

ESAT

Chemistry

Hydrocarbons, Polymers and Crude Oil

Free lesson notes

Covers	C13.1 to C13.4
Format	Lesson, worked examples, self-check
Price	Free

About this lesson

Petrol, diesel, the plastic in a carrier bag, the polyester of a fleece and the nylon of a rope all trace back to one raw material: crude oil. Organic chemistry is the chemistry of carbon compounds, and carbon is unusual because its atoms form four strong bonds and join into long chains and rings. This lesson covers the simplest organic compounds, the **hydrocarbons**, which contain only hydrogen and carbon, and then shows how small molecules are joined into the giant molecules we call polymers.

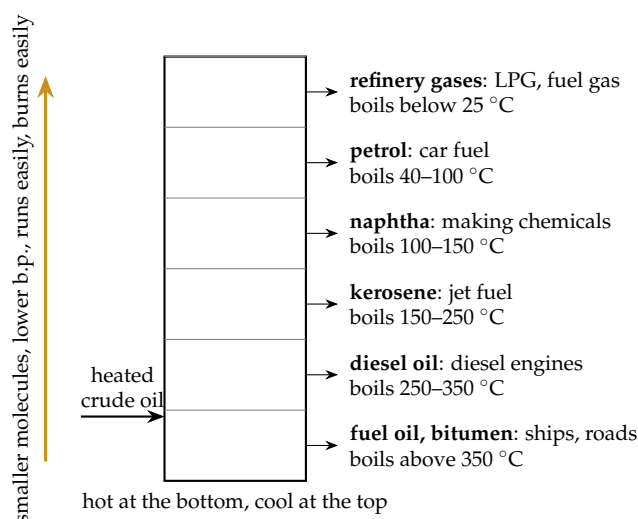
We begin with crude oil and how fractional distillation separates it, then introduce the alkanes and the idea of a homologous series, isomers and the different ways of writing a formula, and combustion (including calculations). We then meet cracking, the alkenes with their test and their addition reactions, and finally addition polymers, condensation polymers (polyesters and polyamides) and proteins, including repeat units and biodegradability. Specification codes: C13.1 to C13.4. Relative atomic masses are given where a calculation needs them: H = 1, C = 12, N = 14, O = 16, Br = 80.

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1 Crude oil and fractional distillation

Crude oil is a thick, dark liquid found in rocks beneath the ground. It formed over millions of years from the remains of tiny sea creatures buried under sediment, and it is a finite (non-renewable) resource. Crude oil is a **mixture** of hydrocarbons, mostly alkanes, with chains of different lengths. Because the substances are not chemically bonded together, they can be separated by a physical method that uses their different boiling points: **fractional distillation**.

How the column works. The crude oil is heated until most of it is a vapour and is fed into the bottom of a tall fractionating column, which is *hot at the bottom and cooler at the top*. The vapours rise. Each hydrocarbon condenses to a liquid at the height where the temperature falls to its boiling point, and is drawn off there. The result is a set of **fractions**, each still a mixture, but of molecules with similar chain lengths and so similar boiling points.



Trends down the column. Compare a fraction taken from the *top* (short chains) with one from the *bottom* (long chains):

property	top (short chains)	bottom (long chains)
boiling point	low	high
viscosity (thickness)	low, runs easily	high, thick and treacly
flammability	ignites easily	ignites with difficulty
colour	colourless	dark

The reason is the forces *between* molecules: long molecules have more contact with their neighbours, so more energy is needed to pull them apart, which means a higher boiling point. Nothing is broken inside a molecule when a hydrocarbon boils; the covalent bonds stay and only the weak intermolecular forces are overcome.

Uses. Refinery gases (LPG) for heating and cooking, petrol for cars, naphtha as a feedstock for making chemicals and plastics, kerosene for jet aircraft, diesel oil for lorries and trains, fuel oil for ships and power stations, and bitumen for road surfaces.

Worked example: which fraction?

A fraction is collected at 20 to 40 °C and another at 250 to 350 °C. Which has the shorter molecules and which is more viscous?

The lower boiling range means weaker intermolecular forces, so shorter molecules: the 20 to 40 °C fraction. The higher boiling fraction has longer chains, which tangle and drag more, so it is more viscous.

