Organic Chemistry

Formulae, functional groups and homologous series, naming organic compounds, fuels and fractional distillation of petroleum, alkanes, alkenes and cracking, alcohols and the manufacture of ethanol, carboxylic acids and esters, addition and condensation polymers, plastics and proteins.

11.1 Formulae, functional groups and terminology

Organic chemistry is the study of compounds of **carbon**. Carbon atoms form four covalent bonds and join together in chains.

Types of formula

Formula	What it shows	Ethanol
molecular	the number of each kind of atom	C_2H_6O
structural	an unambiguous description of how the atoms are arranged	CH_3CH_2OH
displayed	**all** the atoms and **all** the bonds drawn out	see the diagram below

Other structural formulae: ethene $CH_2{=}CH_2$ and methyl ethanoate CH_3COOCH_3. In a displayed formula each line is a single covalent bond, and a double line is a double bond.

Homologous series

A homologous series is a family of compounds with the same functional group, the same general formula, which differ by a $-CH_2-$ unit from one member to the next, show a trend in physical properties and have similar chemical properties.

A **functional group** is an atom or group of atoms that determines the **chemical properties** of a homologous series.

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Homologous series	Functional group	General formula	First member
alkanes	$C-C$ single bonds only	C_nH_{2n+2}	methane CH_4
alkenes	$C=C$ double bond	C_nH_{2n}	ethene C_2H_4
alcohols	$-OH$	$C_nH_{2n+1}OH$	methanol CH_3OH
carboxylic acids	$-COOH$	$C_nH_{2n+1}COOH$	methanoic acid $HCOOH$

TRY IT

An alkane has 8 carbon atoms. Use the general formula to find its molecular formula.

C_nH_{2n+2} with $n = 8$ gives C_8H_{18} (since $2n + 2 = 18$).

Saturated and unsaturated

- A **saturated** compound has molecules in which **all the carbon–carbon bonds are single bonds** (alkanes).
- An **unsaturated** compound has molecules in which **one or more carbon–carbon bonds are not single bonds**, for example $C=C$ (alkenes).

Structural isomers

Structural isomers are compounds with the same molecular formula but different structural formulae.

Molecular formula	Isomers
C_4H_{10}	$CH_3CH_2CH_2CH_3$ (butane) and $CH_3CH(CH_3)CH_3$ (methylpropane)
C_4H_8	$CH_3CH_2CH=CH_2$ (but-1-ene) and $CH_3CH=CHCH_3$ (but-2-ene)

11.2 Naming organic compounds

The **stem** of the name shows the number of carbon atoms in an unbranched chain, and the **ending** shows the homologous series.

Carbon atoms	1	2	3	4
stem	meth-	eth-	prop-	but-

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Series	Ending	Examples (up to four carbon atoms)
alkanes	**-ane**	methane, ethane, propane, butane
alkenes	**-ene**	ethene, propene, but-1-ene, but-2-ene
alcohols	**-ol**	methanol, ethanol, propan-1-ol, propan-2-ol, butan-1-ol, butan-2-ol
carboxylic acids	**-oic acid**	methanoic, ethanoic, propanoic, butanoic acid

The **number** shows the position of the double bond or the $-\mathrm{OH}$ group. Number from the end that gives the lower number. For example, propan-1-ol is $\mathrm{CH_3CH_2CH_2OH}$ and propan-2-ol is $\mathrm{CH_3CH(OH)CH_3}$.

Esters. An ester is named from the **alcohol** and the **acid**: the alcohol gives the **first** word (alkyl) and the acid gives the second (-oate). Ethanol and ethanoic acid give **ethyl ethanoate**, $\mathrm{CH_3COOCH_2CH_3}$, and methanol and propanoic acid give **methyl propanoate**, $\mathrm{CH_3CH_2COOCH_3}$.

> TRY IT
>
> Name the compound $\mathrm{CH_3CH_2CH{=}CH_2}$ and say which homologous series it belongs to.

It has four carbons (but-) and a $\mathrm{C{=}C}$ double bond starting at carbon 1, so it is **but-1-ene**, an **alkene**.

11.3 Fuels

The **fossil fuels** are **coal**, **natural gas** and **petroleum** (crude oil). **Methane** is the main constituent of natural gas.

A **hydrocarbon** is a compound that contains **hydrogen and carbon only**. **Petroleum is a mixture of hydrocarbons**.

Fractional distillation of petroleum

Petroleum is separated into useful **fractions** by **fractional distillation** in a **fractionating column**.

