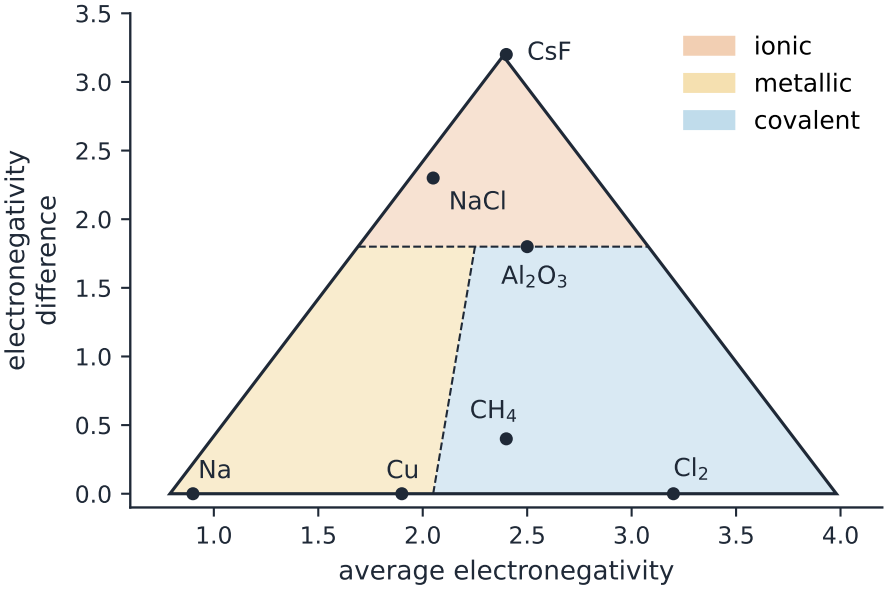
- **Metallic** bonding happens between atoms that both have low electronegativity: they release electrons into a shared sea.

Most bonds have some character of more than one type. In aluminium oxide the bonding is mainly ionic, but the small, highly charged Al^{3+} ion pulls the electrons of the oxide ion towards it, giving the bond some covalent character.

The bonding triangle

The **bonding triangle** (the van Arkel–Ketelaar triangle in the data booklet) places a binary substance by two numbers:

- the **average electronegativity** of the two elements on the x-axis;
- the **electronegativity difference** on the y-axis.



The boundaries are approximate: bonding changes gradually across the triangle

Worked example: placing a compound

Use the triangle to predict the bonding in magnesium oxide. Electronegativities: Mg 1.3, O 3.4.

- Average: $(1.3 + 3.4)/2 = 2.35$.
- Difference: $3.4 - 1.3 = 2.1$.
- The point (2.35, 2.1) is in the ionic region, so MgO is predicted to be mainly ionic: a high melting point, and conduction only when molten.

For silicon dioxide (Si 1.9, O 3.4): average 2.65, difference 1.5. The point lies in the covalent region, which fits its giant covalent structure.

From position to properties

Region	Typical properties
ionic (top)	high melting point, brittle, conducts only when molten or dissolved, often soluble in water
covalent (bottom right)	molecular: low melting point, no conduction; network: very high melting point, no conduction
metallic (bottom left)	conducts when solid, malleable, shiny, most melt high

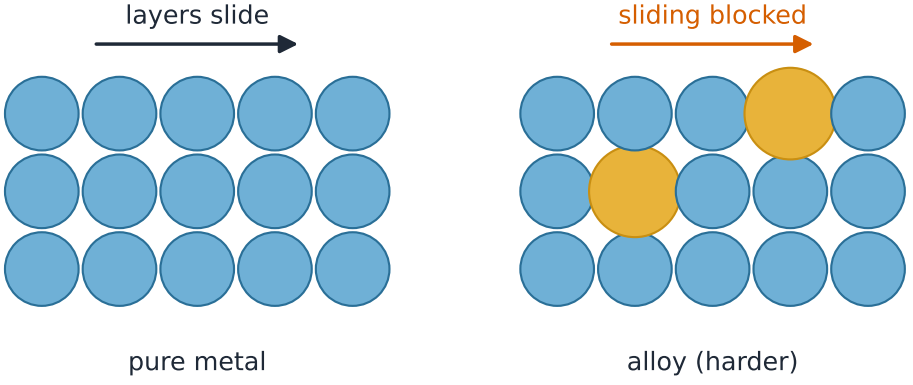
The triangle predicts bonding; it does not decide between a molecular and a network covalent structure. Use other evidence, such as the melting point, for that.

