YOU WILL EXAMINE:

- the structures, names, uses and formulas of the homologous series of alkanes, alkenes, alkynes, alcohols, carboxylic acids and esters up to C₁₀
- physical and chemical properties of hydrocarbons
- properties of alcohols, carboxylic acids and esters
- saturated and unsaturated hydrocarbons
- isomers and their naming
- alcohol, carboxylic acid and ester functional groups
- formation of esters
- the origin of hydrocarbons.

Where the senses fail us, reason must step in.

Galileo Galilei
Organic chemistry

Organic chemistry is the systematic study of the compounds of carbon, excluding oxides of carbon, carbonates, carbides and cyanides. These exceptions plus the compounds of the remaining elements are considered to be inorganic.

Buckminsterfullerene, a soccerball-shaped organic molecule used for research in the pharmaceutical industry. ‘Buckyballs’ such as these are produced at the tip of a candle flame, where C—C bonds form in ring structures.

What are organic compounds?

Organic compounds are a class of chemical compounds that occur naturally (although they are also synthesised in laboratories). They comprise over 90% of all known chemicals. They include not only those compounds that were part of or were derived from plants and animals, but also all carbon compounds except for those mentioned above. Of all the elements in the periodic table, carbon is the only one that has properties that make it possible for living systems to develop. The main reason for carbon’s unique ability to form a wide range of chemicals is that carbon–carbon bonds are strong. Carbon normally forms four covalent bonds. These strong bonds form bonds with other non-metals. Carbon can chemically bond with itself using single, double or triple bonds to form long chain-like structures and even rings.

Hydrocarbons are compounds that contain only carbon and hydrogen atoms. The carbon–carbon bonds can be single, double or triple. If these bonds are all single, the hydrocarbon is described as saturated. If double or triple bonds are present, it is termed unsaturated.

Carbon can form double and triple bonds with itself. The simplest hydrocarbons with carbon–carbon double and triple bonds are ethene and ethyne respectively.

(a) methane
(b) ethene
(c) ethyne
Hydrocarbons

A good place to begin a study of organic chemistry is with hydrocarbons. These are the simplest organic compounds and yet are among the most useful. Hydrocarbons are found in crude oil, and processing the oil yields many useful products. We will look at this process in more detail and the products that are formed later in this chapter. Hydrocarbons are molecules made up of only hydrogen and carbon.

There are different classes of hydrocarbons, based on the carbon bonding involved. These are indicated below.

- **ALIPHATIC** (straight chain)
- **CYCLIC**

**HYDROCARBONS**

- **Saturated**
- **Unsaturated**

**ALKANE**
**ALKENE**
**ALKYNE**

Saturated hydrocarbons contain only single carbon–carbon bonds. Unsaturated hydrocarbons contain double or triple carbon–carbon bonds. In cyclic compounds, the carbon atoms are arranged in a ring.

The simplest hydrocarbon is a carbon atom bonded to four hydrogen atoms. Carbon can form four equivalent bonds that are 109.5° apart, forming a tetrahedral shape. This molecule is called methane. The structure of a methane molecule was described in chapter 6.

![Lewis structure, structural formula, shape, and ball-and-stick model of methane](image)

**Properties of hydrocarbons**

Compounds containing C–H bonds are generally insoluble in water and do not react with it. They are more likely to be soluble in non-polar solvents. This is because the electronegativities of carbon and hydrogen atoms are similar. This means that the C–H bond is nearly non-polar, because of the symmetry of the molecule, and hydrocarbon molecules are non-polar.

This non-polar nature of hydrocarbons also explains why the boiling point of hydrocarbons increases with the length of the chain of carbon atoms. Only dispersion forces hold the molecules together, and these forces increase as the size of the molecules increases. The increase in boiling point with size reflects the increased dispersion forces between the molecules. If a molecule is branched instead of a straight chain, this lowers the boiling point. Branches prevent the molecules from coming closer together and so the dispersion forces have less effect. Table 8.1 shows this trend in the alkanes.

---

Hydrocarbons are insoluble in water.

The boiling point of hydrocarbons increases with the length of the molecule.
The alkanes

The alkanes are a family of hydrocarbons containing only single bonds between the carbon atoms. Notice how the name of each alkane has the same ending: -ane. This is how alkanes are identified. The different prefixes, meth-, eth-, prop- etc., show how many carbon atoms are present in each carbon chain (see table 8.1).

### TABLE 8.1 Common straight chain alkanes

<table>
<thead>
<tr>
<th>Formula</th>
<th>Name</th>
<th>Phase</th>
<th>Typical use</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₄</td>
<td>methane</td>
<td>gas</td>
<td>natural gas</td>
</tr>
<tr>
<td>C₂H₆</td>
<td>ethane</td>
<td>gas</td>
<td>refrigerant</td>
</tr>
<tr>
<td>C₃H₈</td>
<td>propane</td>
<td>gas</td>
<td>liquid petroleum gas</td>
</tr>
<tr>
<td>C₄H₁₀</td>
<td>butane</td>
<td>gas</td>
<td>manufacture of synthetic rubber</td>
</tr>
<tr>
<td>C₅H₁₂</td>
<td>pentane</td>
<td>liquid</td>
<td>solvent</td>
</tr>
<tr>
<td>C₆H₁₄</td>
<td>hexane</td>
<td>liquid</td>
<td>filling for thermometers</td>
</tr>
<tr>
<td>C₇H₁₆</td>
<td>heptane</td>
<td>liquid</td>
<td>testing engine knocking</td>
</tr>
<tr>
<td>C₈H₁₈</td>
<td>octane</td>
<td>liquid</td>
<td>automobile petroleum</td>
</tr>
<tr>
<td>C₉H₂₀</td>
<td>nonane</td>
<td>liquid</td>
<td>gasoline</td>
</tr>
<tr>
<td>C₁₀H₂₂</td>
<td>decane</td>
<td>liquid</td>
<td>gasoline</td>
</tr>
<tr>
<td>C₁₁H₃₄</td>
<td>hexadecane</td>
<td>liquid</td>
<td>lubricating oil</td>
</tr>
<tr>
<td>C₁₂H₂₄</td>
<td>dodecane</td>
<td>liquid</td>
<td>wax candles</td>
</tr>
<tr>
<td>C₁₈H₃₈</td>
<td>octacosane</td>
<td>solid</td>
<td>tar</td>
</tr>
</tbody>
</table>

