# UNIT 1: STRUCTURE, BONDING AND INTRODUCTION TO ORGANIC CHEMISTRY

## TOPIC 1
**FORMULAE, EQUATIONS AND AMOUNTS OF SUBSTANCE**

1. **A** ATOMS, ELEMENTS AND MOLECULES
   - 1. WRITING CHEMICAL EQUATIONS
   - 2. TYPICAL REACTIONS OF ACIDS
   - 3. DISPLACEMENT REACTIONS
   - 4. PRECIPITATION REACTIONS

2. **B** EQUATIONS AND REACTION TYPES
   - 1. WRITING CHEMICAL EQUATIONS
   - 2. TYPICAL REACTIONS OF ACIDS
   - 3. DISPLACEMENT REACTIONS
   - 4. PRECIPITATION REACTIONS

3. **C** ENERGY
   - 1. COMPARING MASSES OF SUBSTANCES
   - 2. CALCULATIONS INVOLVING MOLES
   - 3. CALCULATIONS USING REACTING MASSES
   - 4. THE YIELD OF A REACTION
   - 5. ATOM ECONOMY

4. **D** EMPIRICAL AND MOLECULAR FORMULAE
   - 1. EMPIRICAL FORMULAE
   - 2. MOLECULAR FORMULAE

5. **E** CALCULATIONS WITH SOLUTIONS AND GASES
   - 1. MOLAR VOLUME CALCULATIONS
   - 2. CONCENTRATIONS OF SOLUTIONS
   - 3. CONCENTRATIONS IN PPM
   - 4. THE YIELD OF A REACTION
   - 5. ATOM ECONOMY

## TOPIC 2
**ATOMIC STRUCTURE AND THE PERIODIC TABLE**

1. **A** ATOMIC STRUCTURE
   - 1. STRUCTURE OF THE ATOM AND ISOTOPES
   - 2. MASS SPECTROMETRY AND RELATIVE MASSES OF ATOMS, ISOTOPES AND MOLECULES
   - 3. ATOMIC ORBITALS AND ELECTRONIC CONFIGURATIONS
   - 4. IONISATION ENERGIES

2. **B** THE PERIODIC TABLE
   - 1. PERIODIC TABLE
   - 2. PERIODICITY
   - 3. THINKING BIGGER
   - 4. EXAM PRACTICE

## TOPIC 3
**BONDING AND STRUCTURE**

1. **A** IONIC BONDING
   - 1. THE NATURE OF IONIC BONDING
   - 2. IONIC RADII AND POLARISATION OF IONS
   - 3. PHYSICAL PROPERTIES OF IONIC COMPOUNDS

2. **B** COVALENT BONDING
   - 1. THE COVALENT BOND
   - 2. ELECTRONEGATIVITY AND BOND POLARITY
   - 3. BONDING IN DISCRETE (SIMPLE) MOLECULES
   - 4. DATIVE COVALENT BONDS

