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IB DIPLOMA CHEMISTRY · FIRST ASSESSMENT 2025

# Structure 2.4
# From Models to Materials

## Understandings 2.4.1 – 2.4.6

*The bonding triangle, alloys, polymers, and addition and condensation polymerization*

Complete revision notes & memory points · Standard Level & Higher Level

**How the level tags work in this booklet**

SL + HL Core material. Understandings 2.4.1 to 2.4.5 are common to both levels. Every student must know this.

HL Additional higher level material. Understanding **2.4.6 (condensation polymers)** is HL only. SL students can skip section 7 and the questions marked HL.

**Inside this booklet**


1. What the syllabus actually asks of you
2. 2.4.1 — Bonding as a continuum: the bonding triangle
3. 2.4.2 — Using the bonding triangle
4. 2.4.3 — Alloys
5. 2.4.4 — Polymers
6. 2.4.5 — Addition polymers
7. HL 2.4.6 — Condensation polymers
8. Bringing it all together
9. Key points to memorise
10. Check yourself
11. Answers

# 1 What the syllabus actually asks of you

Structure 2.4 closes the Structure 2 strand by asking one guiding question: *what role do bonding and structure have in the design of materials?* Structures 2.1, 2.2 and 2.3 treated ionic, covalent and metallic bonding as separate models. Real substances rarely fit one model exactly. This topic replaces the three boxes with a single continuous picture, the **bonding triangle**, and then applies bonding ideas to three families of materials that shape modern life: **alloys**, **addition polymers** and (at HL) **condensation polymers**.

| Understanding | What it says | What you must be able to do | Level |
|---|---|---|---|
| **2.4.1** The bonding triangle | Bonding is best described as a continuum between the ionic, covalent and metallic models, and can be represented by a bonding triangle. | Use bonding models to explain the properties of a material. (A triangular bonding diagram is provided in the data booklet.) | SL+HL |
| **2.4.2** Applying the triangle | The position of a compound in the bonding triangle is determined by the relative contributions of the three bonding types to the overall bond. | Determine the position of a compound in the triangle from electronegativity data, and predict its properties. Only binary compounds need to be considered; calculations of percentage ionic character are not required. | SL+HL |
| **2.4.3** Alloys | Alloys are mixtures of a metal and other metals or non-metals. They have enhanced properties. | Explain the properties of alloys in terms of non-directional bonding. Illustrate with common examples such as bronze, brass and stainless steel. (Specific alloys do not have to be learned.) | SL+HL |
| **2.4.4** Polymers | Polymers are large molecules, or macromolecules, made from repeating subunits called monomers. | Describe the common properties of plastics in terms of their structure. Discuss examples of natural and synthetic polymers. | SL+HL |
| **2.4.5** Addition polymers | Addition polymers form by the breaking of a double bond in each monomer. | Represent the repeating unit of an addition polymer from given monomer structures. (Monomer structures will be provided, or must be deduced from the polymer.) | SL+HL |
| **2.4.6** Condensation polymers | Condensation polymers form by the reaction between functional groups in each monomer with the release of a small molecule. | Represent the repeating unit of polyamides and polyesters from given monomer structures. Know that biological macromolecules form by condensation and break down by hydrolysis. | HL |

**Linking questions, Nature of Science and TOK attached to Structure 2.4**

- **Structure 3.1:** how do the trends in properties of period 3 oxides reflect the trend in their bonding? → section 2.3
- **Nature of Science, Structure 2.1, 2.2:** what are the limitations of discrete bonding categories? → section 2.4
- **Structure 2.1, 2.2, 2.3:** why do composites such as reinforced concrete have unique properties? → section 3.3
- **Structure 1.1:** why are alloys more correctly described as mixtures rather than as compounds? → section 4.4
- **Structure 2.3:** what are the structural features of some plastics that make them biodegradable? → section 5.4
- **Structure 3.2:** what functional groups in molecules can enable them to act as monomers in addition reactions? → section 6.1
- **Reactivity 2.1:** why is the atom economy 100% for an addition polymerization reaction? → section 6.5
- HL **Structure 3.2:** what functional groups in molecules can enable them to act as monomers in condensation reactions? → section 7.1
- **TOK:** to what extent do the classification systems we use in the pursuit of knowledge affect the conclusions we reach? Does competition between scientists help or hinder knowledge? → sections 2.4 and 5.3

**What the data booklet gives you — and what it does not**

- **Given:** electronegativity values (**Section 9**) and the bonding triangle itself (**Section 17**), with its axes and the four regions labelled metallic, covalent, polar covalent and ionic.
- **Not given:** how to calculate the two coordinates, the properties associated with each region, any alloy compositions, or any polymer or monomer structures. You must be able to work out a repeating unit from a monomer, and a monomer from a repeating unit.

## 2 Structure 2.4.1 — Bonding as a continuum SL + HL

### 2.1 Why three separate models are not enough

Treating every substance as purely ionic, purely covalent or purely metallic is an over-simplification. You have already met the evidence. In Booklet 2 of Structure 2.2, polar covalent bonds were shown to have some **ionic character**; in Structure 2.1, many ionic compounds were shown to have some **covalent character**. A more accurate picture is a **continuum**, in which each substance has a mixture of the three bonding types in different proportions. The simplest way to represent this is a triangle with one bonding type at each vertex. Every material can be placed somewhere inside it, according to the relative amounts of each type of bonding it contains.

## 2.2 The bonding triangle

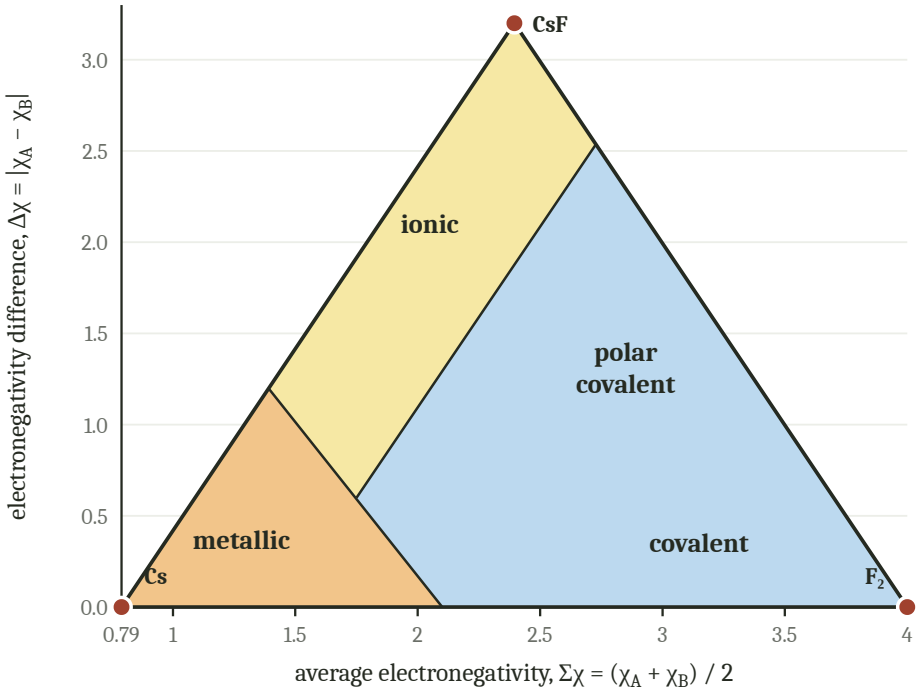



Figure 1 — The bonding triangle (van Arkel–Ketelaar triangle), with the three extreme substances at its corners. Region boundaries are drawn approximately; use the data booklet version (Section 17) in examinations.

