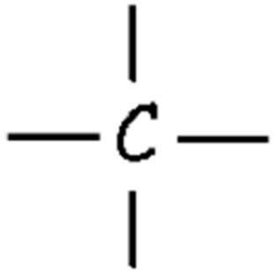
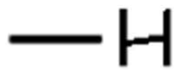
Organic Chemistry

A huge variety of molecules in living organisms, are based on **carbon** with just a few other elements e.g. O and H.

This is possible because carbon always forms 4 bonds (valency = 4), so it can be bonded to other atoms in many different configurations.



oxygen always forms two bonds

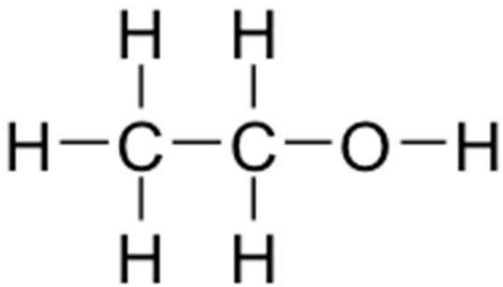


hydrogen always forms one bond

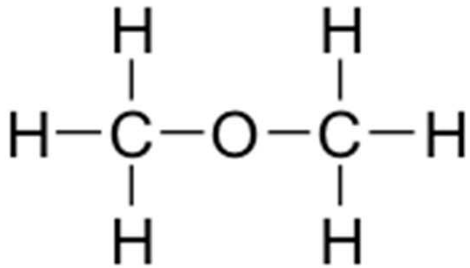
Isomerism

Molecules with the **same numbers of each type of atom** can still have these atoms bonded together in **different spatial arrangements**. This is called isomerism.

e.g. **C_2H_6O** could be…



ethanol



methoxymethane

Types of chemical formula

Molecular formula e.g. **C_2H_6** (the one we normally use)

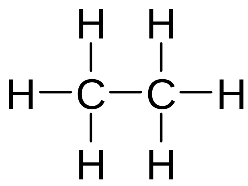
- a list of the atoms in a molecule, and how many of each

Empirical formula e.g. **CH_3**

- the simplest whole-number ratio of the atoms present in the molecule
  (divide the numbers by highest common factor)

Displayed formula

- shows each atom and 'sticks' for the bonds between them, so we can tell isomers apart



Structural formula e.g. **CH_3CH_3**

- lists each carbon atom and what it is bonded to, so this too can tell isomers apart.

Practice: (answers at the end of the topic)

Write the displayed formula for the substance $CH_3CH_2CH_2CH_3$

Write the empirical formula for the substance $C_6H_{12}O_6$

Write the molecular formula for the substance $CH_3CH(CH_3)CH_2NH_2$

Write the structural formulae of all the isomers of C_3H_8O

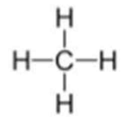
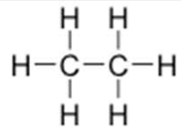
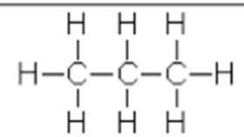
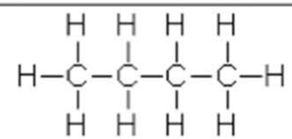
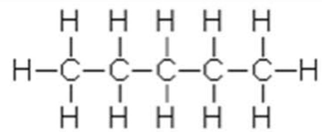
The ALKANES – a chemical family

A **homologous series** is a family of molecules with similar groups of bonded atoms that have the same reactions and a trends in their physical properties.

Each successive member of the series differs from the other by **$–CH_2$-** which means that all the members of the series are related by a **general formula**.

The **alkanes** are a homologous series with general formula **C_nH_{2n+2}.**

('n' is the number of carbon atoms in the molecule)

	molecular formula	structural formula	displayed formula
Methane	CH_4	CH_4	
Ethane	C_2H_6	CH_3CH_3	
Propane	C_3H_8	$CH_3CH_2CH_3$	
Butane	C_4H_{10}	$CH_3CH_2CH_2CH_3$	
Pentane	C_5H_{12}	$CH_3(CH_2)_3CH_3$	

The alkanes are **saturated hydrocarbons**:

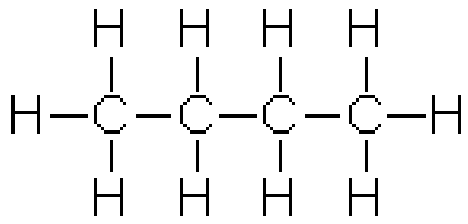
Definitions:

Hydrocarbons: compounds containing only hydrogen and carbon atoms

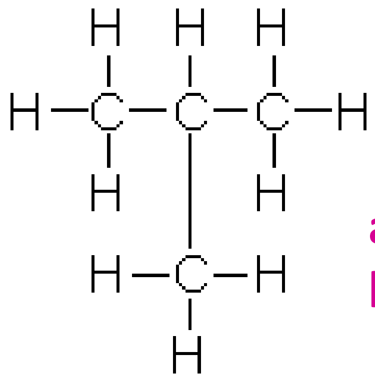
Saturated: containing no carbon-to-carbon double bonds

Isomerism in the alkanes

There is only one alkane with 2 carbon atoms, and only one alkane with 3 carbon atoms, but we can have two different isomers with 4 carbon atoms:



butane

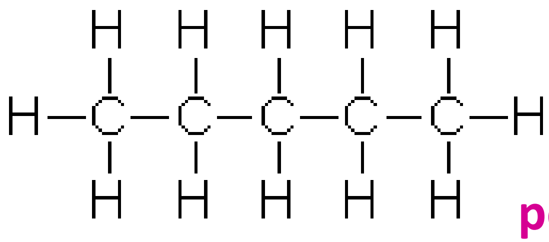


a branched isomer of butane (methylpropane)

Note that the chain of carbon atoms can be bent, but this does not make a different isomer. Branches can be on either side of the chain, or counted from either end of the chain (mirror images), but the isomer still the same. For different isomers, the atoms have to be connected in a different sequence. *(Although there are other forms of isomerism which you may meet if you study Chemistry beyond IGCSE)*

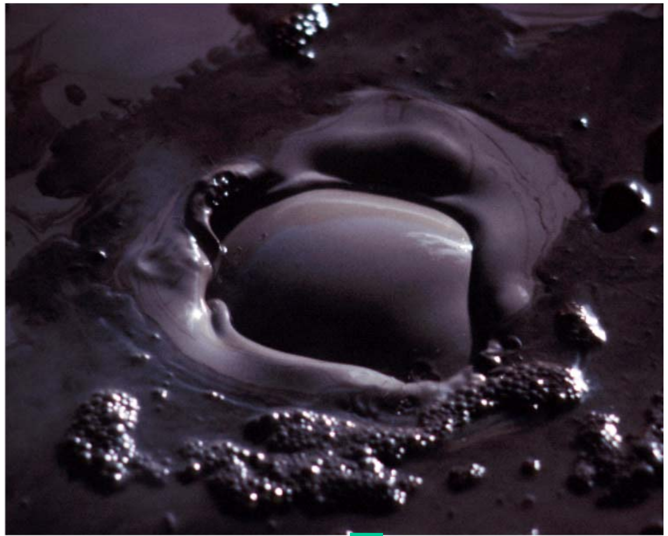
Practice:

What are the structures of the two branched isomers of pentane (with 5 carbon atoms)?
Hint: You may come up with more than two structures, but check that they aren't the same structure just rotated or twisted!