3. **C** SHAPES OF MOLECULES AND IONS
   - 1. ELECTRON PAIR REPULSION THEORY
   - 2. NON-POLAR AND POLAR MOLECULES
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3.D Metallic Bonding</td>
<td>XXX</td>
<td>1 Alkanes from Crude Oil</td>
</tr>
<tr>
<td>3.E Solid Lattices</td>
<td>XXX</td>
<td>2 Alkanes as Fuels</td>
</tr>
<tr>
<td>1 Introduction to Solid Lattices</td>
<td>XXX</td>
<td>3 Alternative Fuels</td>
</tr>
<tr>
<td>2 Structure and Properties</td>
<td>XXX</td>
<td>4 Substitution Reactions of Alkanes</td>
</tr>
<tr>
<td>Thinking Bigger</td>
<td>XXX</td>
<td>Thinking Bigger</td>
</tr>
<tr>
<td>Exam Practice</td>
<td>XXX</td>
<td>Exam Practice</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Topic 5</th>
<th>Alkanes</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.A Alkenes</td>
<td>XXX</td>
</tr>
<tr>
<td>1 Alkenes and Their Bonding</td>
<td>XXX</td>
</tr>
<tr>
<td>2 Geometric Isomerism</td>
<td>XXX</td>
</tr>
<tr>
<td>3 Addition Reactions of Alkenes</td>
<td>XXX</td>
</tr>
<tr>
<td>4 The Mechanisms of Addition Reactions</td>
<td>XXX</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>5.B Addition Polymers</th>
<th>XXX</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Polymerisation Reactions</td>
<td>XXX</td>
</tr>
<tr>
<td>2 Dealing with Polymer Waste</td>
<td>XXX</td>
</tr>
<tr>
<td>Thinking Bigger</td>
<td>XXX</td>
</tr>
<tr>
<td>Exam Practice</td>
<td>XXX</td>
</tr>
<tr>
<td>UNIT 2: ENERGETICS, GROUP CHEMISTRY, HALOGENOALKANES AND ALCOHOLS</td>
<td>THINKING BIGGER XXX</td>
</tr>
<tr>
<td></td>
<td>EXAM PRACTICE XXX</td>
</tr>
<tr>
<td></td>
<td>8.B THE ELEMENTS OF GROUPS 1 AND 2 XXX</td>
</tr>
<tr>
<td></td>
<td>1 TRENDS IN GROUPS 1 AND 2 XXX</td>
</tr>
<tr>
<td></td>
<td>2 REACTIONS OF GROUP 1 ELEMENTS XXX</td>
</tr>
<tr>
<td></td>
<td>3 REACTIONS OF GROUP 2 ELEMENTS XXX</td>
</tr>
<tr>
<td></td>
<td>4 OXIDES AND HYDROXIDES IN GROUPS 1 AND 2 XXX</td>
</tr>
<tr>
<td></td>
<td>5 THERMAL STABILITY OF COMPOUNDS IN GROUPS 1 AND 2 XXX</td>
</tr>
<tr>
<td></td>
<td>6 FLAME TESTS AND THE TEST FOR AMMONIUM IONS XXX</td>
</tr>
<tr>
<td>TOPIC 6 ENERGETICS XXX</td>
<td></td>
</tr>
<tr>
<td>6.A INTRODUCING ENTHALPY AND ENTHALPY CHANGE XXX</td>
<td></td>
</tr>
<tr>
<td>6.B ENTHALPY LEVEL DIAGRAMS XXX</td>
<td></td>
</tr>
<tr>
<td>6.C STANDARD ENTHALPY CHANGE OF COMBUSTION XXX</td>
<td></td>
</tr>
<tr>
<td>6.D STANDARD ENTHALPY CHANGE OF NEUTRALISATION XXX</td>
<td></td>
</tr>
<tr>
<td>6.E STANDARD ENTHALPY CHANGE OF FORMATION XXX</td>
<td></td>
</tr>
<tr>
<td>6.F BOND ENTHALPY AND MEAN BOND ENTHALPY AND HESS’S LAW XXX</td>
<td></td>
</tr>
<tr>
<td>6.G USING MEAN BOND ENTHALPIES XXX</td>
<td></td>
</tr>
<tr>
<td>TOPIC 7 ATOMIC STRUCTURE AND THE PERIODIC TABLE XXX</td>
<td></td>
</tr>
<tr>
<td>7.A INTERMOLECULAR INTERACTIONS XXX</td>
<td></td>
</tr>
<tr>
<td>7.B INTERMOLECULAR INTERACTIONS AND PHYSICAL PROPERTIES XXX</td>
<td></td>
</tr>
<tr>
<td>THINKING BIGGER XXX</td>
<td></td>
</tr>
<tr>
<td>EXAM PRACTICE XXX</td>
<td></td>
</tr>
<tr>
<td>TOPIC 8 REDOX CHEMISTRY AND GROUPS 1, 2 AND 7 XXX</td>
<td></td>
</tr>
<tr>
<td>8.A REDOX CHEMISTRY XXX</td>
<td></td>
</tr>
<tr>
<td>1 ELECTRON LOSS AND GAIN XXX</td>
<td></td>
</tr>
<tr>
<td>2 ASSIGNING OXIDATION NUMBERS XXX</td>
<td></td>
</tr>
<tr>
<td>3 RECOGNISING REACTIONS USING OXIDATION NUMBERS XXX</td>
<td></td>
</tr>
<tr>
<td>4 OXIDATION NUMBERS AND NOMENCLATURE XXX</td>
<td></td>
</tr>
<tr>
<td>5 CONSTRUCTING FULL IONIC EQUATIONS XXX</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8.C INORGANIC CHEMISTRY OF GROUP 7 XXX</td>
</tr>
<tr>
<td></td>
<td>1 TRENDS IN GROUP 7 XXX</td>
</tr>
<tr>
<td></td>
<td>2 REDOX REACTIONS IN GROUP 7 XXX</td>
</tr>
<tr>
<td></td>
<td>3 REACTIONS OF HALIDES WITH SULFURIC ACID XXX</td>
</tr>
<tr>
<td></td>
<td>4 OTHER REACTIONS OF HALIDES XXX</td>
</tr>
<tr>
<td></td>
<td>8.D QUANTITATIVE CHEMISTRY XXX</td>
</tr>
<tr>
<td></td>
<td>1 MAKING STANDARD SOLUTIONS XXX</td>
</tr>
<tr>
<td></td>
<td>2 DOING TITRATIONS XXX</td>
</tr>
<tr>
<td></td>
<td>3 CALCULATIONS FROM TITRATIONS XXX</td>
</tr>
<tr>
<td></td>
<td>4 MISTAKES, ERRORS, ACCURACY AND PRECISION XXX</td>
</tr>
</tbody>
</table>
5 MEASUREMENT ERRORS AND MEASUREMENT UNCERTAINTIES