Common mistakes

- Saying that crude oil is a compound. It is a mixture, so each hydrocarbon keeps its own properties.
- Saying that bonds break when a hydrocarbon boils. Only intermolecular forces are overcome.
- Mixing up the column: it is hot at the bottom, and the *longest* chains (highest boiling points) come off at the bottom.

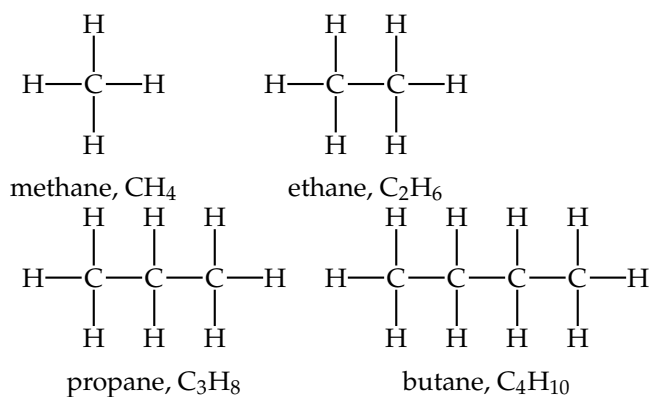
2 Alkanes and homologous series

Hydrocarbons contain hydrogen and carbon atoms only. The simplest are the **alkanes**. They are **saturated**: every carbon-carbon bond is a single bond, so each carbon is joined to as many other atoms as it possibly can be (four). Alkanes have the general formula C_nH_{2n+2} .

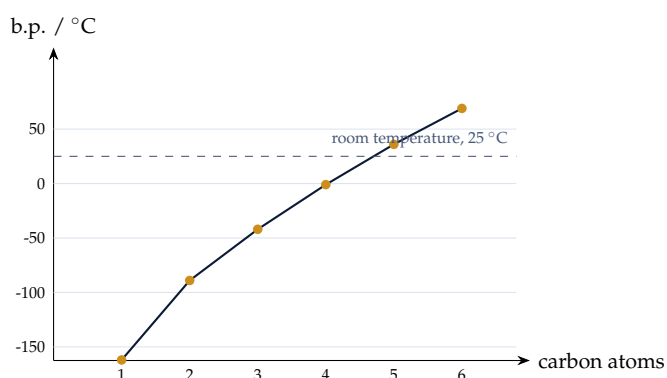
A group of compounds with the same general formula, similar chemical properties and a regular change in physical properties, each member differing from the next by CH_2 , is a **homologous series**. The alkanes from C_1 to C_6 :

carbons	name	molecular formula	state at 25 °C
1	methane	CH_4	gas
2	ethane	C_2H_6	gas
3	propane	C_3H_8	gas
4	butane	C_4H_{10}	gas
5	pentane	C_5H_{12}	liquid
6	hexane	C_6H_{14}	liquid

The names come from a *stem* (meth-, eth-, prop-, but-, pent-, hex-) and the ending **-ane** for an alkane. Learn the stems; they are used for every other organic family.



Trends in the series. As the chain gets longer the boiling point rises (more intermolecular attraction), the liquid gets more viscous, and the compound gets less flammable.



All members of the series burn in the same way and are unreactive towards most reagents (for example they do not decolourise bromine water), because their bonds are strong and non-polar. Their chemical properties are similar; physical properties change gradually.

Worked example: formula from carbons

Give the molecular formula of the alkane with 6 carbon atoms, and check it using the general formula.
 $n = 6$: $\text{C}_n\text{H}_{2n+2}$ gives C_6H_{14} ($2 \times 6 + 2 = 14$). This is hexane.

Exam tip

If a formula has exactly $2n + 2$ hydrogens for n carbons it is an alkane. If it has $2n$ hydrogens (one fewer pair) and one $\text{C}=\text{C}$, it is an alkene.