pentane

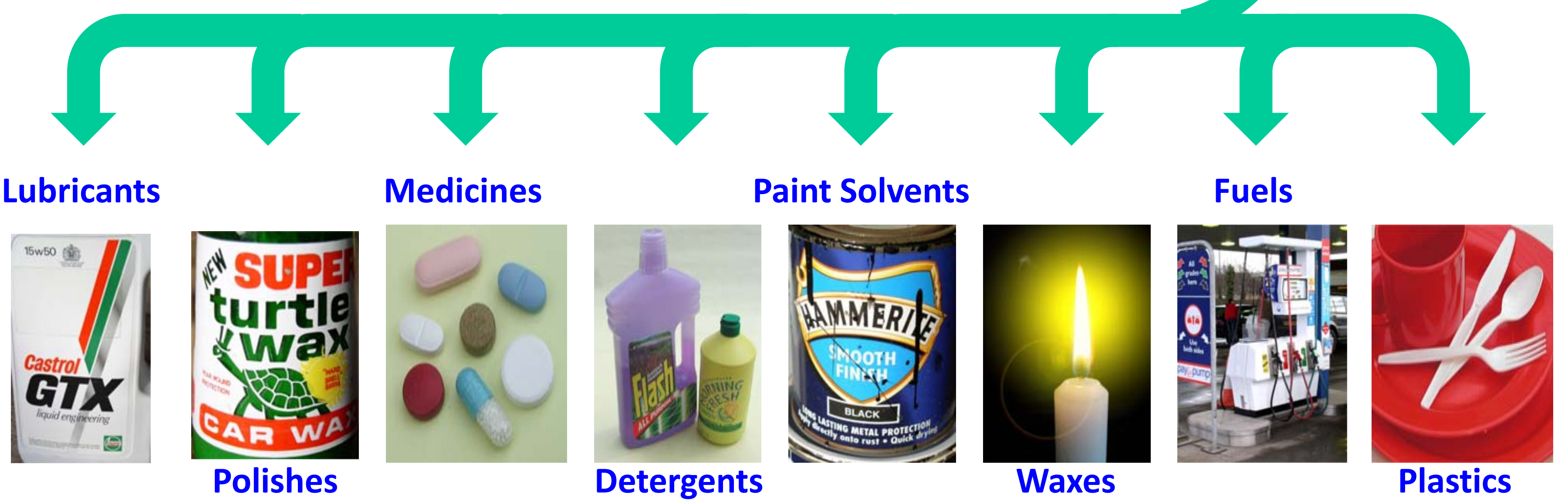
Crude Oil: a **mixture** of very many different compounds, mostly **hydrocarbons,** mainly **alkanes**.



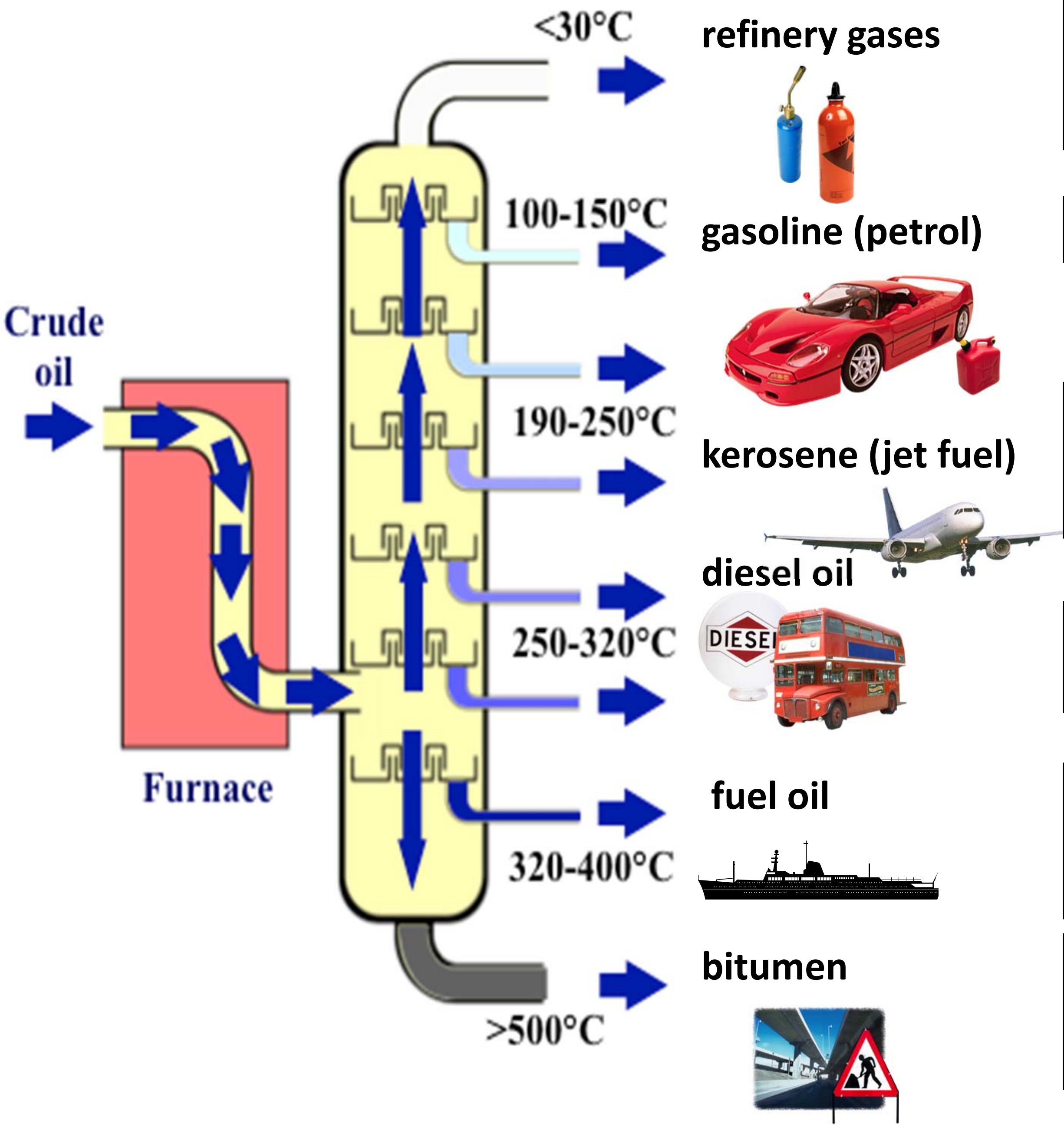
[**Mixture:** can be separated by physical means such as distillation – not chemically bonded together]

Crude oil is not useful itself – we have to separate out alkanes of **similar number of carbon atoms.**

Each group of these is called a **fraction**, and has different properties and uses. e.g. the fraction from 6 to 9 carbons long is petrol



Fractional Distillation of Crude Oil on an Industrial Scale



3 – 4 carbons: used for domestic heating and cooking e.g. LPG, and camping gas

6 – 9 carbons: used for fuel in cars

11-16 carbons: used as aviation fuel, and as paraffin for heaters and lamps

14-20 carbons: used as fuel in lorries, buses, trains and some cars

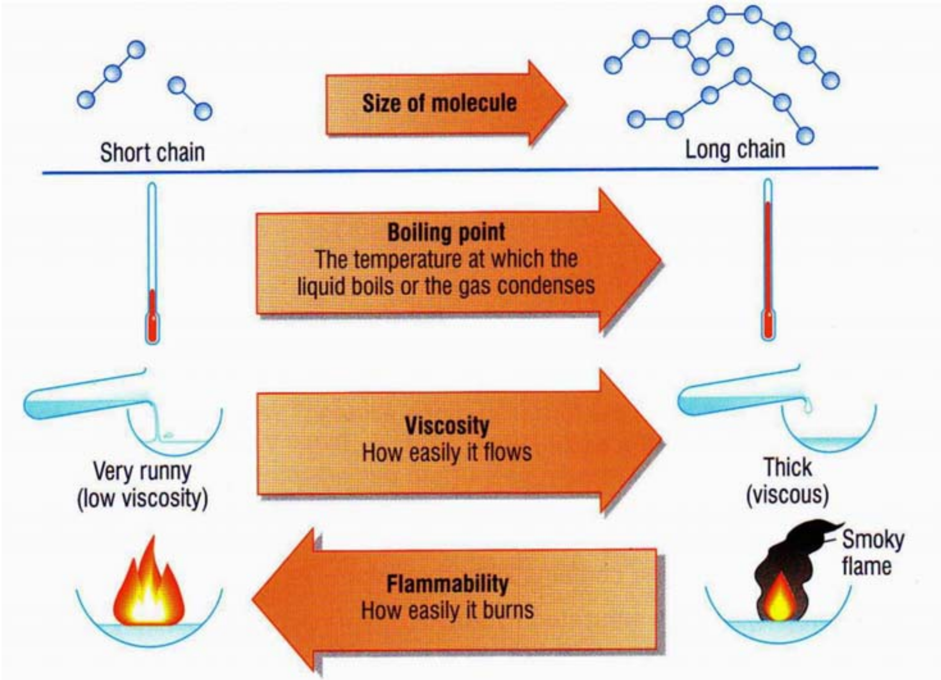
20 – 27 carbons: used for ships' boilers, and for some industrial heating

> 35 carbons: used, mixed with rock chippings, for the top surface of roads

Properties of alkanes vary with size of the molecule

With increasing length of the carbon chain (increasing size of the molecule):

- Boiling point increases
- Melting point increases
- Viscocity (thick, sticky) increases
- Flammability decreases
- Burns less cleanly (more smoke)



Most fractions (except the longest chains) are used as **fuels**.