6 OVERALL MEASUREMENT UNCERTAINTY

THINKING BIGGER

EXAM PRACTICE

TOPIC 10 ORGANIC CHEMISTRY: ALCOHOLS, HALOGENOALKANES AND SPECTRA

10.A GENERAL PRINCIPLES

10.B HALOGENOALKANES

1 HALOGENOALKANES AND HYDROLYSIS REACTIONS

2 COMPARING THE RATES OF HYDROLYSIS REACTIONS

3 HALOGENOALKANE REACTIONS AND MECHANISMS

10.C ALCOHOLS

1 ALCOHOLS AND SOME OF THEIR REACTIONS

2 OXIDATION REACTIONS OF ALCOHOLS

3 PURIFYING AN ORGANIC LIQUID

10.D MASS SPECTRA AND IR

1 MASS SPECTROMETRY IN ORGANIC COMPOUNDS

2 DEDUCING STRUCTURES FROM MASS SPECTRA

3 INFRARED SPECTROSCOPY

4 USING INFRARED SPECTRA

THINKING BIGGER

EXAM PRACTICE

MATH SKILLS

PRACTICALS

PREPARING FOR YOUR EXAMS

COMMAND WORDS

GLOSSARY

INDEX
Organic chemistry is one of the three traditional branches of chemistry (together with physical chemistry and inorganic chemistry). Students of biology will understand the importance of organic chemistry because most types of compounds in this topic are found in, or are formed in, plants and animals, including the human body.

Many aspects of our lives have been revolutionised by the production of new organic compounds, for example new polymers with special properties, more effective drugs to treat diseases, the ongoing search for new antibiotics and sustainable fuels to replace fossil fuels.

Fertilisers and pesticides have increased crop yields to feed the world’s growing population. This is an example of how the application of the knowledge of chemistry can cause unforeseen problems. Some people prefer food grown naturally, without the use of man-made chemicals – ironically these foods are often described as ‘organic’!

In this topic, you will learn about the basics of organic chemistry, such as:

- **homologous series** (compounds that are very similar to each other)
- **nomenclature** (a systematic way of naming organic compounds)
- **isomerism** (two or more compounds that have the same molecular formula but are not the same)

You will then look at simple hydrocarbons called alkanes, including how they are used as fuels.