The position of a substance is fixed by two numbers calculated from the electronegativities ($\chi$) of its two elements, A and B:

- **x-axis — average electronegativity**, $\Sigma\chi = (\chi_A + \chi_B) / 2$.
- **y-axis — electronegativity difference**, $\Delta\chi = |\chi_A - \chi_B|$.

Electronegativity measures how strongly an atom attracts electrons, so these two numbers capture what kind of bond forms: a **large difference** means electron transfer (ionic); a **small difference with high values** means sharing (covalent); a **small difference with low values** means both atoms release electrons into a common pool (metallic).

| Region of the triangle | Coordinates | Type of bonding | Typical substances |
|---|---|---|---|
| **Bottom left** | low $\Sigma\chi$, $\Delta\chi \approx 0$ | metallic | metallic elements and alloys |
| **Bottom right** | high $\Sigma\chi$, $\Delta\chi \approx 0$ | covalent | non-metallic elements; compounds of non-metals with similar $\chi$ |
| **Right, middle** | high $\Sigma\chi$, moderate $\Delta\chi$ | polar covalent | compounds of non-metals with different $\chi$; some metal compounds such as $AlCl_3$ |
| **Top centre** | large $\Delta\chi$ | ionic | compounds of reactive metals with reactive non-metals |

All elements have $\Delta\chi = 0$, so they lie along the bottom edge: metals on the left, non-metals on the right, metalloids such as silicon in between.

**Nature of Science — a tool with predictive power**

The bonding triangle is named after two Dutch chemists: Anton van Arkel, who first proposed it and applied it mostly to elements, and Jan Ketelaar, who extended it to compounds in the mid-twentieth century. Different scientists used different parameters, but electronegativity became the established basis. The triangle is valuable because it is **predictive**: from two numbers in the data booklet, you can estimate the bonding and the properties of a substance you have never met.

## 2.3 The period 3 oxides

Oxygen has an electronegativity of 3.4. Across period 3, the electronegativity of the elements rises from 0.9 (Na) towards that of oxygen. So the electronegativity **difference** in the oxides falls across the period, the **ionic character** of the oxides falls, and their **covalent character** rises.

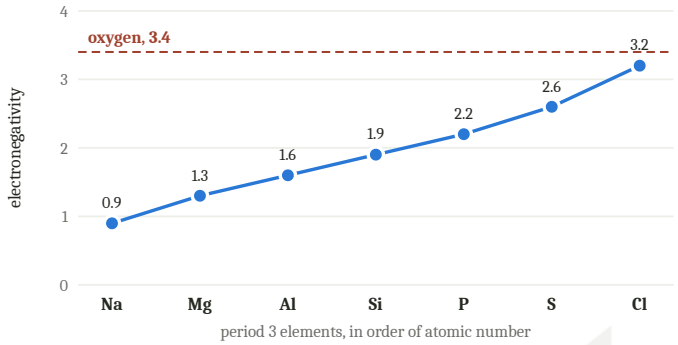



Figure 2 — Electronegativity of the period 3 elements (data booklet, Section 9).

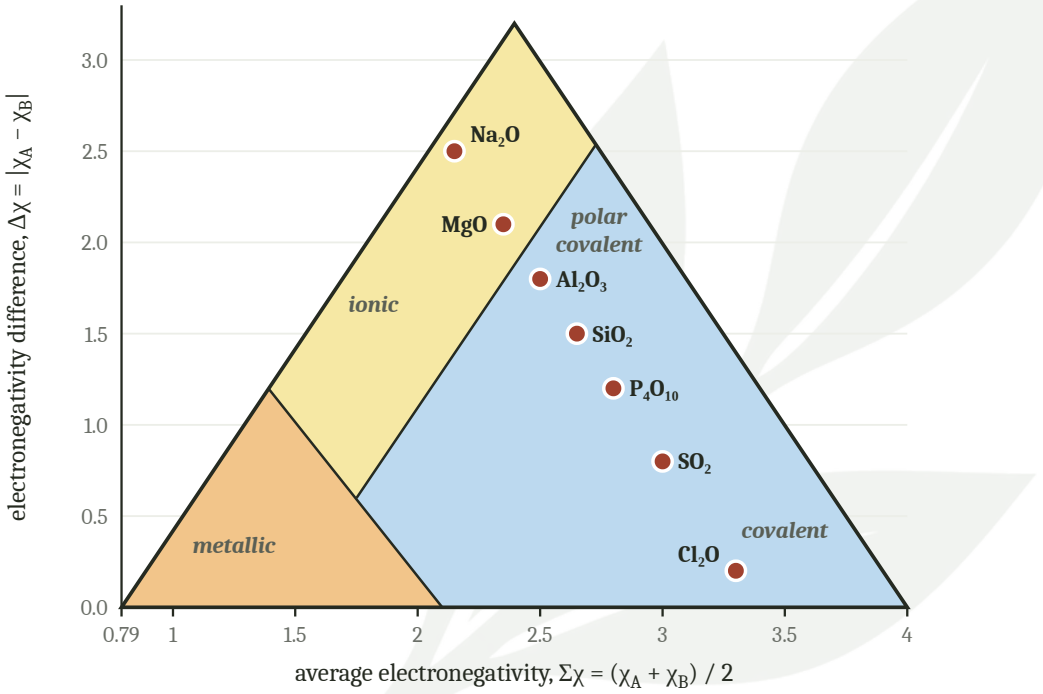



Figure 3 — The period 3 oxides on the bonding triangle.

| Oxide | Σχ | Δχ | Bonding |
|---|---|---|---|
| $Na_2O$ | 2.15 | 2.5 | ionic |
| MgO | 2.35 | 2.1 | ionic |
| $Al_2O_3$ | 2.50 | 1.8 | on the ionic / polar covalent border |
| $SiO_2$ | 2.65 | 1.5 | polar covalent (giant) |
| $P_4O_{10}$ | 2.80 | 1.2 | polar covalent (molecular) |
| $SO_2$ | 3.00 | 0.8 | polar covalent (molecular) |
| $Cl_2O$ | 3.30 | 0.2 | covalent (molecular) |

This answers the Structure 3.1 linking question. The trend in bonding explains the trend in properties: $Na_2O$, MgO and $Al_2O_3$ are **ionic**, with high melting points and electrical conductivity when molten; $SiO_2$ is a **giant covalent** structure, with a high melting point but no conductivity; $P_4O_{10}$, $SO_2$ and $Cl_2O$ are **molecular covalent**, with low melting and boiling points and no conductivity. Their acid–base behaviour follows the same trend (Structure 3.1 and Reactivity 3.1).

### 2.4 The limitations of discrete bonding categories

Aluminium chloride is formed from a metal and a non-metal, so a simple "metal + non-metal = ionic" rule would classify it as ionic and predict a high melting point. In fact $AlCl_3$ sublimes at about 180 °C, far below sodium chloride (801 °C). Its position in the bonding triangle ($\Sigma\chi = 2.4$, $\Delta\chi = 1.6$) lies in the **polar covalent** region, close to the ionic border: $AlCl_3$ has substantial covalent character, which explains its volatility and its existence as $Al_2Cl_6$ molecules in the vapour (Structure 2.2, Booklet 1). Treating bonding as a continuum gives a more accurate prediction than assigning a single category.