- We probably want the fuel to go down fuel lines and through pumps, so it should be runny not thick and sticky – we should avoid very long chain hydrocarbons
- We want the fuel to burn cleanly rather than with a smoky flame – we should avoid very long chain hydrocarbons
- We don't want the fuel to ignite too easily – otherwise it will be difficult to store and handle safely – we should avoid the shortest chain hydrocarbons
- We usually want our fuels to be liquids as they take less space to store than a – we should avoid the shortest chain hydrocarbons
- Given these criteria we can see why there is huge demand for petrol for use in cars, which typically contains chains from 6 – 10 carbon atoms long.

Separating crude oil

- The process is called **fractional distillation.**
- It takes place in a **fractionating column**.
- It works because as the **number of carbon atoms** in an alkane increases, the **boiling points increase.**
- It is **NOT** a reaction (no substances changed) – just a separation

How it works:

Each fraction contains molecules with similar numbers of carbon atoms and similar boiling points. Different size fractions will therefore condense at different temperatures.

The crude oil is vapourised and enters the bottom of a fractionating column which has a temperature gradient. (hot at the bottom, cooler towards the top).

At different levels in the column, different fractions cool down to their boiling points and condense, and are collected.

Complete combustion of alkane fuels

When hydrocarbons burn in a **plentiful** supply of air (oxygen) they are **fully oxidised**. No matter which hydrocarbon you burn, the products are the same: **carbon dioxide and water.**

General equation for complete combustion:

alkane + oxygen → carbon dioxide + water e.g. $CH_{4(g)} + 2O_{2(g)} \rightarrow CO_{2(g)} + 2H_2O_{(l)}$

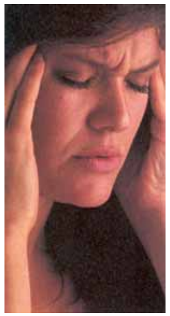
Incomplete combustion of alkane fuels

When hydrocarbons burn in a **limited supply of air** (oxygen) we get **incomplete combustion** – the fuel is **partially oxidised**.

This might happen if a domestic fire is not properly maintained and air-holes are blocked, for example. If there isn't enough oxygen available to form carbon dioxide we can get **carbon monoxide** or solid **carbon** (soot) formed.

alkane + oxygen → carbon monoxide + water

e.g. $2CH_{4(g)} + 3O_{2(g)} \rightarrow 2CO_{(g)} + 4H_2O_{(l)}$



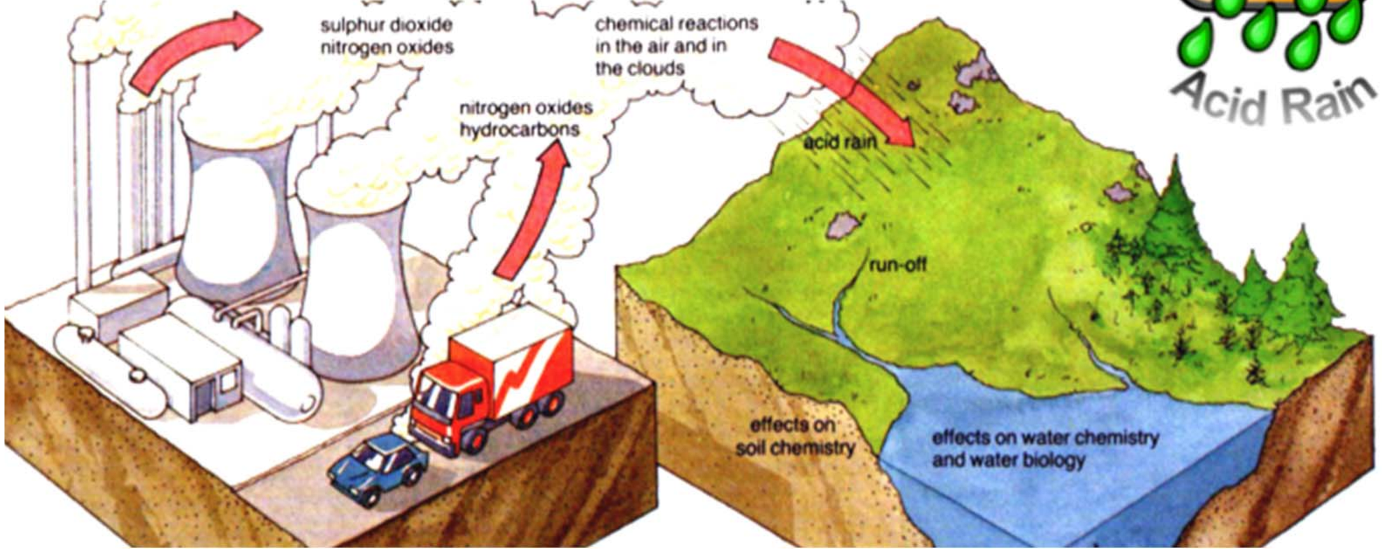
Carbon Monoxide (CO)

- colourless, odourless
- poisonous when inhaled because it **reduces the capacity of the blood to carry oxygen**.

- from domestic fires/heaters,
- from traffic exhaust

Other combustion products

Suphur dioxide, SO_2, and **nitrogen oxides**, NOx, are also produced when fossil fuels are burnt in power stations and factories, and in motor vehicles; they cause **acid rain**.

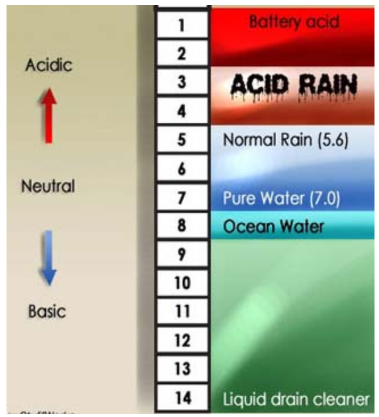


Sulphur dioxide comes from traces of sulphur in fossil fuels, which oxidise to sulphur dioxide when burnt. $S + O_2 \rightarrow SO_2$

Sulphur is therefore removed from liquid fuels such as petrol before sale (it is then used as the raw material in the Contact Process).

Sulphur dioxide dissolves in water droplets in the atmosphere to form sulphurous acid, making **acid rain**. $SO_{2(g)} + H_2O_{(l)} \rightarrow H_2SO_{3(aq)}$

sulphurous acid



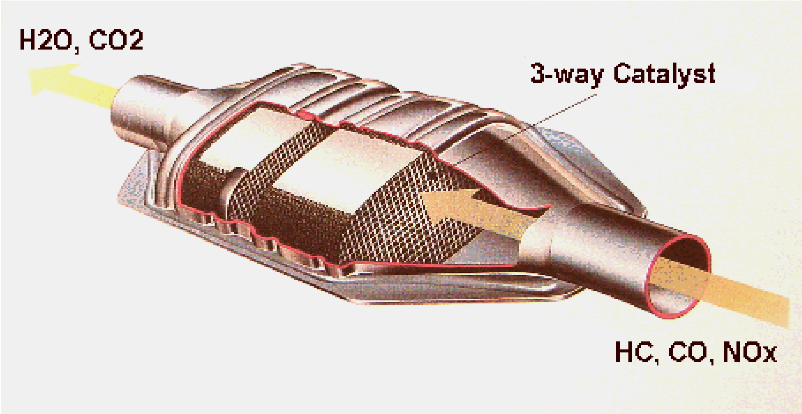
The wind can carry the gases and droplets a long way, so acid rain can fall on regions far from where it was produced.

Acid rain can kill or stunt the growth of plants and trees, and harm or kill aquatic animals. Buildings made of limestone or marble are corroded, and some metals such as iron can also be corroded by acid rain.

The nitrogen oxides come from the very **high temperature** inside car engines, which causes the **nitrogen in the air** to be burnt (i.e. react with the **oxygen in the air**). Nitrogen oxides in the air contribute to the formation of smog, and can lead to respiratory illnesses.

Catalytic converters are used in the exhausts of cars. They convert **NOx** to **N_2**, and CO to **CO_2**, but have no effect on **SO_2**.

$$2NO_{(g)} + 2CO_{(g)} \rightarrow N_{2(g)} + 2CO_{2(g)}$$



Catalytic converters only work when the catalyst is really hot, so are not effective on short trips.