**MATHS SKILLS FOR THIS TOPIC**

- Use ratios to construct and balance equations
- Represent chemical structures using angles and shapes in 2D and 3D structures
What prior knowledge do I need?
- The names of simple organic compounds
- Homologous series and general formula
- Calculation of empirical and molecular formulae
- Representing organic compounds by structural formulae

What will I study in this topic?
- Using different types of formulae to represent organic compounds
- Structural isomerism
- Problems caused by the combustion of fuels, and solutions to these problems
- Using reaction mechanisms to understand how organic reactions occur
- The formation of polymers and dealing with polymer waste

What will I study later?
- Optical isomerism (A level)
- Reactions of carbonyl and carboxyl compounds (A level)
- The type of bonding in benzene and other aromatic compounds (A level)
- Condensation polymers (A level)
- Nitrogen-containing compounds, including amino acids and proteins (A level)
- Planning reaction schemes to prepare organic compounds (A level)
- More practical techniques for preparing and purifying organic compounds (A level)
EARLY DAYS

Since the 1800s, our knowledge and understanding of chemistry has grown rapidly. To help understanding of all this knowledge, chemists divided chemistry into three main categories: inorganic, organic and physical chemistry. Each category is equally important. There are millions of different compounds in existence, and the vast majority are organic compounds. So, what is organic chemistry?

Today, the word ‘organic’ has a very different meaning in everyday life, and it is often applied to farming and food. In 1800s, people believed that there was something special about some substances – that they were only made in plants or animals. One example is the compound called urea, which is present in human urine. People used to believe that it could only be produced in the human body. In 1828, the German chemist Friedrich Wöhler discovered that urea could be made by heating a compound (ammonium cyanate) that was not organic. This meant that the idea of organic compounds only coming from living things was incorrect.

HYDROCARBONS

The main feature of an organic compound is that it contains carbon. Almost all of these compounds also contain hydrogen. Some of the most important compounds contain elements such as nitrogen and oxygen. In this section, we look at some of the large numbers of compounds that contain only carbon and hydrogen. These are called hydrocarbons.

If an organic compound contains other elements as well as carbon and hydrogen, then it is not a hydrocarbon. For example, many foods contain a sugar called sucrose. Sucrose contains carbon and hydrogen, but also oxygen, so it is not a hydrocarbon. It is an example of a carbohydrate – the -ate ending shows that it contains oxygen.

SATURATED OR UNSATURATED?

Although there are many thousands of different hydrocarbons, most of them are classed as saturated or unsaturated. As with many chemical terms, these words have a very different meaning in everyday life. If you are caught in a heavy rain shower, you may say that your clothes are saturated, which means that they cannot absorb any more water.
In organic chemistry, the terms ‘saturated’ or ‘unsaturated’ have nothing to do with water, although there is a connection. A hydrocarbon that is saturated contains as much hydrogen as possible, which depends on the number of carbon atoms in the molecule. If a hydrocarbon has fewer than the maximum possible number of hydrogen atoms, it is not saturated – we say it is unsaturated.

The formula of the simplest hydrocarbon, containing only one carbon atom, is:

\[
\begin{align*}
\text{H} \\
\text{H} \quad \text{C} \quad \text{H} \\
\text{H}
\end{align*}
\]

When a hydrocarbon contains two carbon atoms, there is a maximum of six hydrogen atoms.

There is a hydrocarbon that contains two carbon atoms and six hydrogen atoms, but also one that contains two carbon atoms and only four hydrogen atoms. The formulae of these hydrocarbons are:

\[
\begin{align*}
\text{H} \\
\text{H} \quad \text{C} \quad \text{C} \quad \text{H} \\
\text{H} \quad \text{H}
\end{align*}
\]

saturated

\[
\begin{align*}
\text{H} \\
\text{H} \quad \text{C} \quad \text{C} \quad \text{H} \\
\text{H} \quad \text{H}
\end{align*}
\]

unsaturated

You can see that in all three examples, each carbon atom has four bonds to other atoms. This is a general rule for organic compounds – in most cases, every carbon atom has four bonds.