> **TOK — the costs and benefits of classification**
>
> Classification systems make knowledge manageable, but they also shape the conclusions we draw. Calling $AlCl_3$ "ionic" because of the elements it contains leads to a wrong prediction. The bonding triangle is still a classification, with its own boundaries drawn by people, but its continuous scale reminds us that real substances often lie between our categories.

## 3 Structure 2.4.2 — Using the bonding triangle SL + HL

### 3.1 Locating a substance

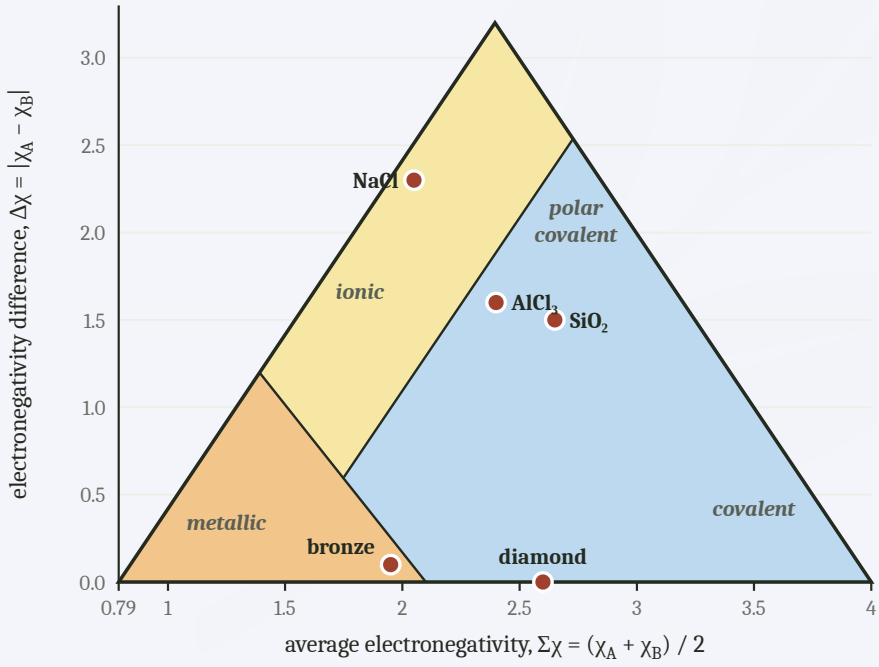
1. Look up the electronegativity of each element in the data booklet, Section 9. For an element, both values are the same.
2. Calculate the **average**, $\Sigma\chi = (\chi_A + \chi_B) / 2$, for the x-axis, and the **difference**, $\Delta\chi = \chi_A - \chi_B$ (larger minus smaller), for the y-axis. Ignore the formula ratio: $Al_2O_3$ uses one Al and one O value.
3. Plot the point on the triangle in Section 17 and read off the region: metallic, covalent, polar covalent or ionic.
4. Use the region to **predict properties** (section 3.2) and explain them using the matching bonding model.

### Worked example — the three corners: Cs, $F_2$ and CsF

| Substance | Σχ | Δχ | Position in the triangle |
|---|---|---|---|
| Cs | 0.8 | 0.8 − 0.8 = 0.0 | bottom left: 100% metallic; caesium has the lowest electronegativity |
| $F_2$ | 4.0 | 4.0 − 4.0 = 0.0 | bottom right: 100% covalent (non-polar) |
| CsF | (4.0 + 0.8) / 2 = 2.4 | 4.0 − 0.8 = 3.2 | the top vertex: the most ionic compound, formed from the most electropositive metal and the most electronegative non-metal |

### Worked example — locate diamond, silicon dioxide, bronze, NaCl and $AlCl_3$

| Substance | Σχ | Δχ | Region |
|---|---|---|---|
| diamond (C) | 2.6 | 0.0 | covalent |
| $SiO_2$ | (1.9 + 3.4) / 2 = 2.65 | 1.5 | polar covalent |
| bronze (Cu/Sn) | (1.9 + 2.0) / 2 = 1.95 | 0.1 | metallic |
| NaCl | (0.9 + 3.2) / 2 = 2.05 | 2.3 | ionic |
| $AlCl_3$ | (1.6 + 3.2) / 2 = 2.4 | 1.6 | polar covalent, near the ionic border |




The right-hand side of the data booklet triangle also shows an approximate percentage of ionic and covalent character (NaCl roughly 75% ionic; $AlCl_3$ roughly 50%). You may read these values, but calculations of percentage ionic character are not required.

## 3.2 Predicting properties from position

| Region | Expected structure | Melting point | Electrical conductivity | Other properties |
|---|---|---|---|---|
| **Metallic** | lattice of cations and delocalized electrons | usually high | good, solid and liquid | malleable, ductile, lustrous |
| **Ionic** | lattice of ions | high | only when molten or aqueous | brittle; often soluble in water |
| **Polar covalent** | molecules with polar bonds, or a giant covalent lattice ($SiO_2$) | low (molecular) or high (giant) | poor | molecular ones often soluble in polar solvents |
| **Covalent** | non-polar molecules, or giant covalent lattice (diamond) | low (molecular) or very high (giant) | none (except graphite) | molecular ones soluble in non-polar solvents |

### What the triangle can and cannot tell you

The position tells you the **type of bonding** and so the **likely properties**. It does **not** tell you the chemical formula, and it cannot by itself distinguish a giant covalent structure from a molecular one: $SiO_2$ (giant) and $P_4O_{10}$ (molecular) both lie in the polar covalent region. An element always lies on the bottom edge ($\Delta\chi = 0$), but a point on the bottom edge could also be an alloy or a compound of two elements with equal electronegativity, such as $CS_2$.

### Model answer: "Use the bonding triangle to explain why aluminium chloride has a much lower melting point than sodium chloride." (3 marks)

NaCl: $\Sigma\chi = 2.05$, $\Delta\chi = 2.3$, so it lies in the ionic region; $AlCl_3$: $\Sigma\chi = 2.4$, $\Delta\chi = 1.6$, so it lies in the polar covalent region **[1]**. NaCl is a giant ionic lattice; melting requires overcoming strong electrostatic attractions between ions throughout the lattice **[1]**. $AlCl_3$ has considerable covalent character and exists as molecules, so only weaker intermolecular forces must be overcome **[1]**.

## 3.3 Composites

This is the Structure 2.1, 2.2 and 2.3 linking question. A **composite** is a heterogeneous mixture of at least two different materials that remain as **separate phases**. Each component keeps its own properties, and the combination is designed to have properties that neither has alone. Reinforced concrete is the classic example: concrete (made largely of ionic and covalently bonded minerals) is strong in compression but weak in tension, while the steel reinforcing bars (metallic bonding) are strong in tension and ductile. Fibreglass (glass fibres in a polymer resin) and ancient adobe bricks (mud bound with straw) are composites too. Unlike an alloy, a composite is not a uniform mixture at the level of particles.

### Examiner traps in 2.4.1 – 2.4.2

- Using the formula ratio when calculating $\Sigma\chi$. For $Al_2O_3$, use one aluminium and one oxygen value.
- Plotting $\Delta\chi$ on the x-axis or $\Sigma\chi$ on the y-axis. The x-axis is the **average**; the y-axis is the **difference**.
- Assuming every metal–non-metal compound is ionic. Check its position: $AlCl_3$ is polar covalent.
- Claiming the triangle gives the formula of a substance, or whether a covalent substance is giant or molecular.