Common mistakes

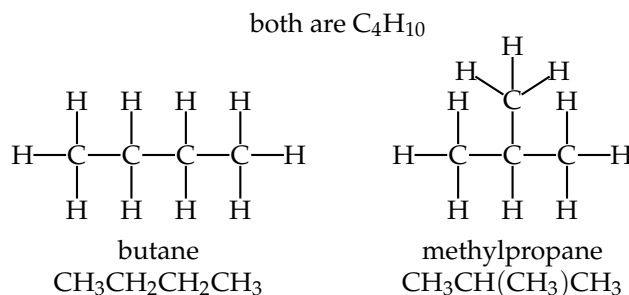
- Writing the alkane formula as C_nH_{2n} ; that is the alkene formula.
- Thinking the boiling point falls as the chain gets longer. It rises.
- Confusing “saturated” with “single bonds only between carbons”; the word means no $\text{C}=\text{C}$ (no more atoms can be added).

3 Isomers and ways of writing formulae

A single formula can be written in several ways, each with a different purpose:

- **Molecular formula:** the numbers of atoms of each element, e.g. C_4H_{10} .
- **Empirical formula:** the simplest whole-number ratio, e.g. CH_2 for C_4H_8 .
- **Structural (condensed) formula:** groups written in order, e.g. $\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_3$.
- **Displayed formula:** every atom and every bond drawn out.

Isomers are compounds with the *same molecular formula but different structures*, so they are different compounds with different properties. For C_4H_{10} there are two: butane, a straight chain, and methylpropane, with a CH_3 branch. (From C_4 upwards, structural isomers appear. Methane, ethane and propane have none.)



Naming a branched alkane (IUPAC). (1) Find the *longest* continuous carbon chain; it gives the parent name. (2) Name each branch by its stem with the ending -yl (methyl is CH_3 , ethyl is C_2H_5). (3) Number the chain from the end that gives the branches the lowest numbers; write the position before the branch name: 2-methylbutane is a four-carbon chain with a methyl on carbon 2. Several identical branches use di-, tri-.

Isomers differ in their physical properties: a branched isomer has a lower boiling point than its straight-chain isomer because the molecules pack less closely and have less contact. Chemical properties are very similar if they have the same functional group.

Worked example: count the isomers

Draw the carbon skeletons for the isomers of C_5H_{12} .

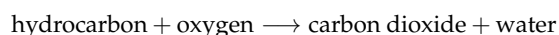
(i) A straight chain of 5: pentane. (ii) A chain of 4 with a methyl on carbon 2: 2-methylbutane. (iii) A chain of 3 with two methyls on carbon 2: 2,2-dimethylpropane. A methyl on carbon 3 of the four-chain would simply be the same as 2-methylbutane numbered from the other end. So there are 3 isomers.

Common mistakes

- Treating a bent-looking chain as a different isomer. Rotating or bending a chain does not change the structure; only the connectivity matters.
- Calling butane and propane isomers; they have different molecular formulae (they are homologues).
- Naming from the wrong end. Number so that the branch gets the lower number, so 2-methylbutane, never 3-methylbutane.

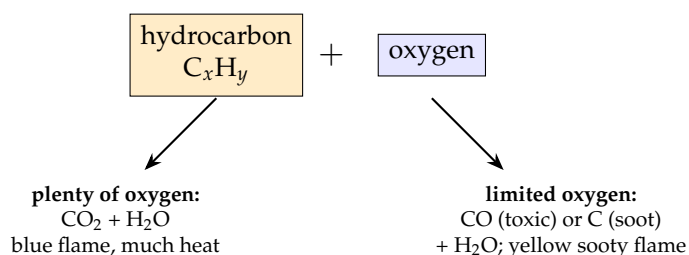
4 Combustion of hydrocarbons

Complete combustion. With plenty of oxygen, a hydrocarbon burns completely to carbon dioxide and water, releasing a lot of heat (the reaction is exothermic; hydrocarbons are used as fuels for this reason):



Balancing method. Balance carbon first (one CO_2 for every C), then hydrogen (one H_2O for every two H), then count oxygen atoms on the right and halve to find the O_2 . For propane: $3CO_2$ and $4H_2O$ contain $6 + 4 = 10$ oxygen atoms, so $5O_2$.

Incomplete combustion. With limited oxygen (a blocked chimney or a faulty boiler) some carbon ends up as **carbon monoxide**, CO, or as soot (carbon, C), and the flame is yellow and smoky instead of blue. Carbon monoxide is a colourless, odourless, toxic gas: it binds to haemoglobin in red blood cells and stops them carrying oxygen.