The difference between a saturated hydrocarbon and an unsaturated hydrocarbon is to do with whether there is room, or not, for more hydrogen atoms.

- If there is no room, then the hydrocarbon is saturated.
- If there is room, then the hydrocarbon is unsaturated.

One easy way to decide whether a hydrocarbon is saturated or unsaturated is to look at structures like the ones above.

- If there are two bonds between the same carbon atoms (a double bond), the hydrocarbon is unsaturated.
- If there are only single bonds between the same carbon atoms, the hydrocarbon is saturated.

**ALKANES AND CYCLOALKANES**

Look at the formulae below:

\[
\begin{align*}
\text{H} \quad \text{H} \\
\text{H} \quad \text{C} \quad \text{C} \quad \text{C} \quad \text{H} \\
\text{H} \quad \text{H} \quad \text{H}
\end{align*}
\]

These are alkanes. Both structures have only single bonds. Therefore they are saturated.

Now look at these formulae below:

\[
\begin{align*}
\text{H} \\
\text{H} \quad \text{C} \quad \text{C} \\
\text{H} \quad \text{H} \quad \text{H}
\end{align*}
\]

\[
\begin{align*}
\text{H} \\
\text{H} \quad \text{C} \quad \text{C} \quad \text{C} \quad \text{H} \\
\text{H} \quad \text{H} \quad \text{H} \quad \text{H}
\end{align*}
\]

These are cycloalkanes. Both structures have only single bonds and so are saturated. They both have carbon atoms joined in a ring structure. The first has a triangular arrangement and the second has a square arrangement. These ring structures mean that they are cyclic compounds. We will look at alkanes and cycloalkanes in more detail in Chapter 4.B.

**CHECKPOINT**

1. A saturated hydrocarbon contains five carbon atoms in its molecule. What are the two possible molecular formulae for this hydrocarbon?

2. Consider the compound with the formula C₂H₄O₂. Is it an organic compound? Explain your answer.

**SUBJECT VOCABULARY**

- **hydrocarbon** a compound that contains only carbon and hydrogen atoms
- **multiple bond** is two or more covalent bonds between two atoms
- **a saturated compound** contains only single bonds.
- **an unsaturated compound** contains one or more multiple bonds
LEARNING OBJECTIVES

- Draw compounds using structural, displayed and skeletal formulae.

USING DIAGRAMS TO REFER TO ORGANIC COMPOUNDS

There are many millions of organic compounds. It can be challenging to be clear about which compounds we are referring to.

There are two main ways to refer to organic compounds. We can use:

- formulae
- names.

In this section we will consider how to refer to organic compounds using formulae. The visual representation of some formula are like diagrams.

DISPLAYED FORMULAE

The formulae you saw in the Chapter 4.A are all displayed formulae – they show (display) every atom and every bond separately. In many situations, these are the best type of formulae to use, but sometimes it is better to simplify them.

Consider the hydrocarbon with this displayed formula (its name is butane):

```
H   H   H   H
\H--C--C--C--C--H\n   H   H   H   H
```

STRUCTURAL FORMULAE

One way to simplify this displayed formula is to group all the atoms joined to a particular carbon atom together. We can choose to show the bonds between the carbons, or we can leave them out. These are both structural formulae of butane:

\[ \text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_3 \]

SKELETAL FORMULAE

Another way to represent a compound is by a skeletal formula. The word skeletal is connected with the word skeleton, which, as you know, shows only the bones in a human body.

A skeletal formula is a zig-zag line that shows only the bonds between the carbon atoms. Every change in direction and every ending means that there is a carbon atom (with as many hydrogen atoms as needed). Atoms other than carbon and hydrogen need to be shown.

This is the skeletal formula of butane:

```
\__\ / \\
|   |   |
|___|___|
```

The start and end both represent \( \text{CH}_3 \), and the two junctions between lines each represent \( \text{CH}_2 \).