# 4 Structure 2.4.3 — Alloys SL + HL

## 4.1 What an alloy is and why it can form

> **Definition to learn**
>
> An **alloy** is a mixture of a metal with other metals or non-metals. Alloys are **homogeneous** mixtures held together by **metallic bonding**, and they have enhanced properties compared with their component elements.

Alloys are usually made by mixing the elements in the **liquid** state and allowing the mixture to solidify. The atoms of the different elements become scattered through one lattice, giving a structure of uniform composition. The delocalized electrons bind all the cations together, whatever their size. This is possible because metallic bonding is **non-directional** — each cation is attracted to the surrounding electron sea, not to particular neighbours — so the lattice can accommodate cations of different sizes, and even small non-metal atoms such as carbon, without losing its bonding.

## 4.2 Why alloys have enhanced properties

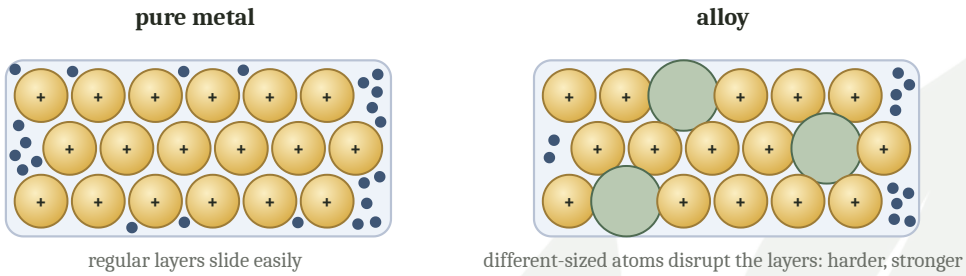



Figure 4 — In a pure metal (left) the layers of identical cations slide easily. In an alloy (right) atoms of a different size disrupt the regular layers, so they cannot slip past one another as easily.

In a pure metal the cations are all the same size and arranged in regular layers that slip over each other easily, which makes pure metals relatively soft and malleable. In an alloy, atoms of a different size **disrupt the regular arrangement**, so the layers can no longer slide past each other as easily. As a result, alloys are typically **harder** and **stronger** than their pure components, and many are also more **resistant to corrosion** or more chemically stable. Steel, for example, which is iron with less than 2% carbon and small amounts of other elements, is very much stronger than pure iron. Because they still contain metallic bonding, alloys keep metallic properties such as electrical and thermal conductivity, and magnetism in the case of many iron-based alloys.

## 4.3 Some common alloys

You do not need to learn these examples, but you should be able to use one or two to explain how the structure of an alloy gives it enhanced properties.

| Alloy | Main components | Enhanced properties and uses |
|---|---|---|
| steel | iron with a small amount of carbon | much greater strength than iron; buildings, bridges, vehicles, tools — but it corrodes |
| stainless steel | iron with chromium and nickel | strong and resistant to corrosion; cutlery, sinks, surgical instruments |
| brass | copper and zinc | harder than copper, corrosion resistant, easily machined; plumbing fittings, musical instruments |

| Alloy | Main components | Enhanced properties and uses |
|---|---|---|
| bronze | copper and tin | hard and corrosion resistant; coins, medals, statues, ship propellers |
| duralumin | aluminium with copper (and magnesium, manganese) | strong but low density; aircraft and boat structures |
| nichrome | nickel and chromium | high electrical resistance and resists oxidation when hot; heating elements, flame-test wires |
| solder | tin with lead (modern solders are lead-free, tin-based) | low melting point; joining metals and electrical components |
| sterling silver | silver (92.5%) and copper | harder and more durable than pure silver; jewellery and tableware |

## 4.4 Why alloys are mixtures, not compounds

This is the Structure 1.1 linking question. A compound has a fixed composition and a chemical formula, and its elements are chemically combined. An alloy has **no fixed composition**: "steel" is the general name for a family of mixtures of iron and carbon (and other metals) in different proportions, so it cannot be represented by a chemical formula. Alloys form by mixing liquid metals without a chemical reaction, and the components keep their metallic character. That makes alloys **homogeneous mixtures**, sometimes described as solid solutions. Even so, the components of an alloy are hard to separate by simple physical methods, because they are uniformly mixed at the level of individual atoms and their melting points can be close together.

### The global impact of science — steel

Steel manufacture is one of the world's largest industries, and global steel production has roughly tripled over the last half century. Traditional blast furnaces use coal and release large amounts of carbon dioxide, so companies are developing processes that use hydrogen, produced by electrolysis using renewable electricity, to reduce iron ore. Steel can be recycled repeatedly without loss of quality, and a large share of new steel already contains recycled material.

**Model answer: "Explain, in terms of bonding and structure, why an alloy of aluminium is used for aircraft rather than pure aluminium." (3 marks)**

The alloy contains atoms of different sizes in the metallic lattice **[1]**, which disrupt the regular layers of cations so that they cannot slide over each other as easily **[1]**. The alloy is therefore stronger and harder than pure aluminium, while keeping its low density **[1]**.

# 5 Structure 2.4.4 — Polymers SL + HL

## 5.1 Monomers, polymers and repeating units

**Definitions to learn**

- **Monomer** — a small molecule that can react with other molecules of the same kind (or a different kind) to form a polymer.
- **Polymer** — a large molecule, or **macromolecule**, made from many repeating subunits (monomers) joined by covalent bonds.
- **Repeating unit** — the smallest part of the polymer chain that repeats. It is drawn with **open bonds** at each end, extending through square brackets, and a subscript *n* to show that it repeats many times.

Polymers can contain thousands of atoms. They vary in the nature of the monomer, in the length of the chain and in how much the chain is branched, and so they have an enormous range of properties. Most of the polymers in this topic are organic: they depend on carbon's ability to form stable chains of bonds with itself. An introduction to organic chemistry is in Structure 3.2.

## 5.2 Natural and synthetic polymers

| | Natural polymers | Synthetic polymers |
|---|---|---|
| **Origin** | made by living organisms | made in industry, mostly from petroleum-derived monomers, since the 1930s |
| **Examples** | proteins (from amino acids), starch and cellulose (from glucose), DNA and RNA (from nucleotides), natural rubber | poly(ethene), poly(propene), PVC, PTFE, polystyrene, nylon, polyesters such as PET, Kevlar |
| **Importance** | understanding the structure of proteins and DNA underpins modern medicine; for example, analysing the structure of viral spike proteins helped researchers develop vaccines | plastics are used in packaging, construction, clothing, transport, electronics and medicine |

## 5.3 Properties of plastics and their structure

Plastics are synthetic polymers. Their widespread use comes from properties that follow directly from their structure:

| Property | Explanation from structure |
|---|---|
| **low density, lightweight** | made of light atoms (C, H, O, N, Cl, F); molecular chains pack less densely than metals or ionic lattices |
| **low reactivity, durable** | long chains of strong C–C and C–H covalent bonds; addition polymers have no reactive double bonds left |
| **water resistant, insoluble in water** | mostly non-polar chains that cannot form hydrogen bonds with water |
| **electrical and thermal insulators** | no ions or delocalized electrons; electrons are held in localized covalent bonds |
| **can be strong and flexible, and easily moulded** | long chains tangle together and are held by many intermolecular forces; the chains can slide when heated, so many plastics soften and can be shaped. Strength increases with chain length and with stronger intermolecular forces (such as hydrogen bonding in nylon and Kevlar) |

**Nature of Science and TOK — Hermann Staudinger and the idea of the macromolecule**

Until about 1929, most chemists did not accept that very large molecules could exist. They believed that rubber, starch and the new plastics were bundles of small molecules held together by unknown intermolecular forces. The German chemist Hermann Staudinger argued that these substances were giant molecules held together by covalent bonds. His ideas met strong resistance: he was even told to "drop the idea of large molecules". The eventual acceptance of his theory was a turning point in polymer chemistry, and he received the Nobel Prize in Chemistry in 1953. Science is a human activity, and sometimes it takes courage to challenge accepted models. (TOK: does competition between scientists help or hinder the production of knowledge?)