Why combustion matters. Burning fossil fuels releases carbon dioxide, a greenhouse gas. Impurities such as sulfur burn to SO_2 , which causes acid rain, and the high temperatures in engines make oxides of nitrogen from the nitrogen of the air.

Calculations. Equations give mole ratios. For gases at the same temperature and pressure, *volumes are in the same ratio as moles*, which makes gas-volume questions easy without a molar volume. The mole of any gas at room temperature and pressure occupies 24 dm^3 .

Worked example: mass of carbon dioxide

What mass of CO_2 forms when 4.4 g of propane, C_3H_8 , burns completely? (A_r : H = 1, C = 12, O = 16.)
 $M_r(C_3H_8) = 44$, so moles = $4.4/44 = 0.10$. The ratio is 1 : 3, so 0.30 mol CO_2 . $M_r(CO_2) = 44$, so mass = $0.30 \times 44 = 13.2\text{ g}$.

Worked example: volumes of gases

10 cm^3 of methane is burnt in 30 cm^3 of oxygen, and the mixture is cooled to room temperature (water is a liquid). What gas volume remains?
 $CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$: 10 cm^3 methane uses 20 cm^3 of oxygen and gives 10 cm^3 of CO_2 . Oxygen left: $30 - 20 = 10$. Gas remaining = $10 + 10 = 20\text{ cm}^3$.

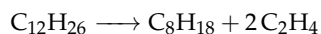
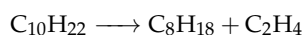
Common mistakes

- Balancing oxygen first. Do carbon, then hydrogen, then oxygen last.
- Giving carbon monoxide as a product of normal combustion. It forms only when oxygen is limited.
- Counting water as gas after cooling to room temperature.

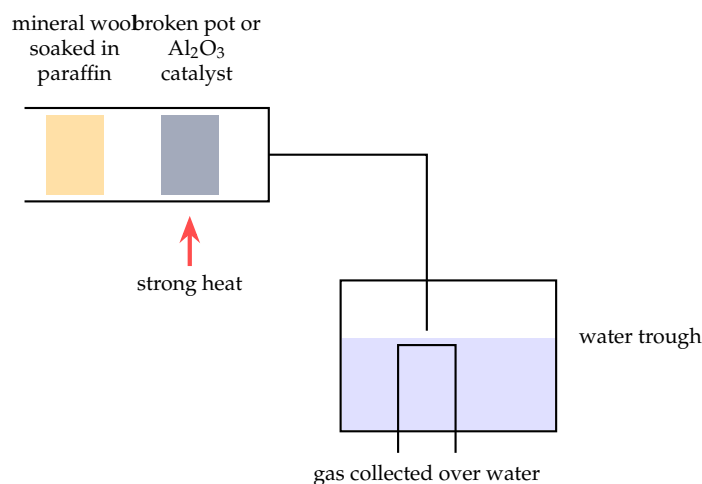
5 Cracking

Crude oil contains more long-chain hydrocarbons than we can use, and fewer short ones than we want: petrol and the small alkenes are in high demand. **Cracking** breaks long-chain alkanes into shorter, more useful molecules. It is a **thermal decomposition**: a long alkane is passed over a hot catalyst (aluminium oxide or silica, about 600 to 700°C), or heated with steam at high temperature (steam cracking).

The products are always a *shorter alkane* and an *alkene* (often ethene or propene), because there are not enough hydrogens for all products to be alkanes. For example:



The equation must balance: count carbons and hydrogens on both sides.



Why do it? Short-chain alkanes make better fuels (petrol), and alkenes are the starting materials (the monomers) for making plastics and many other chemicals. Cracking therefore matches supply to demand.

Worked example: balancing a cracking equation

Find X in $\text{C}_{14}\text{H}_{30} \longrightarrow \text{C}_8\text{H}_{18} + \text{X}$ and name it.

Carbon: $14 - 8 = 6$. Hydrogen: $30 - 18 = 12$. So X is C_6H_{12} , which fits C_nH_{2n} : an alkene, hexene.

Exam tip

In cracking questions, subtract the formulae. The leftover atoms nearly always fit C_nH_{2n} : an alkene.