Any series of organic compounds in which each successive member differs by CH₂ from the previous one is called a homologous series. They can be represented by the general formula CₙH₂ₙ₊₂, where n is the number of carbon atoms in the molecule.

\[
\text{CH₄} \quad \text{H} \quad \text{H} \\
\text{H} \quad \text{H} \\
\text{C} \quad \text{H} \\
\text{H} \\
\text{H} \\
\text{methane, CH₄} \\
\text{C₂H₆} \quad \text{H} \quad \text{H} \\
\text{H} \quad \text{H} \\
\text{C} \quad \text{H} \\
\text{H} \\
\text{H} \\
\text{H} \\
\text{ethane, C₂H₆} \\
\text{C₃H₈} \quad \text{H} \quad \text{H} \\
\text{H} \quad \text{H} \\
\text{C} \quad \text{H} \\
\text{H} \\
\text{H} \\
\text{H} \\
\text{propane, C₃H₈} \\
\]

### Sample problem 8.1

Find the molecular formula of an alkane with six carbon atoms.

\[\text{Solution:}\]

\[n = 6\]

\[\text{Number of hydrogen atoms} = 2n + 2 = (2 \times 6) + 2 = 14\]

The formula is therefore C₆H₁₄.

### Revision questions

1. Draw the Lewis structures for ethane and propane.
2. Give the formula for an alkane with 16 carbon atoms.
3. Give the formula for an alkane with 52 hydrogen atoms.
4. Draw the structure of pentane.
Reactions of alkanes

Alkanes burn in oxygen to form carbon dioxide and water. This is known as an oxidation or combustion reaction. For example:

\[ \text{CH}_4(g) + 2\text{O}_2(g) \rightarrow \text{CO}_2(g) + 2\text{H}_2\text{O}(g) \]

Alkanes react with chlorine or fluorine in a reaction called a substitution reaction. In this type of reaction, one or more of the chlorine or fluorine atoms take the place of one or more of the hydrogen atoms. The products of these reactions are known as haloalkanes. For example:

This reaction may continue with a further series of hydrogen substitutions if there is enough chlorine present. As each remaining hydrogen atom is removed from CH₃Cl and replaced by a chlorine atom, a mixture of CH₂Cl₂, CHCl₃ and CCl₄ is formed.

\[ \text{H} \quad \text{UV light} \quad \text{H} \quad \text{HCl} \quad \text{Cl} \]

\[ \text{methane} \quad \text{chloromethane} \]

Revision questions

6. Complete and balance the following equations.
   (a) \( \text{C}_2\text{H}_6(g) + \text{O}_2(g) \rightarrow \)   (b) \( \text{C}_5\text{H}_{12}(g) + \text{O}_2(g) \rightarrow \)

7. Write a structural chemical equation for the substitution reaction between methane and fluorine gas, F₂(g).

8. Write a balanced chemical equation for the combustion of an alkane that has six carbon atoms.

Structural isomers

Isomers are organic molecules with the same molecular formula but different structural formulas. For example, C₄H₁₀ can be drawn in two ways as shown below.

\[ \text{H} \quad \text{C} \quad \text{C} \quad \text{H} \quad \text{H} \quad \text{H} \text{H} \text{H} \text{H} \text{H} \]

\[ \text{butane} \]

\[ \text{H} \quad \text{C} \quad \text{H} \quad \text{H} \quad \text{H} \quad \text{H} \quad \text{H} \quad \text{H} \quad \text{H} \quad \text{H} \quad \text{H} \]

\[ \text{methylpropane} \]

Structural isomers have different names and chemical properties because the molecules have different shapes.
CHAPTER 8

Organic chemistry

Revision questions

9. Use a molecular modelling kit to form a model of butane. Rearrange your model to form methylpropane.
10. Form a model of pentane. How many isomers of C₅H₁₂ can you form?
11. Draw each of the isomers of C₅H₁₂ that you formed in question 10.
12. Suggest a reason why the boiling point of methylpropane (−11.7 °C) is lower than that of butane (−0.5 °C).

The alkenes

The alkenes make up a family of hydrocarbons that each contains one double bond between two carbon atoms.

Notice that each of these names ends with -ene. This is the characteristic ending used for the alkenes.

The alkenes have a general formula CₙH₂ₙ and are another example of a homologous series.

Reactions

Alkenes undergo combustion reactions with oxygen and, like alkanes, form carbon dioxide and water:

\[
\text{C}_2\text{H}_4(\text{g}) + 3\text{O}_2(\text{g}) \rightarrow 2\text{CO}_2(\text{g}) + 2\text{H}_2\text{O}(\text{g})
\]

Alkenes react with hydrogen or the halogens in addition reactions. The hydrogen or halogen attacks the double bond and breaks it. When chlorine is added to ethene in the presence of a catalyst the following reaction takes place:

\[
\text{H}_2\text{C}==\text{C}==\text{H}(\text{g}) + \text{Cl}_2(\text{g}) \rightarrow \text{ catalyst } \rightarrow \text{H}_2\text{C}==\text{C}==\text{H}(\text{g})
\]

Alkenes can undergo self-addition in which the alkene molecules join together to form long chains called polymers. This will be discussed in chapter 9.