MOLECULAR FORMULAE

The displayed, structural and skeletal formulae above show the structures of the molecules unambiguously. In other words, each formula represents only one compound. With a displayed
formula, this is very clear. With a structural formula, you have to imagine how the atoms are joined together in groups such as CH₂ and CH₃, but that is very straightforward. With a skeletal formula, once you know the rules, you can be sure how every atom is arranged in the molecule.

Now consider the formula C₃H₇Cl. This is clearly not a displayed formula or a skeletal formula, but it is also not a structural formula. This is because, with three carbon atoms, the chlorine atom could be attached to the middle carbon atom or to either of the end carbon atoms. The formula C₃H₇Cl actually represents two different compounds.

Formulae like this are called molecular formulae – they only show the numbers of each type of atom in the molecule, and not its structure. Of course, in very simple molecules such as CH₃Cl, the molecular formula can be used to work out the displayed, structural and skeletal formulae because there is only one way in which these five atoms can be joined together.

EMPIRICAL FORMULAE

Another type of formula is an empirical formula. This shows the compound like a molecular formula, but the numbers of each atom are in their simplest possible whole-number ratio. So, butane (molecular formula C₄H₁₀) has an empirical formula of C₂H₅.

In chemistry, the word empirical usually means ‘as found from practical evidence’. You would normally work out this type of formula mathematically from the results of an experiment.

DIFFERENT TYPES OF FORMULA FOR CHLOROETHANE

So far, we have only considered the different types of formula using a hydrocarbon as the example. Consider an example containing a third element – chloroethane. The table shows its different types of formula.

### CHECKPOINT

1. The displayed formula of a compound is:

   ![Displayed formula](image)

   Use a table (like the one for chloroethane) to show its structural, skeletal, molecular and empirical formulae.

2. The skeletal formula of a compound is:

   ![Skeletal formula](image)

   Use a table (like the one for chloroethane) to show its displayed, structural, molecular and empirical formulae.

### SUBJECT VOCABULARY

- **displayed formula**: a formula which shows every atom and every bond
- **structural formula**: a formula which shows (unambiguously) how the atoms are joined together
- **skeletal formula**: a formula which shows all the bonds between carbon atoms
- **molecular formula**: a formula which shows the actual numbers of each atom in the molecule
- **empirical formula**: a formula which shows the numbers of each atom in the simplest whole-number ratio

### LEARNING TIP

For some compounds, the numbers in the molecular formula cannot be simplified – this means that the molecular formula and the empirical formula are identical.
FUNCTIONAL GROUP

A functional group in a molecule is an atom or group of atoms that gives the compound some distinctive and predictable properties. For example, the functional group of atoms shown as COOH gives molecules containing this group a sour, acidic taste.

There are many organic compounds containing this group. Here are some examples:

\[ \text{HCOOH} \quad \text{CH}_3\text{COOH} \quad \text{CH}_3\text{CH}_2\text{COOH} \quad \text{CH}_3\text{CH}_2\text{CH}_2\text{COOH} \]

HOMOLOGOUS SERIES

If you look at the formulae above, you can see that each formula has one more carbon atom and two more hydrogen atoms than the previous one – they differ by CH₂. These compounds are the first four members of what is called a homologous series. This is a set of compounds with the same functional group, similar chemical properties and physical properties that show a gradation (a gradual change from one to the next).

ALKANES

The organic compounds that are mainly used as fuels are the alkanes (you will learn more about alkanes in Chapter 4.B). They are not considered to contain a functional group, but otherwise they form a homologous series. The displayed formulae of some of them are:

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

GENERAL FORMULAE

In Section 4.A.2 we looked at five different types of formulae. Now we are going to look at another type of formula. For the compounds in a homologous series, we can use a general formula to represent all of them. This is done by using the letter \( n \) for the number of carbon atoms, excluding any in the functional group. For the compounds with formulae ending in COOH, the general formula is \( \text{C}_n\text{H}_{2n+1}\text{COOH} \).

Table A shows some of the homologous series in this book.