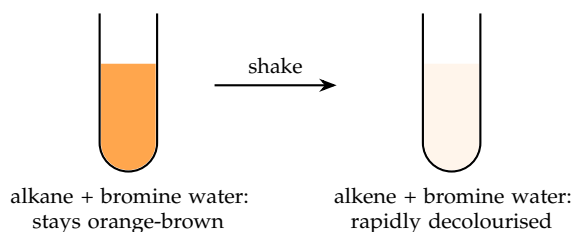
Common mistakes

- Writing that cracking is combustion. It is thermal decomposition and no oxygen is needed.
- Giving two alkanes as products. At least one product is an alkene.
- Forgetting the catalyst or high temperature when asked for the conditions.

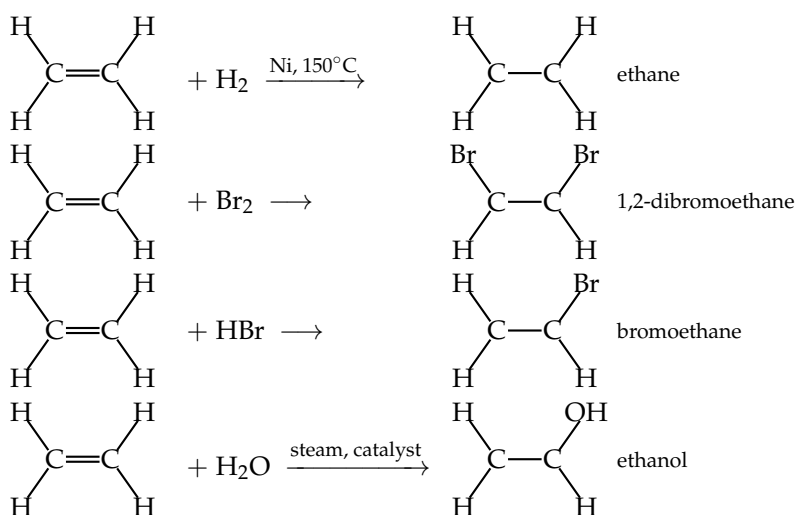
6 Alkenes and addition reactions

Alkenes are hydrocarbons containing a carbon-carbon **double bond**, $\text{C}=\text{C}$. They are **unsaturated**: the double bond can open up and allow extra atoms to join. The series starts at ethene: ethene C_2H_4 , propene C_3H_6 , butene C_4H_8 , pentene C_5H_{10} , hexene C_6H_{12} . The general formula is C_nH_{2n} and the names end in **-ene**. For four carbons or more the position of the double bond is given by a number: but-1-ene $\text{CH}_2=\text{CHCH}_2\text{CH}_3$ and but-2-ene $\text{CH}_3\text{CH}=\text{CHCH}_3$ are different isomers. Alkenes burn like alkanes but with a smoky yellow flame because they have a higher percentage of carbon.

Test for an alkene. Shake the sample with orange-brown **bromine water**. An alkene *decolourises it quickly* (orange to colourless). An alkane leaves it orange.



Addition reactions. In an addition reaction two reactants join to form *one* product. The double bond becomes a single bond and each of the two carbons gains an atom or group:



- **Hydrogenation**, with H_2 and a nickel catalyst at about 150°C , gives the alkane. (Used to make margarine from vegetable oils.)
- **Halogenation**, with Br_2 or Cl_2 , gives a dihalogenoalkane: $\text{C}_2\text{H}_4 + \text{Br}_2 \longrightarrow \text{C}_2\text{H}_4\text{Br}_2$. This is the bromine water reaction.
- **Hydrogen halides**, HCl or HBr , give a halogenoalkane: $\text{C}_2\text{H}_4 + \text{HBr} \longrightarrow \text{C}_2\text{H}_5\text{Br}$.
- **Steam**, with a phosphoric acid catalyst at high temperature and pressure, gives an alcohol: $\text{C}_2\text{H}_4 + \text{H}_2\text{O} \longrightarrow \text{C}_2\text{H}_5\text{OH}$ (ethanol).

Because only one product forms, addition has 100% atom economy.

Worked example: mass of bromine

What mass of bromine reacts with 2.8 g of ethene? (A_r : $\text{Br} = 80$.)