Revision questions

Complete the following chemical reactions:

13. (a) \[
\text{H}_2\text{C}==\text{C}==\text{H}(\text{g}) + \text{Br}_2(\text{g}) \rightarrow \text{ catalyst } \rightarrow
\]

(b) \[
\text{H}_2\text{C}==\text{H}==\text{H}(\text{g}) + \text{HCl}(\text{g}) \rightarrow \text{ catalyst } \rightarrow
\]

14. Explain the terms ‘saturated’ and ‘unsaturated’ in relation to hydrocarbons. Give two examples of each.
The alkynes

Alkynes are hydrocarbons containing one triple bond between two carbon atoms.

\[
\begin{align*}
H & \quad \equiv \quad C & \equiv & \quad C & \quad \equiv & \quad H \\
(\text{a) ethyne (also known by its old name, acetylene}) \\
H & \quad \equiv \quad C & \equiv & \quad C & \equiv & \quad H \\
(\text{b) propyne})
\end{align*}
\]

Note that the ending in each case is -yne. This ending shows that there is a triple bond in the molecule.

The general formula for the alkynes is \( C_nH_{2n-2} \). The alkynes are also another example of a homologous series.

Reactions

Alkynes can undergo combustion (oxidation) and addition reactions.

The combustion of ethyne (acetylene) is used in oxyacetylene welding. The extremely high temperature generated when ethyne is burned with pure oxygen can melt metal and allow surfaces to be welded together. Like all hydrocarbons, the products of this reaction are carbon dioxide and water. The equation for the reaction is:

\[
2C_2H_2(g) + 5O_2(g) \rightarrow 4CO_2(g) + 2H_2O(g).
\]

Cyclic hydrocarbons

The carbon backbone of some hydrocarbons can form a ring. Such compounds are known as cyclic hydrocarbons and have the prefix cyclo- before their name.

\[
\begin{align*}
\text{(a) hexane} & \\
\text{(b) cyclohexane}
\end{align*}
\]
An important category of the hydrocarbons is the unsaturated cyclic compounds making up the aromatic series. The simplest member of this series is benzene, $\text{C}_6\text{H}_6$. This molecule has been shown to have two equivalent forms as shown in diagrams (a) and (b) below.

Benzene is found naturally in crude oil but is usually synthesised from other hydrocarbons when used in making pharmaceuticals.

![Four structural representations of benzene](image)

It has been shown experimentally that all carbon–carbon double bonds in benzene are identical and somewhere between single and double bonds in length and bond strength. The equivalence of the bonds is shown by the alternative structure shown in diagram (c). The circle represents the even distribution of the six electrons around the benzene ring. The six electrons are said to be delocalised. Diagram (d) shows a shorthand representation of benzene.

### Revision questions

15. Draw the Lewis structures and structural formulas of ethane and ethyne, and describe their shapes.
16. Give the structural formula for each of the following.
   - (a) propane
   - (b) octane
   - (c) propene
   - (d) propyne
17. What are the products of the complete combustion of propene?
18. Write a balanced chemical equation for the reaction between propene and oxygen.
19. What is the molecular formula of an alkene having 21 carbon atoms?
20. Give the molecular formula of an alkene having 12 carbon atoms.
21. Alkenes are more reactive than alkanes. In terms of chemical bonding, explain why this is the case.
22. Name two reactions that alkenes can undergo.
23. Complete and balance the following combustion reactions.
   - (a) $\text{C}_4\text{H}_8(\text{g}) + \text{O}_2(\text{g}) \rightarrow$
   - (b) $\text{C}_6\text{H}_{12}(\text{g}) + \text{O}_2(\text{g}) \rightarrow$
24. Give a structural equation for the reaction of ethene with fluorine gas.
25. Draw two possible isomers of $\text{C}_4\text{H}_8$.
26. As the molecular size of the alkanes increases, there is a change from the gaseous phase to the solid phase. Explain why this occurs.

### Naming organic substances

Over the years, as organic chemistry grew and more and more compounds were either discovered or synthesised, naming them became more and more of a problem. To solve this problem, the International Union of Pure and Applied Chemistry (IUPAC) developed a set of rules by which any organic substance could be named depending on the structure of its molecules. This system has widespread use today, although many common substances still retain their ‘old’ or ‘trivial’ names in everyday use. For example, ethyne, mentioned earlier in this chapter, is still called acetylene in everyday use.
Rules for naming hydrocarbons

There are a number of rules for naming hydrocarbons.
- **Rule 1:** Determine the longest chain of carbon atoms.
- **Rule 2:** Determine which end is nearest to a branch, a double bond or a triple bond. (A double or triple bond takes precedence over a branch if they are equidistant from either end of the chain.)
- **Rule 3:** Number the carbon atoms from the end chosen.
- **Rule 4:** Name any branches first with the ending -yl (for example, methane becomes methyl and ethane becomes ethyl), then the longest chain, then any single or double bond.
- **Rule 5:** When two or more branches occur on the same carbon atom, the number of the carbon atom is indicated for each branch, with the names given in alphabetical order (ignoring the prefixes described in rule 6).
- **Rule 6:** When two or more identical branches occur on different carbon atoms, the prefixes di-, tri- and tetra- are used.

Avoid the following common errors when naming hydrocarbons:
- not identifying the longest chain possible
- not listing the side branches in alphabetical order
- omitting the prefixes di-, tri- and tetra- when they are required.

Sample problem 8.2

Name the following compound using rules 1 to 4 above.

Solution:

**STEP 1**
The longest chain has seven carbon atoms, so the hept name is given.

**STEP 2**
The double bond is nearest the left-hand end.

**STEP 3**
Number from the left-hand end.

**STEP 4**
The branch on carbon atom number 5 contains one carbon atom, so it is given the name 5-methyl. There is a double bond on carbon atom number 2 and this is represented by 2-ene.
So, the hydrocarbon is called 5-methylhept-2-ene.

Sample problem 8.3

Name the following compound using rules 1 to 5 above.

Solution:

**STEP 1**
The longest chain has eight carbon atoms, so the oct name is given.

**STEP 2**
The double bond is nearest the right-hand end.
STEP 3
Number from the right-hand end.

STEP 4
The upper branch on carbon atom number 4 contains one carbon atom, so it is given the name 4-methyl. The lower branch contains two carbon atoms, so it is named 4-ethyl. The double bond on carbon atom number 2 is represented as 2-ene.