Reaction of alkanes with halogens

Alkanes can also react slowly with halogens such as bromine, but only in the presence of **uv light**, e.g. from sunlight.

This is a **substitution reaction**. One of the hydrogen atoms in the alkane is substituted for a halogen atom.

e.g. $CH_{4(g)} + Br_{2(g)} \rightarrow CH_3Br_{(g)} + HBr_{(g)}$

methane + bromine → bromomethane + hydrogen bromide

The brown colour of the bromine slowly disappears, as the products are colourless.

Practice – reactions of alkanes:

Write a balanced equation for the complete combustion of ethane, C_2H_6, and of propane, C_3H_8.

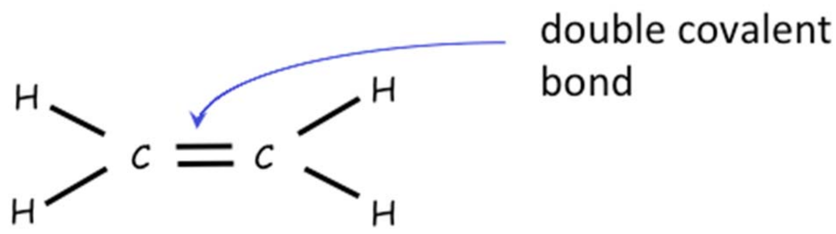
Write a balanced equation for the incomplete combustion of ethane to give carbon monoxide and water, and the incomplete combustion of propane to give carbon (soot) and water.

Write a balanced equation for the reaction between chlorine and ethane, and name the products formed.

Alkenes – another homologous series

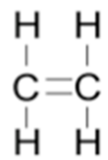
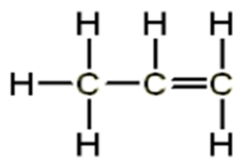
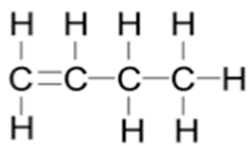
The alkenes are a homologous series of hydrocarbons with general formula C_nH_{2n}.

They are **unsaturated** as they contain one carbon-to-carbon double bond.



Ethene is the simplest alkene

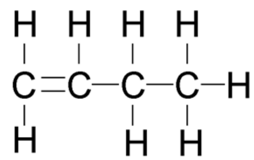
ALKANES are SATURATED hydrocarbons
ALKENES are UNSATURATED hydrocarbons

	molecular formula	structural formula	displayed formula
ethene	C_2H_4	$CH_2{=}CH_2$	
propene	C_3H_6	$CH_2{=}CHCH_3$	
butene	C_4H_8	$CH_2{=}CHCH_2CH_3$	

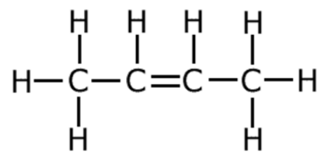
We use a number in the name to show between which carbon atoms the double bond is located.

Isomerism in the alkenes

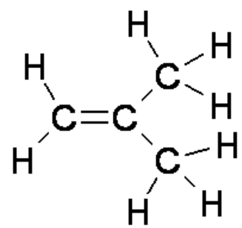
There is only one alkene with 2 carbon atoms, and one with 3 carbon atoms, but we can have three different alkenes with 4 carbon atoms:



but-1-ene



but-2-ene

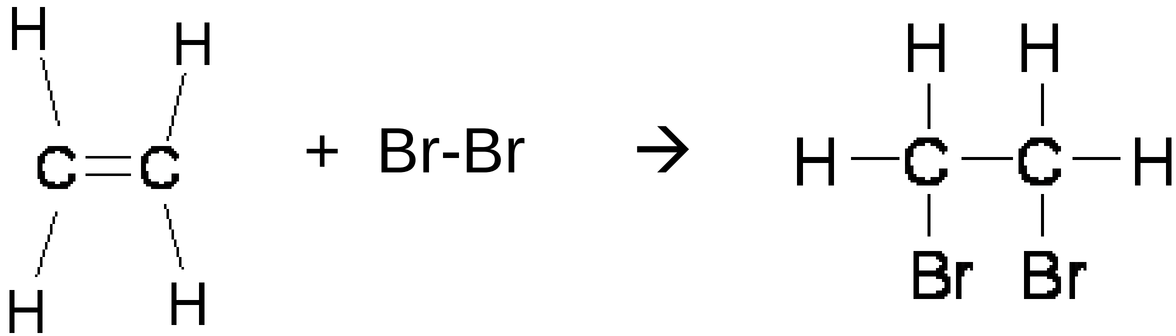


a branched isomer (methylpropene)

Test for alkenes:
Add a few drops of bromine water (orange) to the hydrocarbon, and shake.

- Alkenes can **decolourise bromine water**.
- Alkanes cannot do this (the bromine remains orange)

This is an **addition reaction**. The double bond in the alkene breaks and the two bromine atoms are joined one to each carbon atom.



ethene **bromine** **1,2-dibromoethane**

The numbers in the name indicate which carbon atoms the bromine atoms are attached to.

Other halogens e.g. chlorine or iodine react with alkenes in the same way.

Practice: Write a balanced equation for the reaction between propene and iodine, and name the products.

Where do we get alkenes?

Short-chain hydrocarbons (e.g. in petrol) are in high demand as fuels, because of the very large number of cars we use. Fractional distillation produces less than we need of the short-chain fractions so they are in short supply.

There is lower demand for the longer-chain hydrocarbon molecules such as fuel oils (we have much fewer ships than cars). Fractional distillation produces more than we need.

A reaction called cracking is used to make long chain hydrocarbons into shorter, more useful alkanes, and also produces useful alkenes.

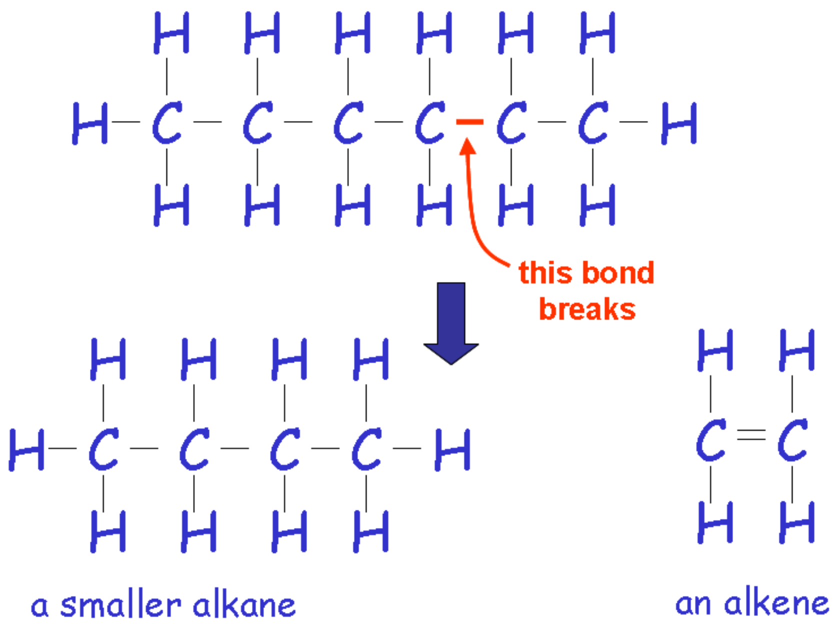
Catalytic cracking

- creates more of products (short chains) which are in demand and in short supply
- makes more efficient use of finite crude oil reserves (uses longer chains)
- The reaction is an example of **thermal decomposition**

Conditions: Long chain alkanes are converted to alkenes using **silica or alumina** as **catalysts** and a **temperature of 600 – 700°C**.

The long chain gets broken into two shorter parts. One will be an alkane, and one will be an alkene.

Where the chain breaks is random, so cracking creates a **mixture of products** which can be **separated** by further **fractional distillation**.



E.g. An alkane 6 carbons long can break into a 4-carbon alkane and a 2-carbon alkene.