<table>
<thead>
<tr>
<th>NAME</th>
<th>GENERAL FORMULA</th>
<th>EXAMPLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>alkane</td>
<td>( \text{C}<em>n\text{H}</em>{2n+2} )</td>
<td>( \text{CH}_4 )</td>
</tr>
<tr>
<td>alkene</td>
<td>( \text{C}<em>n\text{H}</em>{2n} )</td>
<td>( \text{C}_2\text{H}_4 )</td>
</tr>
<tr>
<td>halogenoalkane</td>
<td>( \text{C}<em>n\text{H}</em>{2n-1}\text{X} )</td>
<td>( \text{CH}_3\text{CH}_2\text{Br} )</td>
</tr>
<tr>
<td>alcohol</td>
<td>( \text{C}<em>n\text{H}</em>{2n-1}\text{OH} )</td>
<td>( \text{CH}_3\text{CH}_2\text{OH} )</td>
</tr>
</tbody>
</table>

Table A Examples of homologous series used in this book.
PROPERTIES OF A HOMOLOGOUS SERIES

ALKANES

We can use the alkanes to illustrate the similarity in chemical properties of a homologous series. For example, when alkanes are burned completely in air, they all form the same two products: carbon dioxide and water.

The commonest alkane is methane. The equation for its complete combustion is:

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

ALCOHOLS

We can use the alcohols to illustrate the gradation in physical properties of a homologous series. For example, the boiling temperatures of the first four alcohols are shown in Table B.

<table>
<thead>
<tr>
<th>FORMULA</th>
<th>BOILING TEMPERATURE / °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH(_3)OH</td>
<td>65</td>
</tr>
<tr>
<td>CH(_3)CH(_2)OH</td>
<td>79</td>
</tr>
<tr>
<td>CH(_3)CH(_2)CH(_2)OH</td>
<td>97</td>
</tr>
<tr>
<td>CH(_3)CH(_2)CH(_2)CH(_2)OH</td>
<td>117</td>
</tr>
</tbody>
</table>

You can see that as the number of carbon and hydrogen atoms increases, so does the boiling temperature.

fig A Molecular models are very useful in organic chemistry. Both of these structures contain an oxygen atom (shown in red), but you can see that they belong to different homologous series.

CHECKPOINT

1. The equation for the complete combustion of propane is:

   \[ \text{C}_3\text{H}_8 + 5\text{O}_2 \rightarrow 3\text{CO}_2 + 4\text{H}_2\text{O} \]

   What is the equation for the complete combustion of the alkane with five carbon atoms in its molecule?

2. The structural formula of a compound is CH\(_3\)CH\(_2\)CHO. What are the formulae of the two simpler compounds in the same homologous series?

SUBJECT VOCABULARY

functional group an atom or group of atoms in a molecule that is responsible for its chemical reactions

homologous series a family of compounds with the same functional group, which differ in formula by \( \text{CH}_2 \) from the next member
WHY DO WE NEED RULES TO NAME ORGANIC COMPOUNDS?

As the number of known organic compounds has increased, it has become harder to continue to find new names for them. In Section 4.A.3, we referred to the simplest organic compound (CH₄) as methane. In fact, this compound was originally known as marsh gas (because it was found in marshes when plants decayed). Many other organic compounds were named in similar ways.

International Union of Pure and Applied Chemistry is an organisation which has made rules about how to name organic compounds. The organisation’s name is usually abbreviated to IUPAC (‘eye-you-pack’). These rules create a system which is often known as ‘nomenclature’. The detailed rules needed for naming very complicated compounds are complex, but the simpler rules for the compounds described in this book are much easier to understand and apply.

THE SIMPLE RULES OF NOMENCLATURE

Table A summarises the principles of naming organic compounds, including rules for prefixes, suffixes and locants.