STEP 5
The two branches on carbon atom number 4 both have the number indicated and are written alphabetically as 4-ethyl-4-methyl. So the hydrocarbon is called 4-ethyl-4-methylpent-2-ene.

Sample problem 8.4
Name the following compound.

Solution:
1. The longest chain has four carbon atoms so the name but- is given.
2. There are methyl groups on carbon atoms number 2 and 3. Two of them occur on carbon atom number 2 and one on carbon atom number 3.
3. Number from the left-hand end.
4. Give the number of the carbon atom each time the methyl group occurs on that carbon atom.
5. Use the prefix tri- to indicate the total number of methyl groups.
So, the hydrocarbon is called 2,2,3-trimethylbutane.

Revision questions
27. Write structural formulas for:
(a) hex-2-ene
(b) methylpropene
(c) pent-2-yne.
28. Name each of the following.

29. Draw structural formulas for:
(a) 4-methylpent-2-ene
(b) 2,4-dimethylhexane (one of the components of unleaded fuel).
The condensed formula is a way of representing the structural formula of an organic compound in a single line.

**Condensed formulas**

Hydrocarbons can be represented by condensed formulas. Another name for condensed formulas is semi-structural formulas. Ethane, C₂H₆, can be represented by the condensed formula CH₃CH₃. The condensed formula of propane, C₃H₈, is CH₃CH₂CH₃. When abbreviating a structural formula to its condensed formula equivalent, go ‘carbon by carbon’.

Brackets are used:

(a) to indicate side chains, which are written after the carbon to which they are attached — for example

\[
\begin{array}{c}
\text{CH}_3 \\
\text{CH}_2 \\
\text{CH}
\end{array}
\]

3-methylpentane

\[
\begin{array}{c}
\text{CH}_3 \\
\text{CH}_2 \text{CH} \\
\text{CH} \\
\text{CH} \\
\text{CH}
\end{array}
\]

(b) if there are repeating CH₂ groups — for example:

\[
\begin{array}{c}
\text{H} \\
\text{H} \\
\text{C} \\
\text{C} \\
\text{C} \\
\text{C} \\
\text{H} \\
\text{H} \\
\text{H} \\
\text{H} \\
\text{H}
\end{array}
\]

pentane

\[
\begin{array}{c}
\text{H} \\
\text{H} \\
\text{C} \\
\text{C} \\
\text{C} \\
\text{C} \\
\text{C} \\
\text{H} \\
\text{H} \\
\text{H} \\
\text{H} \\
\text{H}
\end{array}
\]

Condensed formula

30. Write the condensed formula for each of the compound(s) in the previous revision questions: Q27, Q28 and Q29.

31. The condensed formula for methylpropane is CH₃CH(CH₃)₂ and that of 2,3-dimethylhexane. Write a condensed formula for 2,3-dimethylhexane.

**Functional groups**

The bond, atom, or group of atoms that give a molecule its specific properties is called its functional group. For example, the functional group of the alkenes is C=C; the functional group of the alcohols is —OH. The oxygen–hydrogen bond in alcohols and carboxylic acids gives them significantly different properties from those of hydrocarbons.

**Alcohols**

Alcohols are carbon chains containing one or more —OH groups. The —OH group is called the ‘hydroxy’ group. Names of alcohols have the ending -ol.
Hydrogen bonding in alcohols affects boiling point and solubility in water.

There are two isomers of C₃H₈O. Both have the same molecular formula but their structural formulas are different. Their condensed formulas are CH₃CH₂CH₂OH (propan-1-ol) and CH₃CH(OH)CH₂ (propan-2-ol).

Properties of alcohols

In the smaller alcohols, the hydrogen bonding between the alcohol molecules is stronger than the dispersion forces between hydrocarbon molecules in alkanes, alkenes and alkynes. This results in higher boiling points than the corresponding alkane or alkene. More energy is needed to separate methanol molecules than methane molecules.

In addition, the boiling points of alcohols increase with size because the non-polar portion of the molecule increases; this diminishes the effect of hydrogen bonding but increases the influence of the dispersion forces.

Smaller alcohols are soluble in water; hydrogen bonds form between the water molecules and the alcohol molecules. Solubility decreases with increasing size due to the increasing non-polar section of the alcohol molecules.

Reactions

Alcohols also undergo combustion reactions in air. They can be used as fuels, so research is currently being done on so-called ‘alcohol blends’ . These involve adding alcohols (usually ethanol) to petrol to reduce our dependence on fossil fuels. Research is also being done on the viability of pure alcohols as transport fuels. A typical example of this combustion process is the burning of ethanol to produce carbon dioxide and water.

\[ CH₃CH₂OH(l) + 3O₂(g) \rightarrow 2CO₂(g) + 3H₂O(g) \]

Naming of alcohols

The functional group is —OH. The number of the carbon atom to which the —OH has bonded should be given.

(a) propan-1-ol

(b) propan-2-ol

Structural formulas for two different isomers of this alcohol

Revision questions

32. Write molecular, structural and condensed formulas for butan-1-ol.
33. Write the molecular, structural and condensed formulas for butan-2-ol.

Carboxylic acids

Carboxylic acids are another example of a homologous series. These compounds contain the functional group —COOH at the end of a chain. The —COOH group is called the carboxy group. When naming a carboxylic acid,
add the ending -oic acid to the alkyl prefix. Remember to count the carbon atom in the —COOH group. For example, methane becomes methanoic acid.

**Properties of carboxylic acids**

These acids have typical acid properties. They are classed as weak acids, but concentrated ethanoic acid has a very strong pungent odour. When acting as an acid, the proton that is donated is the one that is attached to the oxygen atom in the —COOH group. The hydrogen bonding due to the —OH in the carboxy group is the reason for the relatively high boiling points and solubility of the smaller carboxylic acids; this is consistent with the alcohols.