We can write this equation as: $C_6H_{14} \rightarrow C_4H_{10} + C_2H_4$

hexane → butane + ethene

There are some other possibilities to be aware of…

1) hydrogen can be a product, instead of a shorter alkane

e.g. **butane → butene + hydrogen**

$C_4H_{10} \rightarrow C_4H_8 + H_2$

2) the chain could break twice to give an alkane and two alkenes

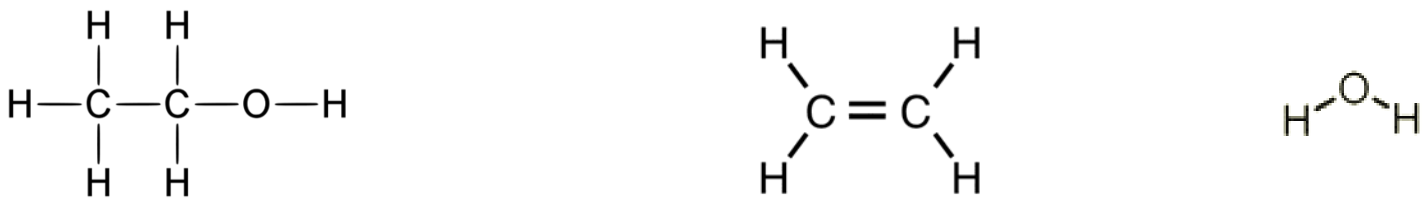
e.g. **octane → butane + ethene**

$C_8H_{18} \rightarrow C_4H_{10} + 2C_2H_4$

Another route for making alkenes

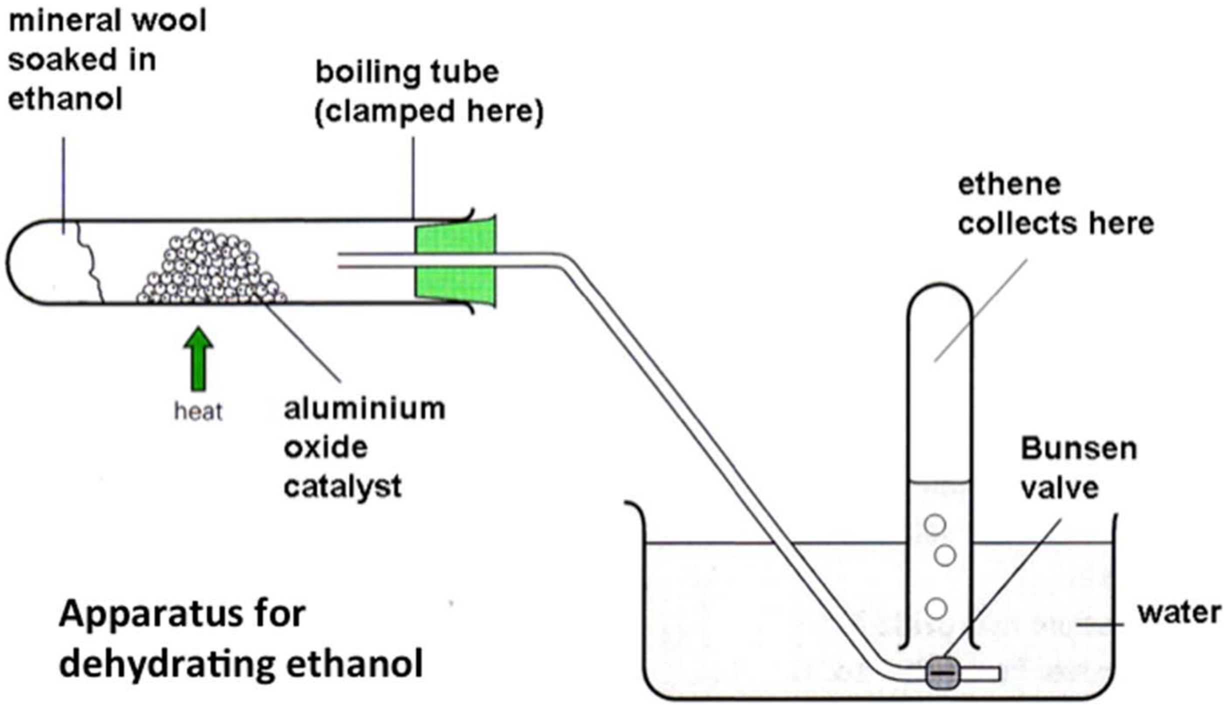
Alkenes can also be made by **dehydration** of alcohols; alcohols can be made as sustainable and as renewable resource by fermentation of sugars (see later).

e.g.



ethanol → **ethene** + **water**

The alcohol vapour is passed over **hot aluminium oxide**, which acts as a **catalyst**.



Apparatus for dehydrating ethanol

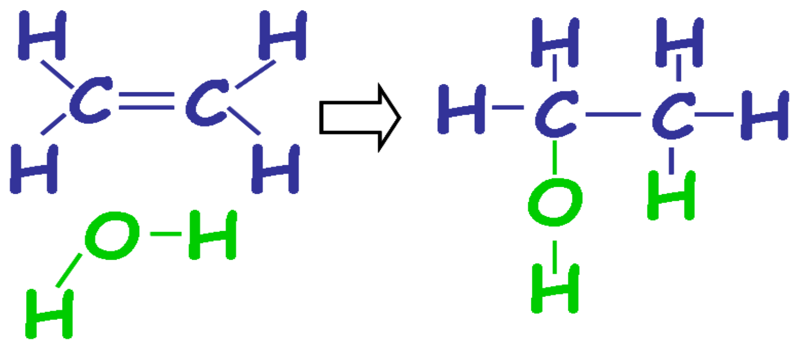
Products from alkenes – Ethanol

Alkenes are used to manufacture many useful substances:

Ethanol can be manufactured by passing ethene and steam over a concentrated phosphoric acid catalyst at a temperature of about 300°C and a pressure of 60-70 atm.

C_2H_4 + H_2O → C_2H_5OH

ethene + water (steam) → ethanol



Advantages of this method of making ethanol:

- *rapid – continuous process with few steps*
- *makes pure ethanol*
- *manufacturing cost is low*
- *higher % yield*
- *best method in countries with good supplies of crude oil*

Disadvantages of this method of making ethanol:

- *Uses ethene from crude oil – finite resource*
- *Lots of energy required – high temperature, which means lots of fuel burnt and high CO_2 emissions leading to more global warming*

Ethanol can also be manufactured by **fermentation of sugars from sugar cane or sugar beet**, at a temperature of about 30°C. The enzyme zymase in yeast catalyses this reaction, but at higher temperatures the enzyme is **denatured**.

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2\,CO_2$$

sugar → ethanol + carbon dioxide

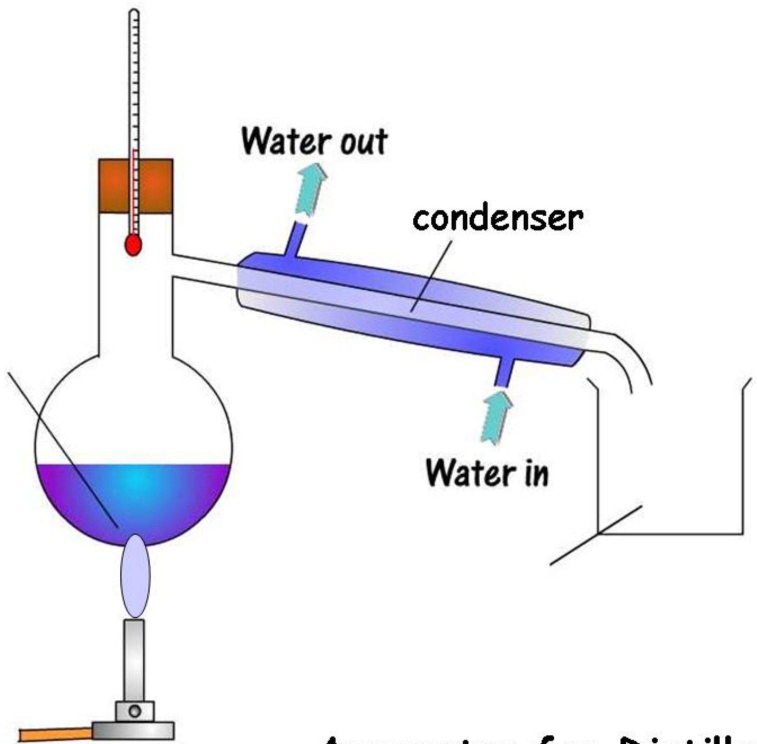
Simple distillation is used to extract the pure ethanol from the resulting aqueous solution that is produced, which works because ethanol and water have **different boiling points**.