1. The petroleum is **heated** and the vapour enters near the bottom of the column.
2. The column is **hot at the bottom** and **cooler at the top**.
3. The vapours rise, and each fraction **condenses** where the temperature is just below its boiling point, and is drawn off. Substances with **large molecules** condense **low** in the column and those with **small molecules** condense **high** in the column.

A **fraction** is a mixture of hydrocarbons with **similar boiling points** (similar chain length).

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Trends from the bottom to the top of the column

Going up the column	Change
chain length	**decreases** (smaller molecules)
volatility (how easily it evaporates)	**higher**
boiling point	**lower**
viscosity (how thick and slow to flow)	**lower** (it flows more easily)

Uses of the fractions

Fraction	Use
refinery gas	gas for **heating and cooking**
gasoline / petrol	fuel for **cars**
naphtha	**chemical feedstock** (for making other chemicals and plastics)
kerosene / paraffin	**jet fuel**
diesel oil / gas oil	fuel for **diesel engines**
fuel oil	fuel for **ships** and **home heating** systems
lubricating oil	**lubricants, waxes and polishes**
bitumen	making **roads**

Note Academy

11.4 Alkanes

Alkanes are **saturated hydrocarbons**. The bonding is **single covalent**. Their general formula is C_nH_{2n+2}.

Alkanes are **generally unreactive**, because the $C{-}C$ and $C{-}H$ bonds are strong. They react in two ways: **combustion** and **substitution by chlorine**.

Combustion. In a plentiful supply of air, alkanes burn completely to carbon dioxide and water:

$$CH_4\,(g) + 2\,O_2\,(g) \longrightarrow CO_2\,(g) + 2\,H_2O\,(l)$$

In a limited supply of air, **incomplete combustion** gives carbon monoxide or carbon (soot) as well.

Substitution. In a **substitution reaction**, one atom or group of atoms is **replaced** by another atom or group of atoms. Alkanes react with **chlorine** in the presence of **ultraviolet light**:

$$CH_4 + Cl_2 \longrightarrow CH_3Cl + HCl$$

$$C_2H_6 + Cl_2 \longrightarrow C_2H_5Cl + HCl$$

The reaction is **photochemical**: the UV light provides the **activation energy**, E_a. Only one hydrogen atom is replaced when we say **monosubstitution**, so the products are chloromethane (or chloroethane) and hydrogen chloride.

11.5 Alkenes

Alkenes are **unsaturated hydrocarbons** with a $C{=}C$ **double bond**, which makes them **more reactive** than alkanes. Their general formula is C_nH_{2n}.

Cracking

> **Cracking is the breaking down of large alkane molecules into smaller, more useful molecules (alkenes and shorter alkanes, and sometimes hydrogen) using a high temperature and a catalyst.**

$$C_{10}H_{22} \longrightarrow C_8H_{18} + C_2H_4$$

Why crack? There is more demand for **shorter-chain** hydrocarbons (such as petrol) than the amount obtained from fractional distillation, and the **alkenes** produced are the starting materials for **polymers** and other chemicals.

Testing for unsaturation

The test for an alkene uses **aqueous bromine** (bromine water).

	Saturated (alkane)	Unsaturated (alkene)
add aqueous bromine	stays **orange-brown**	**decolourised** (orange-brown ⟶ colourless)

Addition reactions

In an **addition reaction** the alkene adds another substance across the double bond, and **only one product** is formed. The $C{=}C$ becomes a single bond.

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Reactant	Conditions	Product (from ethene)
bromine	room temperature	$CH_2{=}CH_2 + Br_2 \longrightarrow CH_2BrCH_2Br$ (1,2-dibromoethane)
hydrogen	**nickel** catalyst	$CH_2{=}CH_2 + H_2 \longrightarrow CH_3CH_3$ (ethane)
steam	an **acid catalyst**, high temperature and pressure	$CH_2{=}CH_2 + H_2O \longrightarrow CH_3CH_2OH$ (ethanol)

TRY IT

Write the equation for the reaction of propene with hydrogen, and name the product.

$$CH_3CH{=}CH_2 + H_2 \longrightarrow CH_3CH_2CH_3$$

The product is **propane**.

11.6 Alcohols

Ethanol, C_2H_5OH, can be made in two ways.