![Structural formulas for two carboxylic acids](image)

(a) ethanoic acid (acetic acid)  
(b) butanoic acid

**TABLE 8.2 Sources and uses of some common organic acids**

<table>
<thead>
<tr>
<th>Name</th>
<th>Sources and uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>methanoic acid (formic acid)</td>
<td>responsible for sensation caused by nettle, bee and ant stings; used in medicine, food preservation and textile industry</td>
</tr>
<tr>
<td>ethanoic acid (acetic acid)</td>
<td>main component of vinegar; used as a solvent; salts of the acid used in insecticides and fungicides</td>
</tr>
<tr>
<td>propanoic acid (propionic acid)</td>
<td>used as an antifungal agent in the baking industry and in ointments (either in salt or acid form)</td>
</tr>
<tr>
<td>butanoic acid (butyric acid)</td>
<td>odour-causing component of rancid butter, rotten socks and body odour</td>
</tr>
<tr>
<td>2-hydroxybenzoic acid (salicylic acid)</td>
<td>used as a food preservative</td>
</tr>
<tr>
<td>2-acetoxybenzoic acid (acetylsalicylic acid, aspirin)</td>
<td>used for relief of fever, pain and rheumatic conditions</td>
</tr>
</tbody>
</table>

*Note: Common names are given in brackets.*
34. **Draw the Lewis structure and structural and condensed formulas for** methanoic acid.

35. **Write molecular, structural and condensed formulas for:**
   (a) ethanoic acid
   (b) propanoic acid
   (c) butanoic acid.

36. **Explain why the carboxylic acid series can be described as a homologous series. Provide names of members of the series and structural formulas to support your explanation.**

**Reactions**

The carboxylic acids react with alcohols to form esters. Esters are a group of compounds that give the pleasant ‘fruity’ smell to various fruits. This is called a condensation or esterification reaction. Concentrated sulfuric acid is used to link the alcohol and carboxylic acid together by removing a water molecule.

\[
\text{carboxylic acid} + \text{alcohol} \xrightarrow{\text{H}_2\text{SO}_4} \text{ester} + \text{water}
\]

\[
\text{CH}_3\text{COOH}(1) + \text{CH}_3\text{OH}(1) \xrightarrow{\text{H}_2\text{SO}_4} \text{CH}_3\text{COOCH}_3(1) + \text{H}_2\text{O}(1)
\]

ethanoic acid + methanol \xrightarrow{\text{H}_2\text{SO}_4} methyl ethanoate + water

Esters have relatively low boiling points because the intermolecular attraction is dipole-dipole (and dispersion forces) instead of the hydrogen bonding that occurs in carboxylic acids.

**Naming an ester**

When naming an ester, the alcohol (alkyl) name is given first, followed by the acid part. For example, the alcohol methanol becomes methyl. The -oic ending of the acid is replaced with -oate. (The carboxylic acid called ethanoic acid becomes ethanoate.) So, methanol reacting with ethanoic acid forms the ester methyl ethanoate.

**Sample problem 8.5**

Name and draw the expanded structural formula of the ester formed when ethanol reacts with propanoic acid.
Revision questions

37. Name the ester formed from ethanol and ethanoic acid.
38. Give the expanded structural formula of ethyl pentanoate.
39. What is the role of concentrated sulfuric acid in the formation of an ester?
40. What is the functional group in the carboxylic acids?
41. Give an expanded structural formula for pentanoic acid.
42. Which of the carboxylic acids would you be most likely to eat? Explain.

Where do hydrocarbons come from?

Hydrocarbons are found in crude oil, and processing the oil yields many useful products. The hydrocarbons described so far in this chapter are largely synthesised or produced from fossil fuels. Fossil fuels also form the major part of our fuel resources. As the name suggests, they are derived from the fossil remains of living organisms, which have been altered by heat and pressure.

Petroleum

Petroleum is also known as crude oil. The word ‘petroleum’ is derived from two Latin words, petro meaning ‘rock’ and oleum meaning ‘oil’. So it is literally ‘rockoil’. It was given this name because it was originally found seeping through rocks to the Earth’s surface. Petroleum takes many thousands of years to form. In ancient times, warm seas covered much of the area that is now land. These areas contained plant and animal life that died, fell to the sea floor and became covered with sediment. Increased pressure and temperature over a long period of time caused these substances to change into petroleum. Later, movements of the Earth’s crust pushed these deposits closer to the surface and trapped pockets of natural gas, crude oil and salt water.

Refining crude oil

Many mixtures of liquids, including crude oil, may be separated into its components, called fractions, using the process known as fractional distillation. This process is used to separate one liquid from a mixture of liquids with different boiling temperatures. In industry, this process is used on a large scale to separate crude oil into a number of fractions based on boiling temperatures. This is the first stage of refining. It represents a ‘rough sorting out’ of the thousands of different compounds that are in the crude oil.

In this process, hot crude oil (which is essentially a very complicated mixture of alkanes) enters the base of the fractionating tower and almost all of it is immediately vaporised. The small portion that remains liquid (due to the high boiling temperature caused by its large molecules) is removed from the base to make products such as bitumen for roads. As the vapours rise up the tower, they cool and re-liquefy at different heights depending on their boiling (or condensation) temperatures. The lighter fractions have the smallest molecules and, therefore, the lowest condensation temperatures; they are collected near the top of the tower. Moving down the tower, the fractions collected become ‘heavier’; that is, they contain larger and larger molecules. Special arrangements inside the tower called bubble caps let vapours rise while allowing any condensed liquids to be collected on special trays.
Chapter 8: Organic chemistry

Fractional distillation of crude oil

Summary screen and practice questions

A fractionating tower showing oil products and their uses

- Crude oil
- Heater
- Cracking
- Reforming
- Lube oil plant
- Fuel for ships, factories and central heating
- Wax candles
- Chemicals
- Ointments
- Polishes
- Roads
- Roofing
- Waterproofing

Temperatures:
- 20 °C
- 70 °C
- 140 °C
- 190 °C
- 270 °C
- 320 °C
- >350 °C

Products:
- Bottled gas
- Petrol for cars
- Diesel fuels and heating oil
- Kerosene for lighting and heating homes
- Lubricating oils
- Chemicals
Distillation is used to separate the complicated crude oil mixture into fractions. These fractions contain molecules of roughly equal size that therefore have similar boiling temperatures.