## 5.4 Plastics and the environment

The properties that make plastics so useful — low reactivity and water resistance — also mean that most are **non-biodegradable**: they cannot be broken down by natural processes, so they persist in the environment for very long periods. Global plastic production has risen enormously since 1950, and a large proportion ends up in the oceans, where it harms ecosystems. **Microplastics** (pieces smaller than 5 mm) come from the breakdown of larger items and from products such as cosmetic microbeads; they are eaten by marine organisms and enter the food chain.

This answers the Structure 2.3 linking question. A **biodegradable** plastic can be broken down by microorganisms into products found in nature, such as carbon dioxide and water. Many are plant-based, containing natural polymers such as starch or cellulose, often from corn. Their chains contain **functional groups**, especially **ester and amide links** or **–OH groups** from starch, that enzymes and water can attack. Polymers built only from C–C and C–H bonds, such as poly(ethene), have no such weak points. **Compostable** plastics break down together with food and garden waste under the conditions in a compost heap.

| Strategy | Meaning | Advantages | Limitations |
|---|---|---|---|
| **reduce** | use less plastic, especially single-use items | tackles the source of the problem | needs changes in behaviour and in industry |
| **reuse** | use the same item many times | saves energy and raw materials | items wear out; hygiene concerns |
| **recycle** | collect, sort and remelt plastics to make new products | saves raw materials (PET bottles become fibres and new containers) | sorting is costly; quality often falls each cycle; not all plastics are recyclable |
| **biodegradable plastics** | designed to be broken down by microorganisms | do not persist for centuries | need specific conditions; may compete with food crops for land |

**Nature of Science — responsibility for consequences**

Plastics have brought great benefits to food supply, clothing, health care and infrastructure, but at a significant environmental cost, and their long-term consequences are still being worked out. Scientists share responsibility for both the intended and the unintended consequences of their work, and for finding solutions, such as recycling technologies, biodegradable plastics and even microorganisms that can digest some plastics.

# 6 Structure 2.4.5 — Addition polymers SL + HL

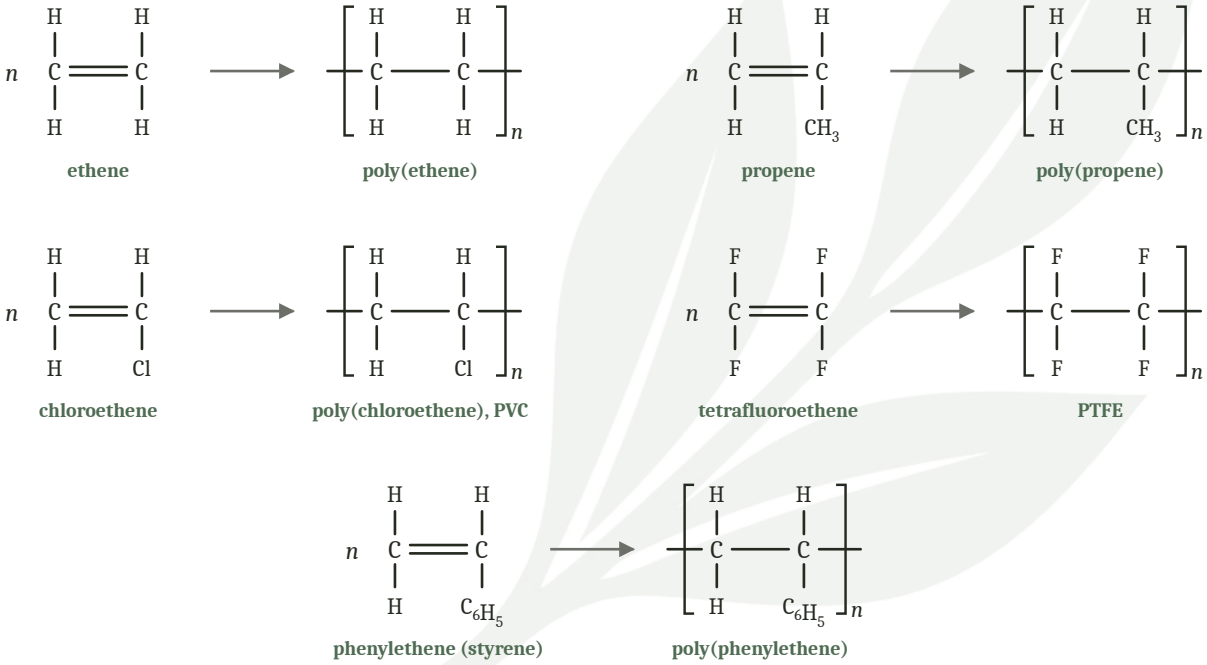
## 6.1 Monomers with a double bond

This answers the Structure 3.2 linking question. An **addition reaction** occurs when a multiple bond breaks and the two atoms it joined each form a new bond. Alkenes contain a C=C double bond, so they readily undergo addition reactions (Reactivity 3.4) and can act as monomers. In **addition polymerization**, the double bond in each monomer breaks, and the monomers join to their neighbours to form a long chain. **No other product is formed.**

> **Definition**
>
> An **addition polymer** forms when the double bonds of monomer molecules break and new covalent bonds form between neighbouring monomers, giving a long chain with no other product.

## 6.2 Drawing the repeating unit

1. Draw the monomer with the **C=C double bond in the middle** and its four substituents (H, $CH_3$, Cl and so on) pointing up and down, at 90° to the double bond.
2. Replace the double bond with a **single bond**. Keep every substituent in exactly the same position.
3. Draw **open bonds** extending horizontally from each carbon, out through **square brackets**, and add a subscript ***n*** after the closing bracket.

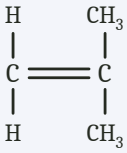



The repeating unit of an addition polymer has the **same molecular formula** as its monomer (and so the polymer has the same empirical formula as the monomer), because no atoms are lost. Note that only the two carbon atoms of the C=C end up in the main chain; groups such as $CH_3$, Cl and $C_6H_5$ become side groups.

| Polymer | Monomer | Properties and uses |
|---|---|---|
| poly(ethene), polythene | $CH_2{=}CH_2$ | flexible, cheap, good insulator; bags, food wrap, containers, water tanks, piping |
| poly(propene), polypropylene | $CH_2{=}CHCH_3$ | tough; ropes, crates, clothing fibres including thermal wear |
| poly(chloroethene), PVC | $CH_2{=}CHCl$ | rigid or flexible; window frames, pipes, cable sheathing; its chlorine content makes recycling difficult |
| poly(tetrafluoroethene), PTFE | $CF_2{=}CF_2$ | very unreactive and very low surface friction; non-stick pans, waterproof breathable fabrics |
| poly(phenylethene), polystyrene | $CH_2{=}CHC_6H_5$ | expanded foam for packaging and insulation; disposable cups |

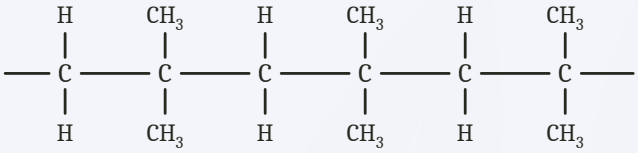
## 6.3 Worked example: from monomer to polymer

**Worked example — deduce the structure of the addition polymer formed from methylpropene, showing three repeating units.**



**1.** Draw the monomer, $CH_2{=}C(CH_3)_2$, with the double bond in the middle: two H atoms on one carbon, two $CH_3$ groups on the other.