	Fermentation	Hydration of ethene
raw material	glucose from sugar or starch	ethene from petroleum
conditions	25–35 °C, **yeast**, **no oxygen**	300 °C, 6000 kPa (60 atm), **acid catalyst** (steam)
equation	$C_6H_{12}O_6 \longrightarrow 2\,C_2H_5OH + 2\,CO_2$	$C_2H_4 + H_2O \rightleftharpoons C_2H_5OH$
advantages	uses **renewable** raw materials, low temperature (less energy) and simple equipment	**fast**, a **continuous** process, and gives **pure** ethanol
disadvantages	**slow**, a **batch** process, makes impure ethanol that must be distilled	uses a **finite** resource (crude oil), and needs high temperature and pressure (expensive)

Combustion. Alcohols burn in air to carbon dioxide and water:

$$C_2H_5OH\,(l) + 3\,O_2\,(g) \longrightarrow 2\,CO_2\,(g) + 3\,H_2O\,(l)$$

Uses of ethanol: as a **solvent** (in perfumes and inks) and as a **fuel** (alone or mixed with petrol).

11.7 Carboxylic acids

Carboxylic acids contain the $-COOH$ group. They are **weak acids** and react like other acids, with the salt named after the acid, "-oate":

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Reacts with	Products	Example with ethanoic acid
a **metal**	salt + hydrogen	$Mg + 2\,CH_3COOH \longrightarrow (CH_3COO)_2Mg + H_2$ (magnesium ethanoate)
a **base**	salt + water	$NaOH + CH_3COOH \longrightarrow CH_3COONa + H_2O$ (sodium ethanoate)
a **carbonate**	salt + water + carbon dioxide	$Na_2CO_3 + 2\,CH_3COOH \longrightarrow 2\,CH_3COONa + H_2O + CO_2$

Making ethanoic acid

Ethanol is **oxidised** to ethanoic acid:

- by heating with **acidified aqueous potassium manganate(VII)**, which changes from **purple to colourless**, or
- by **bacterial oxidation** in air, which is how **vinegar** is made from wine or beer.

$$CH_3CH_2OH + 2\,[O] \longrightarrow CH_3COOH + H_2O$$

Esters

A carboxylic acid reacts with an **alcohol**, with an **acid catalyst** (concentrated sulfuric acid), to make an **ester** and water. The reaction is reversible.

$$CH_3COOH + CH_3CH_2OH \rightleftharpoons CH_3COOCH_2CH_3 + H_2O$$

The ester ethyl ethanoate has a sweet, fruity smell. Esters are used in perfumes and food flavourings.

11.8 Polymers

A polymer is a large molecule built up from many smaller molecules called monomers. Plastics are made from polymers.

Addition polymers

In **addition polymerisation**, the monomers are **unsaturated** (alkenes). The double bonds open up and the monomers join in a long chain, and **no other product** is made.

$$n\,CH_2{=}CH_2 \rightarrow [-CH_2-\overset{-}{C}H_2]_n$$

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To find the **repeat unit** of an addition polymer, take the alkene's two carbon atoms with the groups on them, open the double bond into a single bond, and show the bonds extending out of the brackets. To find the monomer from a polymer, **reverse** this.

Monomer	Polymer	Repeat unit
ethene $CH_2=CH_2$	poly(ethene)	$-CH_2-CH_2-$
propene $CH_3CH=CH_2$	poly(propene)	$-CH(CH_3)-CH_2-$
chloroethene $CH_2=CHCl$	poly(chloroethene), **PVC**	$-CH(Cl)-CH_2-$

Condensation polymers

In **condensation polymerisation**, two **different** monomers, each with **two functional groups**, join, and a **small molecule (water)** is lost each time a link forms.

Type	Monomers	Link	Example
polyamide	a **dicarboxylic acid** (a $-COOH$ group at each end) and a **diamine** ($-NH_2$ at each end)	**amide** link, $-CONH-$	**nylon**
polyester	a **dicarboxylic acid** and a **diol** ($-OH$ at each end)	**ester** link, $-COO-$	**PET**

	Addition polymerisation	Condensation polymerisation
monomers	unsaturated, with a $C=C$	two functional groups on each monomer
products	**only** the polymer	the polymer **and a small molecule** such as water
number of monomer types	usually one	usually two

PET can be **converted back into its monomers and re-polymerised**, so it is recycled.

Proteins

Proteins are **natural polyamides**. They are made from **amino acid** monomers, which have the general structure $H_2N-CHR-COOH$, where R is a side-chain that is different in different amino acids. The amino acids join by **amide links** ($-CONH-$), with the loss of water.

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Plastics and the environment

Most plastics are **not biodegradable**, so they cause problems when disposed of:

- in **landfill sites**, they last for hundreds of years and take up space;
- they **accumulate in the oceans**, harming and killing marine life, and breaking into tiny pieces (microplastics);
- when **burned**, they produce **toxic gases**, for example carbon monoxide, and hydrogen chloride from PVC.

The properties of plastics (strong, light, not rotting) make them useful, but their disposal is a challenge. **Recycling** helps, as does using fewer plastics.

Note Academy