Cracking converts larger and less useful alkane molecules into smaller, more useful ones. Small alkene molecules are usually formed at the same time. Cracking may be done either at high temperatures (thermal cracking) or at lower temperatures in the presence of a catalyst (catalytic cracking).

In order to obtain more diesel and other smaller molecules, a process has been developed whereby some of the excess larger hydrocarbons are broken into smaller ones — the ones that, generally speaking, are more useful. This process is called ‘cracking’. There are two main ways that this can be done. The first uses high temperatures and is termed thermal cracking. The second uses a catalyst at much lower temperatures to produce the same effect. This is called catalytic cracking. Both methods have their own advantages and disadvantages, and both are used at a number of locations around Australia.

A number of different fractions can be obtained from crude oil. Unfortunately, demand does not equal the output of the various fractions.

### Revision questions

43. What property of the lighter fractions of crude oil makes them burn more easily than the heavier ones?
44. Viscosity refers to how well a liquid flows; honey is described as a viscous liquid. Why do you think the fractions that are recovered later in the fractional distillation process have increasing viscosity?
45. Explain why the fractions with the fewest carbon atoms in their molecules rise to the greatest height in the fractionating tower. Use table 8.3.

### Cracking

We need far more diesel fuel than the amount obtained from the fractional distillation of Australian crude oil. This process also produces far more kerosene than we need.

#### Table 8.3 Products from the fractional distillation of crude oil

<table>
<thead>
<tr>
<th>Product</th>
<th>Number of carbon atoms</th>
<th>Boiling point (°C)</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>gas</td>
<td>1–4</td>
<td>&lt;40</td>
<td>bottled gas, plastics, chemicals</td>
</tr>
<tr>
<td>petrol</td>
<td>4–12</td>
<td>40–75</td>
<td>fuel for vehicles, chemicals</td>
</tr>
<tr>
<td>kerosene</td>
<td>9–16</td>
<td>150–240</td>
<td>jet fuel, chemicals</td>
</tr>
<tr>
<td>diesel oil</td>
<td>15–25</td>
<td>220–250</td>
<td>fuel</td>
</tr>
<tr>
<td>lubrication oil</td>
<td>20–70</td>
<td>250–350</td>
<td>lubricants, waxes</td>
</tr>
<tr>
<td>bitumen residue</td>
<td>&gt;70</td>
<td>&gt;350</td>
<td>road surfaces</td>
</tr>
</tbody>
</table>

#### Bar graph

A bar graph showing the composition of Australian crude oil and the amount used in Australia.

- **Product**: petrol, kerosene, diesel, residue
- **Percentage**: 0 to 70
- **Legend**:
  - Composition of Australian crude oil
  - Amount used in Australia

<table>
<thead>
<tr>
<th>Product</th>
<th>Composition</th>
<th>Amount used in Australia</th>
</tr>
</thead>
<tbody>
<tr>
<td>petrol</td>
<td>40%</td>
<td>30%</td>
</tr>
<tr>
<td>kerosene</td>
<td>30%</td>
<td>25%</td>
</tr>
<tr>
<td>diesel</td>
<td>20%</td>
<td>15%</td>
</tr>
<tr>
<td>residue</td>
<td>10%</td>
<td>10%</td>
</tr>
</tbody>
</table>
An example of cracking is the breakdown of decane (a large hydrocarbon) into octane (used in motor fuel) and ethene (used for the manufacture of plastic).

\[ \text{C}_{10}\text{H}_{22}(g) \xrightarrow{\text{catalyst}} \text{C}_{8}\text{H}_{18}(g) + \text{C}_2\text{H}_4(g) \]

This is just one possible way in which decane could crack. It could also crack at other points to produce different molecules.

**Revision questions**

46. Write a chemical equation to show one way in which dodecane, \( \text{C}_{12}\text{H}_{26} \), could crack when subjected to catalytic cracking. Compare your answers with others in the class. Who is correct?

47. One kind of catalyst used in catalytic cracking is made of silicon. What is the role of the catalyst in catalytic cracking?

48. Give two advantages of using a catalyst when cracking large hydrocarbons.
Summary

- Organic chemistry is the study of the compounds of carbon. The oxides of carbon, carbonates, carbides and cyanides, as well as compounds of the remaining elements, are considered to be inorganic substances.
- Carbon in organic compounds always forms four covalent bonds.
- Hydrocarbons are organic compounds made up of only carbon and hydrogen atoms. Dispersion forces are involved in intermolecular bonding in hydrocarbons. This means that boiling temperatures are low. Hydrocarbon molecules are non-polar so they are insoluble in water.
- Saturated hydrocarbons contain only single bonds; unsaturated hydrocarbons contain double or triple bonds.
- Alkanes are hydrocarbons containing only single bonds between carbon atoms. Alkanes can undergo oxidation (combustion) and substitution reactions. They burn in oxygen to give off carbon dioxide and water.
- Haloalkanes contain one or more halogen atoms.
- Alkenes are hydrocarbons containing one double bond between two carbon atoms. Alkenes can undergo combustion, addition and polymerisation reactions. These reactions involve, respectively, reacting with oxygen to form carbon dioxide and water; reacting with hydrogen (or the halogens) so that the double bond between the two carbon atoms is broken; and forming long chains called polymers as a result of alkene molecules joining together.
- Alkynes are hydrocarbons containing one triple bond between two carbon atoms. Alkynes can undergo combustion and addition reactions.
- In a homologous series, successive members differ by a \(-\text{CH}_2\)- group.
- Isomers of a compound have the same molecular formula but different structural formulas.
- A functional group is the bond, atom or group of atoms that gives a group of molecules its specific properties.
- Alcohols contain one or more hydroxy \((-\text{OH})\) groups. Due to the presence of hydrogen bonding, alcohols have a higher boiling temperature than the corresponding alkane. Smaller alcohols are soluble in water.
- Carboxylic acids contain a carboxy \((-\text{COOH})\) group at the end of a chain. Due to the presence of hydrogen bonding, carboxylic acids have a higher boiling temperature than the corresponding alkane. Smaller carboxylic acids are soluble in water.
- Esters form when alcohols react with carboxylic acids. Esters are named by changing the name of the alcohol to the alkyl form and replacing the ending of the name of the carboxylic acid with \(-\text{oate}\). For example, the ester formed from propanol and ethanoic acid is propyl ethanoate.
- The three main groups of fossil fuels are natural gas, petroleum and coal.
- Hydrocarbons are obtained from petroleum (crude oil).
- Petroleum is separated using fractional distillation. Fractional distillation separates components according to boiling points. In a fractionating tower, components with lower boiling points are drawn up closer to the top.
- Catalytic and thermal cracking are used to increase the number of industrially important smaller molecules produced from the fractional distillation of crude oil.