**2.** Draw three monomers side by side, open each double bond and join neighbouring carbons with single bonds, leaving open bonds at both ends of the chain.



## 6.4 Working backwards: from polymer to monomer

Find the smallest unit that repeats: in the main chain it always contains **two carbon atoms**. Remove the open bonds and put a **double bond between those two carbons**. For example, the section $–CH(CH_3)–CH_2–CH(CH_3)–CH_2–$ has the repeating unit $–CH(CH_3)–CH_2–$, so the monomer is $CH(CH_3){=}CH_2$, propene, $C_3H_6$.

## 6.5 Atom economy

This is the Reactivity 2.1 linking question.

$$\%\ \text{atom economy} = (\text{molar mass of desired product} / \text{molar mass of all reactants}) \times 100$$

Addition polymerization produces **no by-product**: every atom of the monomers ends up in the polymer, so the atom economy is **100%**. This does not mean there is no waste. The yield may be less than 100%, leaving unreacted monomer, and many polymerizations use solvents, catalysts and high temperatures and pressures, all of which affect the environmental impact of the process.

**Examiner traps in 2.4.4 – 2.4.5**

- Leaving the double bond in the repeating unit. It must become a **single** bond.
- Putting a side group such as $CH_3$ into the main chain, so that the chain contains three carbons per repeating unit.
- Forgetting the open bonds through the brackets, or the subscript *n*.
- Calling an addition polymer a "compound with a fixed formula like the monomer". The polymer has the same **empirical** formula as the monomer, but a much larger, variable molecular formula.
- Saying plastics are unreactive "because they are big molecules". The reason is their strong C–C and C–H bonds and lack of reactive groups.

# 7 Structure 2.4.6 — Condensation polymers HL

## 7.1 Monomers with two functional groups

A **condensation reaction** occurs when two functional groups react to form a new covalent bond, releasing a **small molecule**, usually $H_2O$ (sometimes HCl or $NH_3$). To build a polymer, each monomer needs **two** functional groups, one at each end, so that it can form links with neighbours on both sides — just as a person can join a human chain only by holding hands on both sides. This answers the Structure 3.2 linking question: the functional groups that allow condensation polymerization are mainly **carboxylic acid (–COOH)**, **alcohol (–OH)** and **amine (–$NH_2$)** groups.

**Definition**

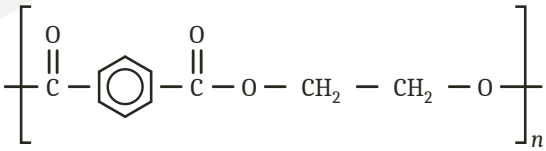
A **condensation polymer** forms by the reaction between functional groups on each monomer, with the release of a small molecule (usually water) for each covalent bond formed between monomers.

## 7.2 Polyesters: carboxylic acid + alcohol

When a monomer with two –COOH groups reacts with a monomer with two –OH groups, an **ester link**, –COO–, forms between them and a water molecule is released. Because the chain can grow in both directions, the product is a **polyester**. It helps to treat each monomer as a box with a functional group sticking out of each end:



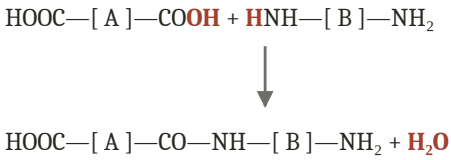

**PET**, poly(ethylene terephthalate), is made from benzene-1,4-dicarboxylic acid and ethane-1,2-diol. It is used for drinks bottles, food containers and polyester fibres, and it can be fully recycled by washing and remelting. Its repeating unit is:




Other polyesters include the natural fats and oils, and the phosphodiester links in DNA and RNA.

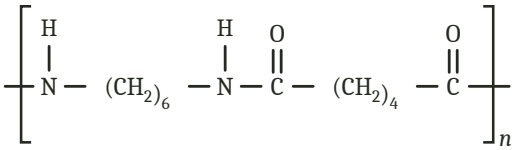
## 7.3 Polyamides: carboxylic acid + amine

When a monomer with two –COOH groups reacts with a monomer with two –$NH_2$ groups, an **amide link**, –CONH–, forms and water is released. The product is a **polyamide**. A polyamide can also form from a single monomer that has one –COOH and one –$NH_2$ group — an **amino acid**. Proteins are polyamides made from amino acids.

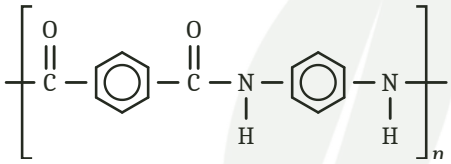



**amide link, –CONH–**
*a small molecule (water) is released for every link formed*

**Nylon-6,6** is made from 1,6-diaminohexane, $H_2N(CH_2)_6NH_2$, and hexanedioic acid, $HOOC(CH_2)_4COOH$. The name "6,6" records the six carbon atoms in each monomer. Nylon was first produced commercially in 1939 as a substitute for silk; it is strong, elastic and resistant to moisture, and is used in clothing, carpets, ropes and surgical sutures.




**Kevlar** is made from benzene-1,4-dicarboxylic acid and 1,4-diaminobenzene. The functional groups at opposite (1,4) positions of each benzene ring give straight, rigid chains that pack closely side by side, held together by many hydrogen bonds between the C=O and N–H groups of neighbouring chains. This makes Kevlar extremely strong for its weight; because it is made of light atoms, it is much less dense than steel. It is used in body armour, sports equipment and protective clothing.

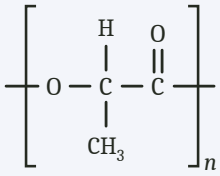



## 7.4 Drawing repeating units and deducing monomers

1. Draw the two monomers side by side, with the reacting functional groups facing each other.
2. Remove –OH from the –COOH group and H from the –OH or –$NH_2$ group (together, one $H_2O$), and join the C and the O (ester) or the C and the N (amide).
3. Put brackets round one unit from each monomer, with open bonds at both ends, and add *n*. Show one $H_2O$ as a product for each link formed ($2n - 1$, often approximated to $2n$, for the whole chain).

To **deduce the monomers** from a polymer, find each ester or amide link and break it by adding back a water molecule: –OH goes onto the C=O carbon (forming –COOH) and H goes onto the O or N (forming –OH or –$NH_2$).

**Worked example — deduce the monomer of poly(lactic acid), PLA**



PLA is a biodegradable plastic made from fermented plant starch. Its repeating unit contains one ester link. Breaking it by adding water gives a single monomer with an –OH group and a –COOH group: $CH_3CH(OH)COOH$, 2-hydroxypropanoic acid (lactic acid). Like an amino acid, one monomer carries both functional groups.