Alloys

Metals mixed with other elements

An **alloy** is a mixture of a metal with other metals, or with a non-metal such as carbon. Alloys are made by mixing the molten elements and letting them cool. They still have metallic bonding: cations of different elements in a sea of delocalized electrons.

Pure metals are often too soft. In a pure metal all the cations are the same size, so the layers slide easily. In an alloy, atoms of a different size distort the regular layers. The layers can no longer slide easily, so the alloy is **harder** and stronger.



Different-sized atoms distort the layers, so they cannot slide past each other easily

Alloy	Composition	Improved property	Use
steel	iron with up to about 2% carbon	harder and stronger than iron	buildings, bridges
stainless steel	iron with chromium and nickel	resists corrosion	cutlery, medical tools
brass	copper and zinc	harder than copper, resists corrosion	taps, musical instruments
bronze	copper and tin	harder, resists corrosion	statues, bearings
duralumin	aluminium with copper and magnesium	stronger, still light	aircraft bodies

Alloys can also change other properties: some melt at lower temperatures than any of their parts (solder), and some resist corrosion because the added element forms a protective oxide layer (chromium in stainless steel).

Polymers

Long chains from small units

A **polymer** is a very large molecule (a macromolecule) made of many small units joined in a chain. The small molecules that join are **monomers**, and the part of the chain that repeats is the **repeating unit**.

Polymers can be natural, such as starch, cellulose, proteins and DNA, or synthetic, such as poly(ethene) and nylon. Most plastics are synthetic polymers.

Properties of plastics

The properties of a plastic come from its long chains:

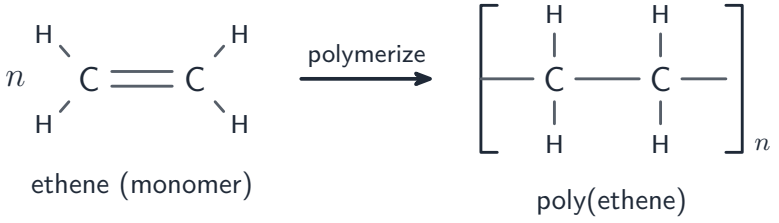
- Chains are held together by intermolecular forces. Longer chains have more contact between them, so the forces are stronger and the plastic is stronger and melts higher.
- Chains with no side branches pack closely (high-density poly(ethene), HDPE); branched chains pack loosely (low-density poly(ethene), LDPE), so LDPE is softer and more flexible.
- Plastics are light, cheap, easy to shape and unreactive. Most do not conduct electricity, so they are good insulators.

The same unreactive covalent bonds cause a problem: most plastics are not **biodegradable**. They last for hundreds of years in landfill and in the oceans. Burning them releases carbon dioxide and, for PVC, toxic hydrogen chloride. Recycling sorts plastics by type, using the resin identification code printed on them.

Addition polymers

Joining alkenes

In **addition polymerization** monomers with a C=C double bond join together. The pi bond in each double bond breaks, and the electrons form new single bonds to the neighbouring monomers. No other product forms: every atom of the monomers ends up in the polymer.



The double bond opens; the repeating unit has the same atoms as the monomer, joined by single bonds

To draw the repeating unit from a monomer:

1. Draw the two carbons of the C=C with a **single** bond between them.
2. Keep every group that was attached to those carbons in the same place.
3. Add a continuation bond on each side, through square brackets, and write n after the bracket.

Monomer	Formula	Polymer	Repeating unit
ethene	$CH_2 = CH_2$	poly(ethene)	$-CH_2 - CH_2-$
propene	$CH_2 = CHCH_3$	poly(propene)	$-CH_2 - CH(CH_3)-$
chloroethene	$CH_2 = CHCl$	poly(chloroethene), PVC	$-CH_2 - CHCl-$
tetrafluoroethene	$CF_2 = CF_2$	PTFE (Teflon)	$-CF_2 - CF_2-$

To go backwards from a polymer to its monomer, find the two-carbon repeating unit and put a double bond between those two carbons.

Note that the side group (such as CH_3 or Cl) hangs **off** the main chain; it is never part of the chain itself.