Multiple choice questions

1. The structure that is not an isomer of \(\text{C}_8\text{H}_{18}\) is:

   - \(\text{A}\)
   - \(\text{B}\)
   - \(\text{C}\)
   - \(\text{D}\)
2. Which of the following is not the formula of an alkane?
   A  C₄H₁₀  C  C₁₁H₂₂
   B  C₇H₁₆  D  C₁₄H₃₀

3. The process of changing large hydrocarbon molecules into smaller hydrocarbon molecules is called:
   A  distillation  C  cracking
   B  polymerisation  D  esterification.

4. The bonds between carbon atoms in benzene are:
   A  single bonds
   B  double bonds
   C  alternate double and single bonds
   D  intermediate between double and single bonds.

5. Which of the following statements does not represent a basis for the existence of a large number of carbon compounds?
   A  A single carbon atom can form up to four covalent bonds.
   B  Carbon can link to a number of other elements by strong bonds.
   C  Carbon forms a great variety of chains and rings.
   D  Carbon exists in a number of structural forms in the solid state.

6. Which of the following statements best describes a saturated compound?
   A  A saturated compound, when used as a solvent, does not dissolve any more solute at a particular temperature.
   B  A saturated compound contains carbon and hydrogen atoms only.
   C  A saturated compound has only single carbon-carbon bonds.
   D  A saturated compound does not react with chlorine.

7. Which one or more of the following compounds is saturated?
   A  H₂C = CH₂
   B  HC = C
   C  
   D  CH₃CH₂CH₃

8. Which of the following could not be an alkane?
   A  C₃H₈
   B  C₄H₁₀
   C  CH₃CH₂CH₂CH₂CH₃
   D  C₆H₁₄

9. An alkyl group is:
   A  a strongly basic group in an organic molecule
   B  a group of organic compounds related to the alkanes

10. Which one or more of the following statements is not correct? A functional group:
    A  remains unchanged in most chemical reactions
    B  is common to all members of the particular homologous series
    C  may be regarded as being responsible for a characteristic set of chemical reactions for a given homologous series
    D  varies from member to member by —CH₂.

11. An organic compound has the formula:

    CH₃—CH₂—CH—CH—CH₃
    \[ \text{CH₃ — CH₂ — CH₂ — CH₃} \]

The name of the compound above is:
   A  2-ethyl-3-methylpentane
   B  octane
   C  3,4-dimethylhexane
   D  3-methyl-4-ethylpentane.

12. The group in which all the compounds are members of the same homologous series is:
    A  CH₄; C₂H₄; C₃H₈
    B  CH₃OH; CH₃CH₂OH; CH₃CH₂CH₂OH
    C  CH₄; CH₃OH; HCOOH
    D  CH₃OCH₃; CH₃CH₂OH; C₂H₅OH.

13. 2-methyl-2-butanol is an isomer of:
    A  butan-2-ol
    B  pentanoic acid
    C  pentan-1-ol
    D  2,3-dimethyl-butan-2-ol.

14. An organic compound has the formula:

    H — C ≡ C — CH — CH₂ — CH₂ — CH₃
    \[ \text{CH₃ — CH₂ — CH₂ — CH₃} \]

The name of this compound is:
   A  3-methyl-4-ethylhept-1-yn e
   B  decyne
   C  4-ethyl-3-methylhept-1-ene
   D  3-methyl-4-propylhex-1-ene.

15. The formula of a compound is:

    CH₃
    \[ \text{CH₃ — C — CCl₃} \]
    \[ \text{CH₃} \]

The name of this compound is:
   A  trichloroisopentane
   B  2,2-dimethyl-3,3,3-trichloropropene
   C  1,1,1-trichloro-2,2,2-trimethylpropane
   D  1,1,1-trichloro-2,2-dimethylpropane.
16. The alkane in the following group with the highest boiling point is:
A methane  C propane 
B ethane  D butane.

17. The organic compound in the following group with the highest boiling point is:
A acetylene (ethyne) 
B ethane 
C 1,1,1-trichloroethane 
D ethan-2-ol.

18. When the ring on the Bunsen burner is closed during combustion, soot forms. Soot is:
A carbon  C carbon dioxide 
B carbon monoxide  D unburnt propane.

Review questions

Hydrocarbons

1. (a) What is meant by the term ‘hydrocarbon’?
(b) Give the names and formulas of three hydrocarbons each containing three carbon atoms.

2. (a) Alkanes and alkenes are examples of hydrocarbons. In what way do they differ? Give an example of each.
(b) Write an equation for the oxidation of the second member of the alkene series and the third member of the alkane series.

3. (a) How are alkanes ‘produced’?
(b) What are the major uses of alkanes?

4. (a) How are alkenes ‘produced’?
(b) What are their uses?

5. Define the term ‘isomer’. Illustrate your answer with the isomers of pentane and butene.

6. (a) Distinguish between saturated and unsaturated hydrocarbons.
(b) Which is more reactive?

7. Write a formula for each of the following:
(a) an alkane with 22 carbon atoms
(b) an alkene with 17 carbon atoms
(c) an alkyne with 13 carbon atoms.