### 7.5 Hydrolysis: breaking condensation polymers




**hydrolysis: one water molecule is added for every link broken**

The reverse of condensation is **hydrolysis**, in which a water molecule is added for every link broken, regenerating the monomers. A polyamide hydrolyses to a diamine and a dicarboxylic acid (or, for a protein, to amino acids). All biological macromolecules — proteins, polysaccharides such as starch, and nucleic acids — are built by condensation reactions in cells and broken down by hydrolysis, for example during digestion or when a germinating seed breaks down its stored starch. Both kinds of reaction are controlled in living things by enzymes. Because ester and amide links can be hydrolysed, condensation polymers are generally more **biodegradable** than addition polymers, whose chains contain only C–C bonds.

**Model answer: "Compare addition and condensation polymerization." (3 marks)**

Addition polymerization requires monomers with a C=C double bond, whereas condensation polymerization requires monomers with two functional groups **[1]**. Addition polymerization forms the polymer as the only product (100% atom economy), whereas condensation releases a small molecule such as water for each link formed **[1]**. The repeating unit of an addition polymer has the same atoms as the monomer, whereas a condensation polymer's repeating unit contains ester or amide links and has lost atoms from the monomers **[1]**.

**Examiner traps in 2.4.6**

- Forgetting to show water as a by-product, or showing water from the wrong atoms.
- Leaving a whole –COOH or –OH group inside the repeating unit, or putting open bonds on the wrong atoms.
- Drawing a polyester link as –C–O–O– or an amide as –C–$NH_2$–. The links are –CO–O– and –CO–NH–.
- Saying hydrolysis "removes" water. Hydrolysis **adds** water to break each link.

## 8 Bringing it all together SL + HL

**The thread that runs through Structure 2**

**Electronegativity** (Structure 1.3/3.1) decides the **type of bonding** — ionic, covalent, metallic or somewhere between, as shown by the bonding triangle. The bonding decides the **structure**: lattice, giant covalent network or discrete molecules. Structure decides **properties**: melting point, conductivity, malleability, solubility. Materials science runs this chain backwards — choose the properties you want, then design the bonding and structure to give them, as in alloys, composites and polymers.

| Material | Bonding within | Key structural feature | Typical properties |
|---|---|---|---|
| pure metal | metallic | regular layers of identical cations | malleable, conducts, relatively soft |
| alloy | metallic | cations of different sizes disrupt the layers | harder and stronger; still conducts |
| composite | different in each phase | separate phases with complementary properties | combines the strengths of each component |
| addition polymer | covalent (C–C backbone) | long chains, held by intermolecular forces | light, unreactive, insulating, mostly non-biodegradable |
| HL condensation polymer | covalent (ester or amide links) | chains with polar links; often hydrogen bonded | strong fibres; hydrolysable, often more biodegradable |

## 9 Key points to memorise

Everything below is either wording that examiners look for, or knowledge you must carry into the exam yourself.

### A Definitions — near-verbatim

- **Bonding continuum:** bonding is best described as a continuum between the ionic, covalent and metallic models, represented by the bonding triangle.
- **Alloy:** a homogeneous mixture of a metal with other metals or non-metals, held together by metallic bonding.
- **Composite:** a heterogeneous mixture of two or more materials present as separate phases.
- **Polymer:** a macromolecule made of many repeating subunits (monomers) joined by covalent bonds.
- **Addition polymer:** formed by breaking the double bond in each monomer; no other product.
- HL **Condensation polymer:** formed by reaction between functional groups on each monomer, with the release of a small molecule.
- HL **Hydrolysis:** breaking a link by adding a molecule of water.

### B The bonding triangle

- x-axis: average $\chi = (\chi_A + \chi_B) / 2$. y-axis: $\Delta\chi = \chi_A - \chi_B$. Use one value per element, whatever the formula.
- Bottom left metallic; bottom right covalent; middle right polar covalent; top ionic. Corners: Cs, $F_2$, CsF.
- Period 3 oxides: ionic ($Na_2O$, MgO, $Al_2O_3$) → giant covalent ($SiO_2$) → molecular covalent ($P_4O_{10}$, $SO_2$, $Cl_2O$).
- $AlCl_3$ (2.4, 1.6) is polar covalent, so its melting point is far below NaCl's.

### C Alloys

- Possible because metallic bonding is **non-directional**: the electron sea holds cations of different sizes.
- Different-sized atoms disrupt the layers, so they cannot slide easily: harder and stronger.
- Mixtures, not compounds: no fixed composition, no chemical formula.

### D Polymers

- Plastics: light, unreactive, water-resistant, insulating, mouldable — and mostly non-biodegradable.
- Addition: C=C opens; draw substituents at 90°, single bond, open bonds through brackets, *n*. Atom economy 100%.
- Polymer → monomer: two-carbon repeating unit; put the double bond back.
- HL Ester link –COO– (acid + alcohol); amide link –CONH– (acid + amine); one $H_2O$ per link. Examples: PET, nylon-6,6, Kevlar, proteins, PLA.

### E Command terms — what each one is actually asking for

- **Determine** (position in the triangle) — show the calculation of both $\Sigma\chi$ and $\Delta\chi$, then name the region.
- **Predict** (properties) — name the bonding type, then state the properties that follow.
- **Explain** (alloy properties) — non-directional bonding, different-sized atoms, layers cannot slide.
- **Represent / Draw** (repeating unit) — brackets, open bonds, *n*; for condensation, also the water.
- **Deduce** (monomer) — work backwards: restore the double bond, or add water across each link.

## 10 Check yourself

Cover the answers on the next pages. Use electronegativity values from Section 9 of the data booklet. Questions marked HL are for Higher Level students.

1. Which of the following **cannot** be deduced from the position of an unknown substance X in the bonding triangle?

   A the chemical formula of X  B the type of bonding in X  C the likely physical properties of X

   D whether X is likely to conduct electricity

2. Calculate $\Sigma\chi$ and $\Delta\chi$, and use the bonding triangle to classify the bonding in: (a) $Cl_2O$ (b) $PbCl_2$ (c) $Al_2O_3$ (d) HBr (e) NaBr

3. Silicon dioxide and aluminium oxide are both found in the Earth's crust. Use the bonding triangle to deduce which has the greater covalent character. **[2]**

4. Complete the table, predicting one property for each substance.

| Substance | $\Sigma\chi$ | $\Delta\chi$ | Position and type of bonding | Predicted property |
|---|---|---|---|---|
| Sn | | | | |
| $P_4O_{10}$ | | | | |
| $Cd_3Mg$ | | | | |
| MgO | | | | |
| $NCl_3$ | | | | |

5. In the bonding triangle, substance X is at the top, substance Y in the bottom left corner and substance Z in the bottom right corner. (a) Which is likely to be an element? (b) Which will be the most brittle? (c) Which is likely to have the lowest boiling point? (d) Give one property that X and Y share. **[4]**

6. Lanthanum ($\chi$ = 1.1) and antimony ($\chi$ = 2.0) both form bromides with the formula $MBr_3$. (a) Determine the type of bonding in $SbBr_3$, showing your method. (b) Explain why crystals of $LaBr_3$ are brittle. **[4]**

7. Explain the limitation of classifying aluminium chloride simply as "ionic" because it contains a metal and a non-metal. **[2]**

8. Which is **not** an alloy?

   A solder  B silver  C bronze  D brass

9. Explain how alloying modifies the structure and properties of a metal, and why metals are able to form alloys at all. **[3]**

10. Explain why alloys are described as mixtures rather than compounds, and state the difference between an alloy and a composite. **[3]**