Advantages of this method of making ethanol:

- *uses renewable resources (plant matter)*
- *fuel is carbon-neutral*
- *low energy consumption, reducing carbon dioxide emissions and resulting in less global warming*
- *best in countries with good availability of sugar cane and poor supplies of crude oil*

Disadvantages of this method of making ethanol:

- *slow – batch process involving more steps*
- *labour intensive*
- *product impure – has to be distilled to purify*
- *product is more expensive to manufacture*



Apparatus for Distillation

Products from Alkenes – Addition Polymers

Fire resistant polymer fibre suits for F1 pit crews

Polymer canopy on military aircraft is light and tough

Modern climbing ropes are woven from polymer fibres

Breathable weather-resistant sportswear uses polymer fibres

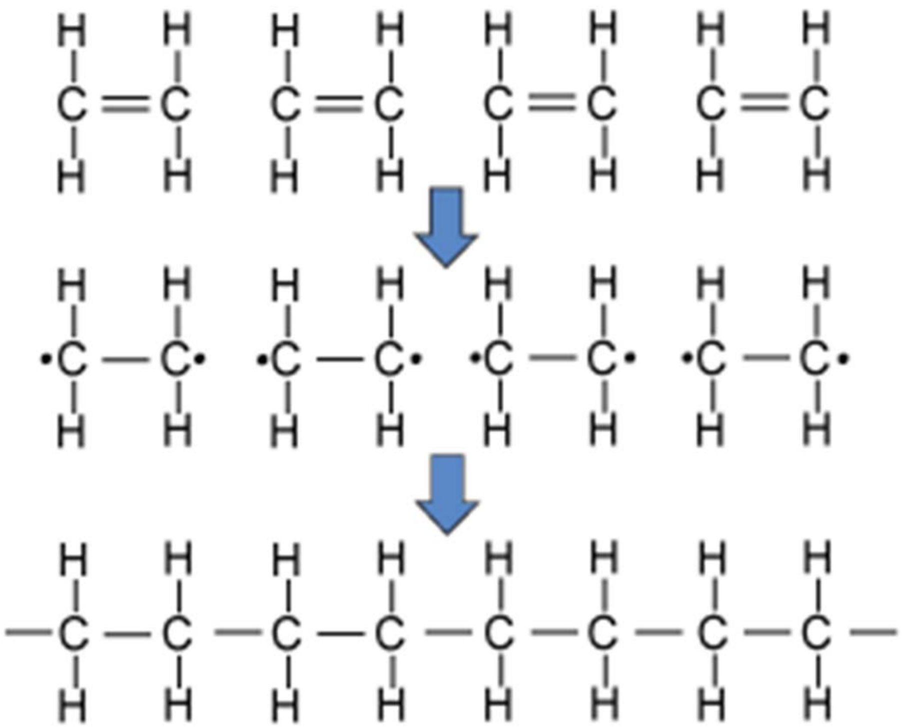
Common household objects made from polymer materials

Plastics and manmade fibres consist of very long chain molecules. These are made up from lots of small molecules that have joined together.

We call the small molecules **MONOMERS** and the long chain they make, a **POLYMER**. The name of the polymer comes from the monomer, with ‘poly’ in front of it.

Alkenes can act as monomers because they have a C=C double bond, which allows them to join together

This reaction is called **addition polymerisation** because the alkene monomers add on to one another to make one product only.

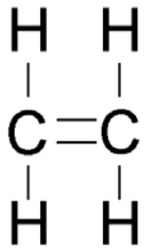


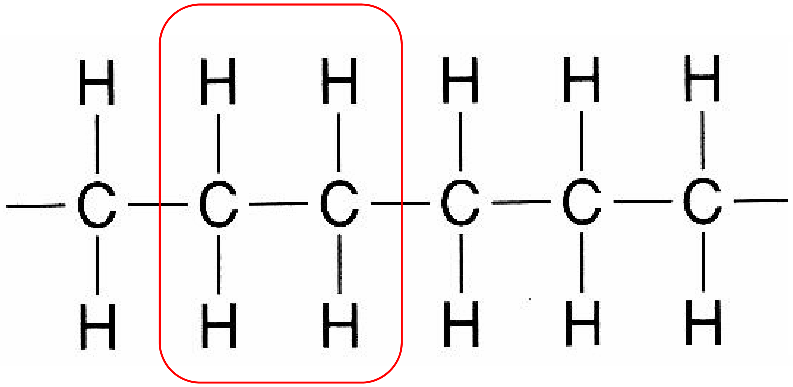
Changes that take place when a polymer forms

- The **double bond breaks** in each monomer, ‘opening up’ to join with the next monomer.
- **Many monomers** join together in this way to make a **very long chain.**

ethene → poly(ethene) common name: polythene or PE

the monomer, ethene



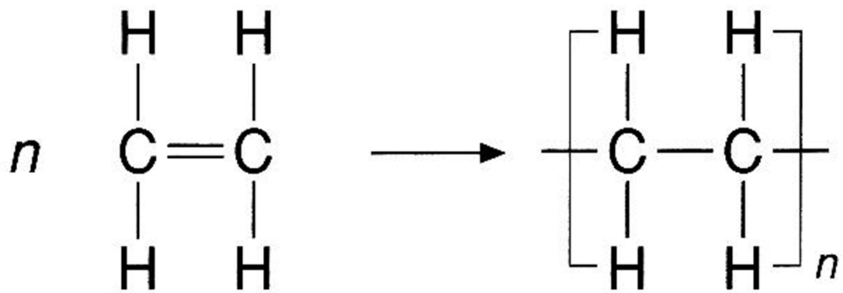


a repeat unit of poly(ethene)

Poly(ethene) is a really useful plastic. It is easy to shape, strong, and transparent.
e.g.
- plastic bags, drinks bottles,
- dustbins,
- clingfilm

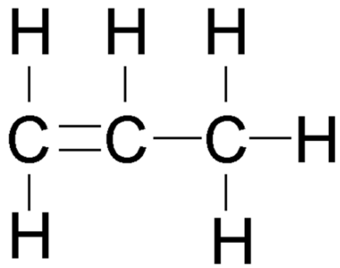
BUT it melts easily and catches fire easily !

How to write an equation for the reaction:



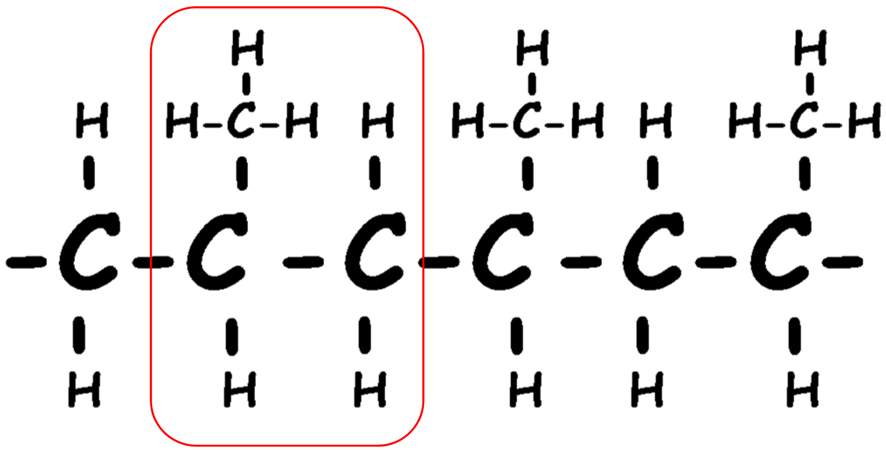
propene → poly(propene) **common name: PP or polypropylene**

the monomer, propene



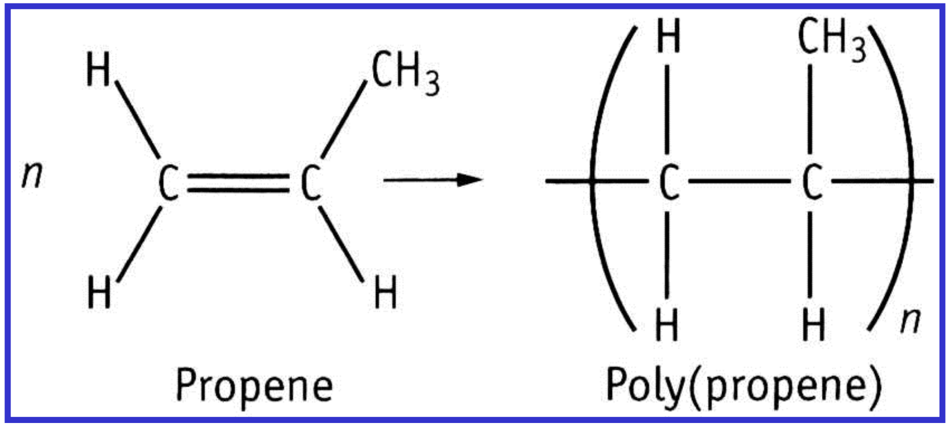
Poly(propene) is more rigid than poly(ethene), tough and durable.