8. Name the following organic compounds.
(Note: The longest continuous chain may not be written in a straight line.)
(a) CH₃—CH₂—CH—CH₃
(b) CH₂—CH—CH₂—CH₃
(c) CH₃—CH₂—CH—CH₂—CH₃
(d) CH₃—CH₂—C—CH₃
(e) CH₃—CH₂—CH—CH₂—CH—CH₃
(f) CH₃—CH₂—C—CH₂—C—CH₃

9. Draw structural formulas for the following compounds.
(a) 3,3-dimethylpentane
(b) 3-ethylhexane
(c) 2,2,4-trimethylpentane
(d) 2,3-dimethylhexane
(e) 3-ethylheptane
(f) 3-ethyl-2,4-dimethyloctane

10. Draw structural formulas for:
(a) 2-methylheptane
(b) 2,3-dimethylbut-2-ene
(c) pent-2-yne
(d) 2,6-dimethylhept-3-ene
(e) oct-3-ene
(f) 3-methyl-4-ethylhex-2-ene
(g) 3,4-diethyl-3-methylhexane
(h) 3-ethyl-4,5-dipropylheptane.

11. Name each of the following.
(a) [Structural formula example]
(b) [Structural formula example]
(c) [Structural formula example]
12. Peter isolated the following compound and named it 2-ethyl-2,4-dimethylhexane. Sally said that the compound was incorrectly named. Explain why Sally is right and give the correct name for the compound.

\[
\begin{align*}
\text{(d)} & \quad \text{CH}_3 - \text{CH} = \text{C} - \text{CH}_2 - \text{CH}_2 - \text{C} - \text{CH}_3 \\
\text{(e)} & \quad \text{CH}_3 - \text{CH} - \text{CH} - \text{CH} - \text{CH}_3 \\
\text{(f)} & \quad \text{CH}_5 - \text{CH} - \text{CH} - \text{CH}_2 - \text{CH}_3
\end{align*}
\]

Functional groups

13. The alkanols form a homologous series. What does this mean?

14. Briefly explain the meanings of the following terms. Use examples in your answers.
   (a) Substitution reactions
   (b) Addition reactions
   (c) Functional group
   (d) Fractional distillation
   (e) Catalytic cracking

15. Draw structural formulas for the following compounds:
   (a) the paint remover dichloromethane
   (b) the water repellent used in Scotchgard, 1,1,1-trichloroethane.

16. Use a labelled diagram of a methanol molecule and a water molecule to explain why methanol is soluble in water.

17. (a) Draw the Lewis structures and structural and condensed formulas of ethane and ethanoic acid.
   (b) Outline the similarities and differences between these two compounds.

18. Volatile compounds readily vaporise.
   (a) Explain why esters are volatile compounds.
   (b) Would you expect esters to be soluble? Explain your answer.

19. Consider the following reaction:
    \[\text{CH}_3\text{COOH} + \text{CH}_3\text{CH}_2\text{OH} \rightarrow \text{CH}_3\text{COOCH}_2\text{CH}_3 + \text{H}_2\text{O}\]
    (i) Draw the structural formulas represented by the equation above, and name the compounds (i) to (iv).
    (b) What type of reaction is this?
    (c) If four bottles contained, respectively, pure samples of (i), (ii), (iii) and (iv), how might you identify them?

20. Name the esters formed from the following reactions.
    (a) methanol and butanoic acid
    (b) 1-propanol and propanoic acid
    (c) ethanol and methanoic acid

21. Write formulas for the following esters.
    (a) ethyl butanoate
    (b) propyl ethanoate
    (c) butyl propanoate

22. A molecular compound contains four carbon atoms. Write a condensed formula for the compound if it is:
    (a) an alkene
    (b) an alcohol
    (c) a carboxylic acid
    (d) an ester.

Calculations in organic chemistry

Refer to chapter 5 to answer questions 23–27.

23. Find the percentage of carbon in:
    (a) ethane
    (b) ethene
    (c) ethyne.


25. A 5.00 g sample of a hydrocarbon contains 0.908 g of hydrogen. Its molar mass is 44.0 g mol\(^{-1}\).
    (a) Find its empirical formula.
    (b) Draw its structure.
    (c) State the homologous series to which it belongs.

26. An ester that is used in making nail polish remover is manufactured using ethanol. It has the following composition: 54.5% C, 9.15% H and 36.3% O. Its molar mass is 88.0 g mol\(^{-1}\). Calculate the empirical formula and molecular formula of the ester and draw its structure.

27. An alcohol containing only the elements C, H and O was shown by analysis to contain 60.0% carbon and 13.3% hydrogen. Its molar mass is 60.0 g mol\(^{-1}\). Identify the alcohol and draw possible structures.
Exam practice questions

In a chemistry examination you will be required to answer a number of short and extended response questions.

Multiple choice questions

1. An organic compound has the formula: \( \text{CH}_3\text{CH} = \text{CH} = \text{CH} = \text{CH} = \text{CH}_2\text{CH}_3 \)
   The name of this compound is:
   A 3-methyl-4-butyloctanoic acid
   B 4-propyl-5-methyloctanoic acid
   C 5-propyl-6-methyloctanoic acid
   D 3-methyl-4-propyloctanoic acid.  
   1 mark

2. The boiling points of the homologous series of alkanes:
   A decrease with increase in molecular size
   B decrease with decrease in molecular mass
   C are all approximately the same
   D are all significantly higher than the corresponding alkenes containing the same number of carbon atoms. 
   1 mark

Extended response questions

3. In terms of bonding, explain why heavier hydrocarbons such as diesel oil (those with a high number of carbon atoms) have higher boiling temperatures than lighter hydrocarbons such as propane (those with fewer carbon atoms).  
   2 marks

4. If a mixture of lubricating oil, diesel oil, petrol, paraffin and kerosene were placed in a fractional distillation apparatus:
   (a) which fraction would be collected first
   (b) which would have the lowest boiling temperature
   (c) which would have the highest boiling temperature
   (d) what could be done if the fractions collected were found to still be mixtures? 
   4 marks