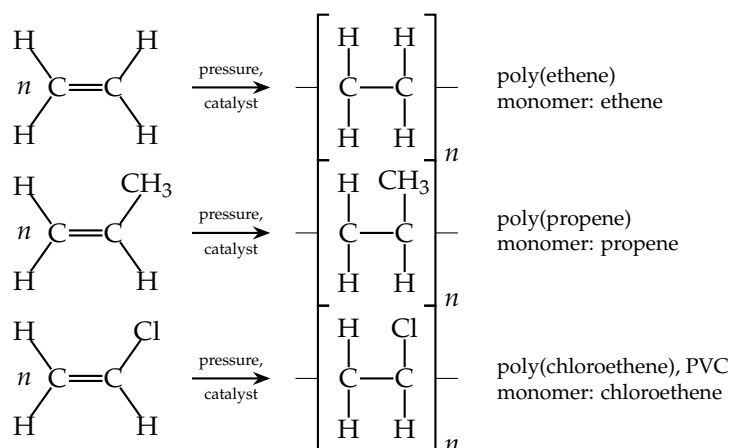
$M_r(\text{C}_2\text{H}_4) = 28$, so moles = 0.10. The ratio with Br_2 is 1 : 1, so 0.10 mol Br_2 , $M_r = 160$: mass = $0.10 \times 160 = 16$ g. The product $\text{C}_2\text{H}_4\text{Br}_2$ has $M_r = 188$, so 18.8 g forms, which equals $2.8 + 16$ (mass is conserved).

Common mistakes

- Saying bromine water turns *colourless* means it “bleaches”. The bromine has reacted by addition with the double bond.
- Saying an alkane “turns bromine water clear” in the dark. In sunlight alkanes can slowly react by a different type (substitution), but not rapidly, and not in the test.
- Giving two products for an addition reaction. There is only one.

7 Addition polymers

A **polymer** is a very long molecule built from many small molecules called **monomers** joined end to end. Alkenes are used as monomers because the $\text{C}=\text{C}$ bond can open: each monomer joins the next, forming a long saturated chain. This is **addition polymerisation**. It happens at high pressure with a catalyst, and *only one product forms: the polymer*, so no atoms are lost.



The repeat unit. The part of the polymer that repeats is shown in square brackets with the subscript n . For poly(ethene) it is $-\text{CH}_2-\text{CH}_2-$. To draw the repeat unit from a monomer, open the double bond so the two carbons each have one free bond; keep everything the monomer had on those two carbons, and draw the free bonds sideways through the brackets. Note that in propene the CH_3 side group is *not* part of the chain: the main chain is still just two carbons.

To find the monomer from a polymer, take one repeat unit, replace the two free bonds with a double bond between the two chain carbons, and put each atom back.

Properties and uses. Poly(ethene) is used for bags and bottles, poly(propene) for rope, crates and carpets, and poly(chloroethene) (PVC) for pipes, window frames and cable insulation. Polymers are usually unreactive, strong and light, but they are a problem at the end of their life: the strong covalent bonds in the chain mean that these addition polymers are **not biodegradable**, because microorganisms cannot break them down. They persist in landfill, can harm wildlife, and release toxic gases if burnt (for example, hydrogen chloride from PVC). Ways to reduce the harm are recycling, reuse, burning for energy under controlled conditions, and developing **biodegradable** polymers (for example poly(lactic acid), made from plant starch, which is also a polyester) that micro-organisms can break down.

Worked example: monomer from a polymer

The repeat unit of a polymer is $-\text{CH}_2-\text{CHCl}-$. Name the monomer.

Replace the two free bonds with a double bond: $\text{CH}_2=\text{CHCl}$, which is chloroethene. The polymer is poly(chloroethene), PVC.

Exam tip

A repeat unit for an addition polymer has only *two* carbons in the backbone. If you draw three or more carbons in the chain, you have the wrong monomer.

Common mistakes

- Keeping the double bond in the repeat unit. Addition polymers contain only single bonds in the chain.
- Putting the CH_3 of propene into the chain. It is a side group on the two-carbon backbone.
- Forgetting the bonds through the brackets and the n .

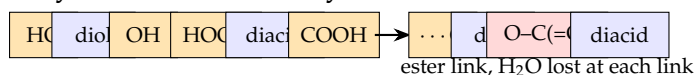
8 Condensation polymers and proteins

In **condensation polymerisation** the monomers have *two reactive groups*, one at each end. When two groups react they join and a small molecule, usually **water**, is released. Because the small molecule is lost, the polymer is always *less massive than the sum of the monomers*.