11. What do poly(ethene) and ethene have in common?

    A the same molecular formula  B the same empirical formula  C the same physical properties

    D the same chemical properties

12. Draw the repeating unit of the addition polymer formed from: (a) propenenitrile, $CH_2$=CHCN (b) but-2-ene, $CH_3CH$=$CHCH_3$

13. Part of a polymer chain is –$CH_2$–CHCl–$CH_2$–CHCl–$CH_2$–CHCl–. Name and give the formula of the monomer.

14. Explain why addition polymerization has an atom economy of 100%, and why it may still not be entirely "green". **[2]**

15. Describe two properties of plastics and explain each in terms of structure. Explain why most plastics are not biodegradable. **[4]**

16. HL Nylon-6,10 is made from 1,6-diaminohexane, $H_2N(CH_2)_6NH_2$, and decanedioic acid, $HOOC(CH_2)_8COOH$. Draw the repeating unit and name the by-product. **[3]**

17. HL Draw the repeating unit of the polymer formed from butane-1,4-diol, $HO(CH_2)_4OH$, and butanedioic acid, $HOOC(CH_2)_2COOH$. State the type of polymer and its link. **[3]**

18. HL A polyamide is broken down by hydrolysis. What are the two products?

    A a dicarboxylic acid and an ammonium salt  B an amine and an alcohol  C a diamine and a dicarboxylic acid

    D a diol and an amine

19. HL Which statement describes the formation of a dipeptide from two amino acids?

    A It has an atom economy of 100%.  B It forms an ester link and releases water.

    C It involves breaking C=C double bonds.  D It forms an amide link and releases water.

20. HL Kevlar is made from monomers with their functional groups at the 1 and 4 positions of a benzene ring. Explain why Kevlar is so strong, and why it has a lower density than steel. **[3]**

## 11 Answers

1. **A.**
2. (a) $Cl_2O$: $\Sigma\chi = (3.2 + 3.4)/2 = 3.3$, $\Delta\chi = 0.2$ — covalent (b) $PbCl_2$: $(1.8 + 3.2)/2 = 2.5$, $\Delta\chi = 1.4$ — polar covalent (c) $Al_2O_3$: 2.5, 1.8 — on the border between polar covalent and ionic (d) HBr: $(2.2 + 3.0)/2 = 2.6$, $\Delta\chi = 0.8$ — polar covalent (e) NaBr: $(0.9 + 3.0)/2 = 1.95$, $\Delta\chi = 2.1$ — ionic.
3. $SiO_2$: $\Sigma\chi = 2.65$, $\Delta\chi = 1.5$; $Al_2O_3$: $\Sigma\chi = 2.5$, $\Delta\chi = 1.8$ **[1]**. $SiO_2$ has the smaller electronegativity difference and lies further into the polar covalent region, so it has the greater covalent character **[1]**.
4. Sn: 2.0, 0.0 — bottom edge, metallic; conducts electricity, malleable. $P_4O_{10}$: 2.8, 1.2 — polar covalent (molecular); low melting point, does not conduct. $Cd_3Mg$: $(1.7 + 1.3)/2 = 1.5$, $\Delta\chi = 0.4$ — metallic (an alloy); conducts, malleable. MgO: 2.35, 2.1 — ionic; high melting point, conducts when molten. $NCl_3$: $(3.0 + 3.2)/2 = 3.1$, $\Delta\chi = 0.2$ — covalent (molecular); low boiling point, does not conduct.
5. (a) Y or Z — both corners have $\Delta\chi = 0$; Y (bottom left) is a metal, Z (bottom right) a non-metal **[1]**. (b) X, ionic: shifting a layer brings like charges together **[1]**. (c) Z, a covalent molecular substance held by weak intermolecular forces **[1]**. (d) high melting point, or electrical conductivity when molten **[1]**.
6. (a) $\Sigma\chi = (2.0 + 3.0)/2 = 2.5$ and $\Delta\chi = 3.0 - 2.0 = 1.0$ **[1]**; this lies in the polar covalent region **[1]**. (b) $LaBr_3$: $\Sigma\chi = 2.05$, $\Delta\chi = 1.9$, so it is ionic **[1]**; when a force is applied, layers of ions shift so that ions of the same charge come together and repel, and the crystal shatters **[1]**.
7. A simple metal + non-metal rule predicts ionic bonding and a high melting point, but $AlCl_3$ sublimes at about 180 °C **[1]**. Its position (2.4, 1.6) shows it is polar covalent, so a continuum gives a more accurate prediction than discrete categories **[1]**.
8. **B.** Silver is an element.
9. Metallic bonding is non-directional, so the delocalized electrons can hold together cations (and atoms) of different sizes **[1]**. The atoms of the added element disrupt the regular layers of cations **[1]**, so the layers cannot slide easily and the alloy is harder and stronger than the pure metal **[1]**.
10. Alloys have no fixed composition and cannot be given a chemical formula **[1]**; they are formed by mixing molten metals without a chemical reaction, and the components keep their metallic properties **[1]**. An alloy is a homogeneous mixture at the atomic level; a composite is a heterogeneous mixture in which the components remain as separate phases **[1]**.
11. **B.**
12. (a) $-[CH_2–CH(CN)]_n-$, drawn with the CN group as a side group on one carbon, open bonds through the brackets and $n$. (b) $-[CH(CH_3)–CH(CH_3)]_n-$, with one $CH_3$ side group on each carbon of the main chain.
13. Chloroethene (vinyl chloride), $CH_2{=}CHCl$. The repeating unit is $–CH_2–CHCl–$.
14. All the atoms of the monomers end up in the polymer, with no by-product **[1]**. However, the yield may be below 100%, and the process may use solvents, catalysts and high temperatures and pressures, which have environmental costs **[1]**.
15. Any two, each with an explanation **[2]**, for example: unreactive, because the chains contain only strong C–C and C–H bonds; insoluble in water, because the chains are non-polar and cannot hydrogen bond with water; electrical insulators, because there are no ions or delocalized electrons. Most plastics are non-biodegradable because their chains of C–C and C–H bonds have no functional groups that microorganisms' enzymes can break **[1]**, so they persist in the environment **[1]**.
16. Repeating unit $–[NH–(CH_2)_6–NH–CO–(CH_2)_8–CO]_n–$ **[1]**, with amide links drawn correctly (C=O and N–H shown) **[1]**, brackets, open bonds and $n$; by-product water **[1]**.
17. $–[O–(CH_2)_4–O–CO–(CH_2)_2–CO]_n–$ with open bonds and $n$ **[2]**; a polyester, with ester links –COO– **[1]**.

18. **C.**

19. **D.**

20. The 1,4 positions give straight, rigid chains that line up parallel to each other **[1]**, held together by many hydrogen bonds between the C=O and N–H groups of neighbouring chains **[1]**. It is made of light atoms (C, H, N, O) in molecular chains, which pack less densely than iron atoms in a metallic lattice **[1]**.

### Structure 2 is complete

- **Structure 2.1** — the ionic model.
- **Structure 2.2** — the covalent model (Booklets 1–4).
- **Structure 2.3** — the metallic model.
- **Structure 2.4** — from models to materials (this booklet).
- Links forward: **Structure 3.1** (periodic trends, period 3 oxides); **Structure 3.2** (functional groups, organic nomenclature); **Reactivity 2.1** (atom economy); **Reactivity 3.4** (addition reactions of alkenes).

**These notes are a free resource, shared for any IB student who finds them useful.**

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