AHL: Condensation polymers

Joining two functional groups

In **condensation polymerization** each new bond forms between two functional groups, and a small molecule, usually water or hydrogen chloride, is released. Each monomer must have **two** functional groups, one at each end, so that the chain can keep growing in both directions.

polyester: -C(=O)-OH + H-O- → -C(=O)-O- + H_2O

polyamide: -C(=O)-OH + H-N(H)- → -C(=O)-NH- + H_2O

every new ester or amide link loses a small molecule (condensation)

Every new ester or amide link releases one small molecule

- **Polyesters** form from a dicarboxylic acid and a diol. Each link is an **ester link**, −COO−. Example: PET, from benzene-1,4-dicarboxylic acid and ethane-1,2-diol, used for drinks bottles and polyester fibres.
- **Polyamides** form from a dicarboxylic acid (or a diacyl chloride) and a diamine. Each link is an **amide link**, −CONH−. Examples: nylon-6,6 from hexanedioic acid and hexane-1,6-diamine; Kevlar, whose flat chains form many hydrogen bonds, which makes it strong enough for body armour.
- With a diacyl chloride, $ClOC - R - COCl$, the small molecule released is HCl instead of water.

Biological condensation polymers

Many natural polymers are condensation polymers:

- **Proteins** are polyamides made from amino acids, each joined by an amide (peptide) link with loss of water.
- **Polysaccharides**, such as starch and cellulose, are made from glucose units joined with loss of water.
- **Nucleic acids** (DNA and RNA) are made from nucleotides joined with loss of water.

Addition against condensation

	Addition polymer	Condensation polymer
monomer	contains C=C	two functional groups per monomer (or two different monomers)
other product	none	a small molecule (H_2O or HCl)
main chain	C–C bonds only	contains ester or amide links
breaking down	very slow; not hydrolysed	ester and amide links can be hydrolysed, so many are more biodegradable

Hydrolysis is the reverse of condensation: water breaks the ester or amide link and gives back the monomers. This is how the body digests proteins and starch, and how some polyesters can be chemically recycled.

Practice

1. Electronegativities: Na 0.9, Cl 3.2, C 2.6, H 2.2, Cu 1.9, Zn 1.6. Use the bonding triangle to predict the main type of bonding in: (a) NaCl, (b) CH_4, (c) CuZn (brass).
2. Explain why aluminium oxide is described as ionic with some covalent character.
3. Explain why steel is harder than pure iron.
4. Draw the repeating unit of poly(propene), and the monomer of a polymer with repeating unit $-CH_2-CH(CN)-$.
5. State two properties that make poly(ethene) useful for packaging and one environmental problem it causes.
6. Explain why HDPE is stronger and denser than LDPE.
7. **AHL.** Name the two monomers needed to make nylon-6,6, state the link formed and name the other product.
8. **AHL.** Give two differences between addition and condensation polymerization.

Answers.

1. (a) average 2.05, difference 2.3: ionic. (b) average 2.4, difference 0.4: covalent. (c) average 1.75, difference 0.3: metallic.
2. The electronegativity difference (Al 1.6, O 3.4: difference 1.8) is on the boundary of the ionic region. The small Al^{3+} ion with a high charge distorts the electron cloud of O^{2-}, pulling electron density between the ions, so the bond has some covalent character.
3. Steel contains carbon atoms of a different size among the iron cations. They distort the regular layers, so the layers cannot slide over each other easily.
4. Poly(propene): $-CH_2-CH(CH_3)-$ in square brackets with continuation bonds and n. The monomer is $CH_2=CHCN$ (propenenitrile).
5. Any two of: light, cheap, flexible, waterproof, unreactive, easy to shape. Problem: not biodegradable, so it stays in landfill and the oceans for hundreds of years (or: burning releases CO_2).
6. HDPE chains have no branches, so they pack closely together. There is more contact between chains, so the London forces are stronger and more mass fits in the same volume.
7. **AHL.** Hexanedioic acid and hexane-1,6-diamine. An amide link, $-CONH-$, forms and water is released.
8. **AHL.** Any two: addition monomers contain C=C, condensation monomers have two functional groups; addition gives only the polymer, condensation also releases a small molecule such as water; the addition polymer chain has only C–C bonds,

the condensation chain contains ester or amide links that can be hydrolysed.

Exam tips

- Use the bonding triangle with **both** numbers: the average electronegativity and the difference.
- Say that bonding is a **continuum**: the triangle regions have no sharp boundaries.
- For alloys, explain hardness with **different-sized atoms** that **distort the layers** so they cannot slide.
- When drawing an addition repeating unit, change C=C to C–C, keep the side groups off the chain, and add continuation bonds with n.
- **AHL.** For condensation polymers, always name the **small molecule** lost and the **link** formed.