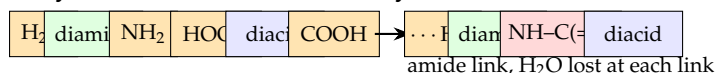
Polyesters form from a **diol** (an alcohol with $-\text{OH}$ at both ends) and a **dicarboxylic acid** (with $-\text{COOH}$ at both ends). Each $-\text{OH}$ reacts with a $-\text{COOH}$ to form an **ester link** $-\text{COO}-$ and a molecule of water. A well-known example is PET, used for drinks bottles and fleece fabric.

Polyamides form from a **diamine** ($-\text{NH}_2$ at both ends) and a **dicarboxylic acid**. Each $-\text{NH}_2$ reacts with a $-\text{COOH}$ to form an **amide link** $-\text{CONH}-$ and a molecule of water. Nylon is a polyamide.

Polyester: diol + dicarboxylic acid



Polyamide: diamine + dicarboxylic acid



Proteins are natural polyamides. The monomers are **amino acids**: each has an amine group $-\text{NH}_2$ and a carboxylic acid group $-\text{COOH}$, so a single type of monomer can polymerise with itself. The link is called a **peptide bond**.



The new C-N link is a **peptide (amide) bond**. Many amino acids joined this way form a **protein**.

Counting links. Joining x monomer units in a line forms $x - 1$ links and releases $x - 1$ molecules of water (for a chain of many monomers this is approximately the number of monomers).

Biodegradable? Polyesters and polyamides contain ester or amide links that can be broken by hydrolysis (reaction with water, often catalysed by acids or enzymes), so they are more easily broken down by microorganisms than addition polymers, though many commercial examples such as nylon and PET still last a long time.

Comparing the two types.

	addition	condensation
monomer(s)	alkene (one type)	two functional groups per monomer
products	polymer only	polymer + small molecule (water)
link in chain	C-C	ester $-\text{COO}-$ or amide $-\text{CONH}-$

Worked example: mass of a repeat unit

A polyamide forms from hexane-1,6-diamine ($M_r = 116$) and hexanedioic acid ($M_r = 146$). What is the relative mass of one repeat unit?

One repeat unit combines one diamine and one diacid, and *two* molecules of water are lost (one at each end, or equivalently one per link and two links per unit): $116 + 146 - 2 \times 18 = 226$.

Common mistakes

- Forgetting the water. If the product mass is asked, subtract the water lost.
- Saying a condensation polymer needs a $\text{C}=\text{C}$ in the monomer. It needs two functional groups.
- Mixing up the links: ester is $-\text{COO}-$ (from an alcohol), amide is $-\text{CONH}-$ (from an amine).

Check yourself

Try these without looking back, then compare with the answers on the next page.

1. Why does the boiling point increase along the alkanes?
2. Give the molecular formula of the alkene with five carbons.
3. Describe the test for an alkene and the positive result.
4. Write the equation for the complete combustion of ethane, C_2H_6 , using whole numbers.
5. Why is cracking carried out?
6. Draw the repeat unit of poly(ethene).
7. What is lost when a polyester forms?
8. Give one reason why addition polymers are a problem to dispose of.

Answers to the self-check

1. Longer molecules have stronger intermolecular forces, so more energy is needed to separate them.
2. C_5H_{10} (pentene).
3. Shake with bromine water; it changes from orange-brown to colourless.
4. $2\text{C}_2\text{H}_6 + 7\text{O}_2 \longrightarrow 4\text{CO}_2 + 6\text{H}_2\text{O}$.
5. To turn long, less useful alkanes into shorter alkanes (fuels) and alkenes (for plastics).
6. $-\text{CH}_2-\text{CH}_2-$ in brackets, with bonds through the brackets and a subscript n .
7. A small molecule of water for each ester link formed.
8. They are not biodegradable (micro-organisms cannot break the strong C–C chain), so they last in landfill.

Next step

Heurisco's *ESAT Chemistry: Hydrocarbons, Polymers and Crude Oil Practice Set* has twenty original exam-style questions on this lesson, with structures, boiling-point graphs and repeat units, in order of difficulty, with a full worked solution for each.