It is used for making crates, ropes and fibres in some carpets



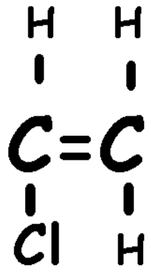
A repeat unit of poly(propene)

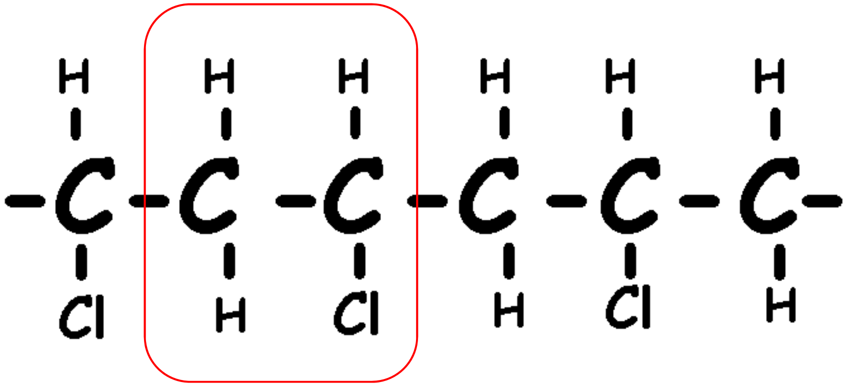
How to write an equation for the reaction:



chloroethene → Poly(chloroethene) common name: PVC

the monomer, chloroethene



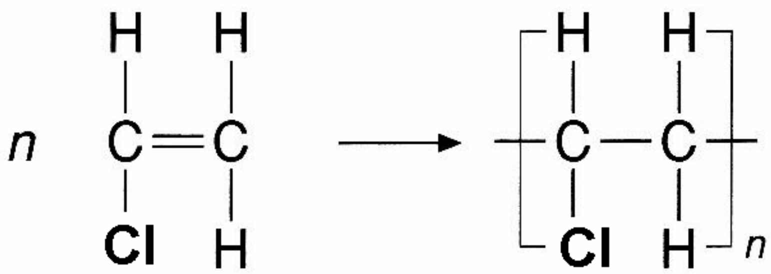


a repeat unit of poly(chloroethene)

PVC is also useful e.g. for window frames (because it is stiff, and doesn't bend easily)

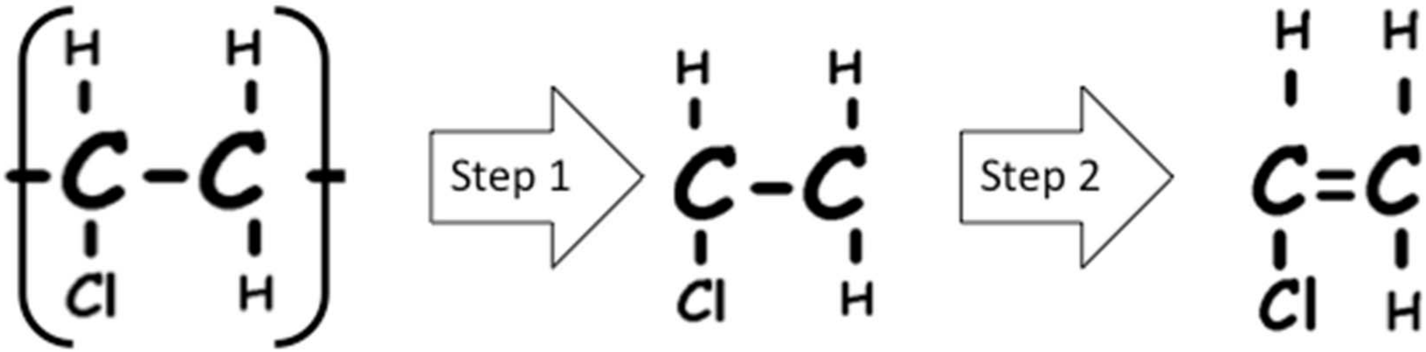
and insulation on wires (because it does not catch fire easily, and is easy to add a colour to)

How to write an equation for the reaction:



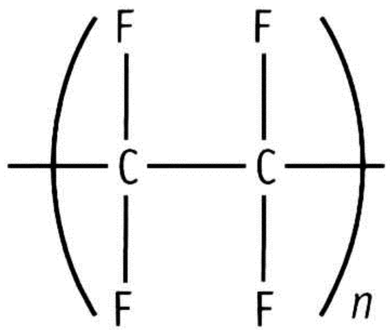
Given a repeat unit for a polymer, you should be able to draw the monomer from which it was formed:

1. remove the connecting bonds and any brackets
2. make the bond between the two carbon atoms of the chain into a double bond



repeat unit monomer

Practice: Draw the monomers that formed these two polymers:



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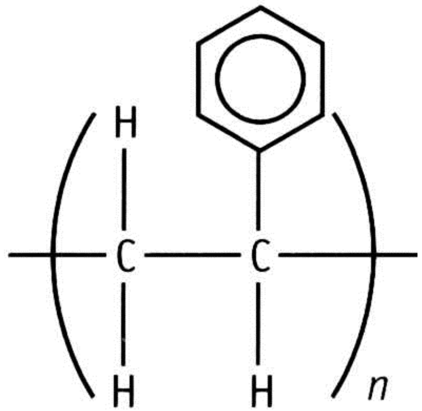


poly(styrene)

Problems with polymers
Because they are very inert (unreactive) addition polymers are not easily broken down by micro-organisms – they are not **biodegradable**.

Being non-biodegradable can be good - plastic structures used outside don't need painting or maintaining like wooden objects.

But this does cause problems when we want to dispose of polymers…

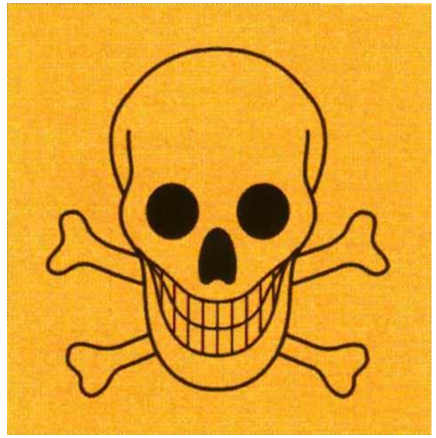
We currently have three options:
- dump plastic waste in **landfill**
- **incinerate** plastic waste
- collect, sort and **recycle** it

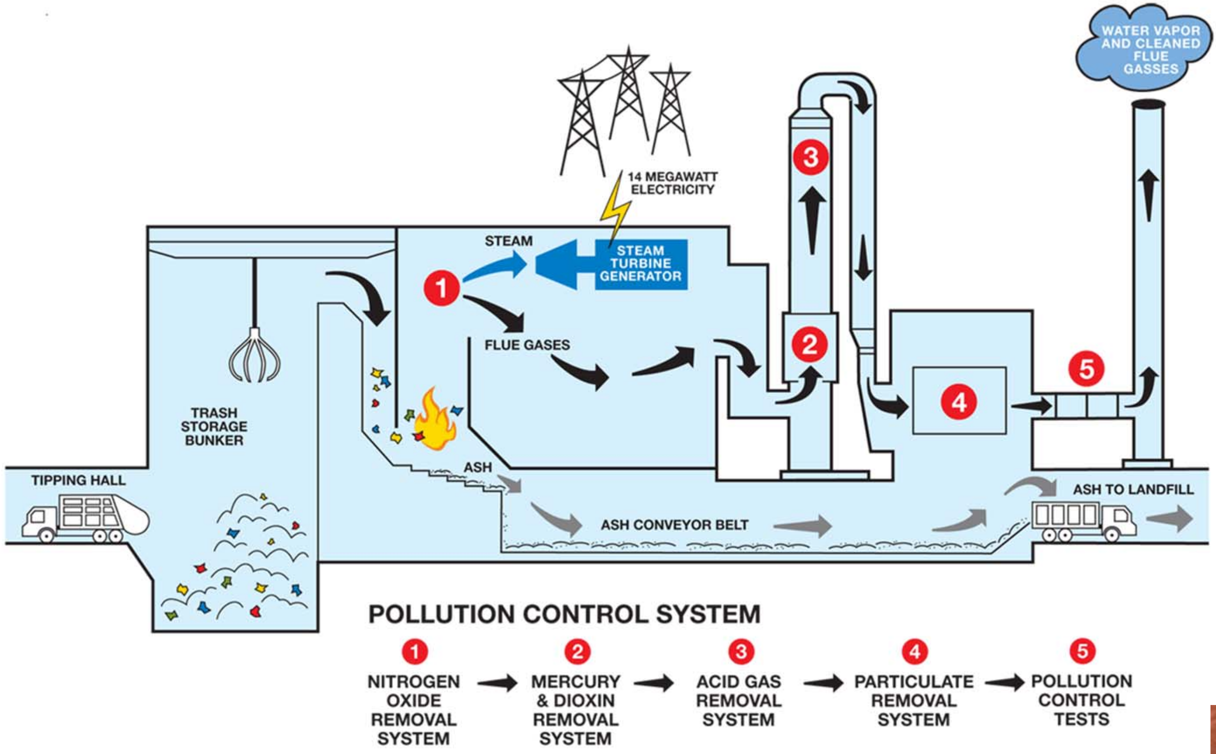
Landfill is a poor solution:

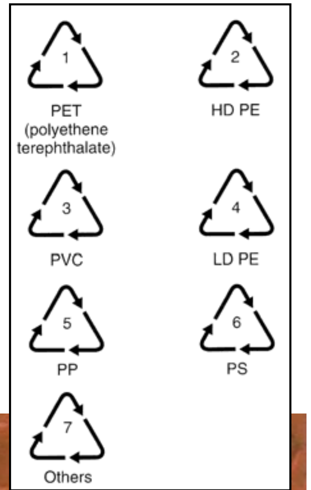
- the plastics never rot away
- more and more space is needed, and land is valuable
- wildlife may be harmed by eating plastics or getting entangled.

Burning (incinerating):

- Incinerators are expensive to build
- Toxic fumes can be released
- Energy from burning is useful e.g. for home/factory heating







Sorting and recycling plastics:

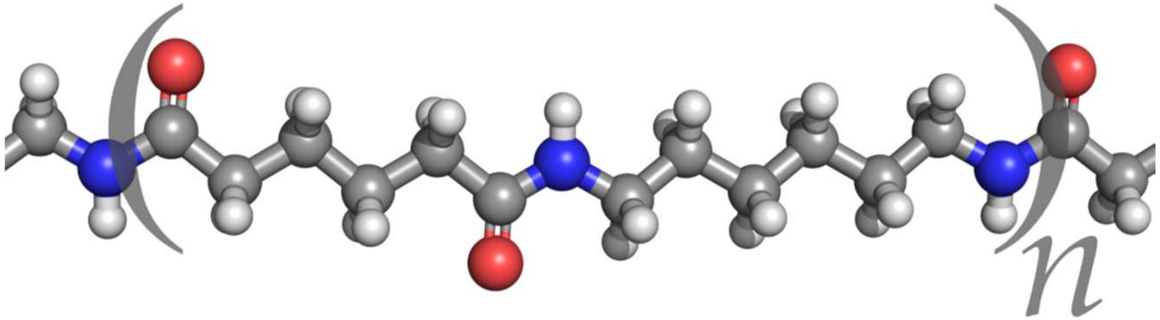
- very labour intensive to collect and sort
- plastics must be washed before sorting into different types
- not all types of plastic can be recycled

The cost of recycled plastic can be higher than new plastic !

Condensation Polymers
Unlike addition polymers, when the monomers in **condensation polymers** join together there is a **small molecule released**, such as water, when each link is formed.

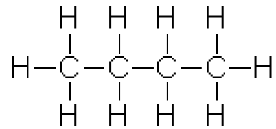
Condensation polymers are often formed by reacting two different monomers together.

e.g. **nylon** is a condensation polymer.



Answers

Write the displayed formula for the substance $CH_3CH_2CH_2CH_3$



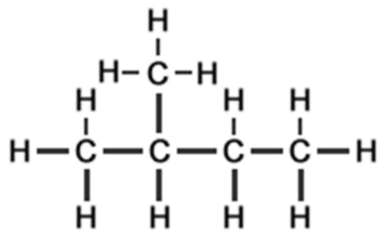
Write the empirical formula for the substance $C_6H_{12}O_6$ CH_2O

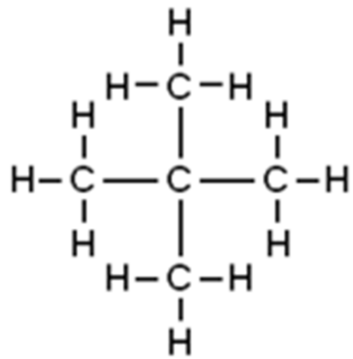
Write the molecular formula for the substance $CH_3CH(CH_3)CH_2NH_2$ $C_4H_{11}N$

Write the structural formulae of all the isomers of C_3H_8O

$CH_3CH_2CH_2OH$ $CH_3CH(OH)CH_3$ $CH_3CH_2OCH_3$

What are the structures of the two <u>branched</u> isomers of pentane (with 5 carbon atoms)?
Hint: You may come up with more than two structures, but check that they aren't the same structure just rotated or twisted!





Write a balanced equation for the complete combustion of ethane, C_2H_6, and of propane, C_3H_8.

$$2C_2H_6 + 7O_2 \rightarrow 4CO_2 + 6H_2O$$
$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$$

Write a balanced equation for the incomplete combustion of ethane to give carbon monoxide and water, and the incomplete combustion of propane to give carbon (soot) and water.

$$2C_2H_6 + 5O_2 \rightarrow 4CO + 6H_2O$$
$$C_3H_8 + 2O_2 \rightarrow 3C + 4H_2O$$

Write a balanced equation for the reaction between chlorine and ethane, and name the products formed.

$$C_2H_6 + Cl_2 \rightarrow C_2H_5Cl + HCl$$

chloroethane + hydrogen chloride

Write a balanced equation for the reaction between propene and iodine, and name the product.

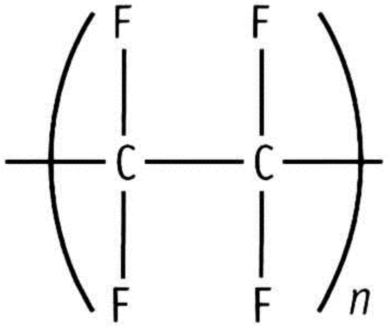
$$C_3H_6 + I_2 \rightarrow C_3H_6I_2$$

1,2-diiodopropane

Write a symbol equation for the cracking of heptane in which propane is one of the products

$$C_7H_{16} \rightarrow C_3H_8 + C_4H_8$$

Draw the monomers that formed these two polymers:



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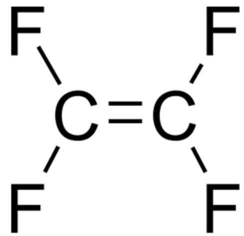
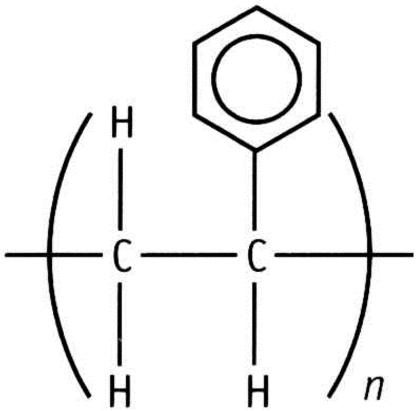
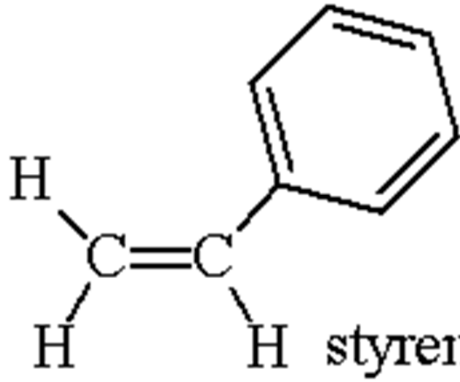
Monomer = 



Monomer = 

poly(styrene)