<table>
<thead>
<tr>
<th>THE PART OF THE NAME</th>
<th>HOW TO WRITE IT</th>
<th>EXAMPLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of carbon atoms</td>
<td>This is shown by using a letter code (usually 3 or 4 letters).</td>
<td>meth = one carbon atom</td>
</tr>
<tr>
<td>Prefixes Suffixes</td>
<td>The presence of atoms other than carbon and hydrogen is shown by adding other letters before or after the code for the number of carbon atoms.</td>
<td>bromo = an atom of bromine ol = a hydroxyl group (OH)</td>
</tr>
<tr>
<td>Multiplying prefixes</td>
<td>The presence of two or more identical groups is shown by using the prefixes di-, tri-, etc.</td>
<td>di = two</td>
</tr>
<tr>
<td>Locants</td>
<td>Where atoms and groups can have different positions in a molecule, numbers and hyphens are used to show their positions. The numbers represent the carbon atoms in the longest chain that the atoms and groups are attached to.</td>
<td>2- = the atom or group is attached to the second carbon atom in the chain</td>
</tr>
</tbody>
</table>

Table A. The principles of naming organic compounds.

The letter codes for the number of carbon atoms (up to ten) are:

<table>
<thead>
<tr>
<th>NUMBER</th>
<th>CODE</th>
<th>PREFIX</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>meth</td>
<td>methyl</td>
</tr>
<tr>
<td>2</td>
<td>eth</td>
<td>ethyl</td>
</tr>
<tr>
<td>3</td>
<td>prop</td>
<td>propyl</td>
</tr>
<tr>
<td>4</td>
<td>but</td>
<td>butyl</td>
</tr>
<tr>
<td>5</td>
<td>pent</td>
<td>pentyl</td>
</tr>
<tr>
<td>6</td>
<td>hex</td>
<td>hexyl</td>
</tr>
<tr>
<td>7</td>
<td>hept</td>
<td>heptyl</td>
</tr>
<tr>
<td>8</td>
<td>oct</td>
<td>octyl</td>
</tr>
<tr>
<td>9</td>
<td>non</td>
<td>nonyl</td>
</tr>
<tr>
<td>10</td>
<td>dec</td>
<td>decyl</td>
</tr>
</tbody>
</table>
APPLYING IUPAC RULES TO WRITE NAMES OF COMPOUNDS

ALKANES

We can see how these rules work for some of the alkanes. The names of all the alkanes end in \textit{ane}.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
\textbf{STRUCTURAL FORMULA} & \textbf{NAME} \\
\hline
\text{CH}_3\text{CH}_2\text{CH}_3 & \text{propane} \\
\hline
\text{CH}_3\text{CH}(-\text{CH}_3)\text{CH}_3 & \text{methylpropane} \\
& The locant 2- is not needed because if the methyl group below the horizontal chain were attached to one of the carbon atoms at either end of the chain, then there would be a sequence of four carbon atoms, and the compound would be named butane. \\
\hline
\text{CH}_3\text{CH}_2\text{CH}(-\text{CH}_2\text{CH}_3)\text{CH}_3 & \text{3-methylpentane} \\
& The longest carbon chain contains five carbon atoms, and there is a methyl group attached to the third one. \\
\hline
\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}(-\text{CH}_3)\text{CH}_3 & \text{2-methylpentane} \\
& This is not 4-methylpentane because another rule is that the lowest locant numbers should be used. \\
\hline
\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3 & \text{3-methylpentane} \\
\hline
\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_3 & \text{2,3-dimethylbutane} \\
& This example shows the use of a comma between the locants when the attached groups are the same. \\
\hline
\text{CH}_3\text{CH}_2\text{CH}_3\text{CH}_2\text{CH}_3\text{CH}_3 & \text{3-ethyl-2-methylpentane} \\
& This example illustrates the rule about prefixes being in alphabetical order. Ethyl comes before methyl because e comes before m in the alphabet. \\
& Notice also that it is not called 3-ethyl-4-methylpentane because these numbers (3 + 4) total more than the numbers 3 + 2 in the correct name. \\
\end{tabular}
\caption{Naming alkanes from structural formulae using the rules of IUPAC nomenclature.}
\end{table}

ALCOHOLS

Next, look at the alcohols in Table C. The rules for these are a bit different because the presence of the alcohol functional group is indicated by a suffix, not a prefix.

The names for all the alcohols end in \textit{-ol}.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
\textbf{STRUCTURAL FORMULA} & \textbf{NAME} \\
\hline
\text{CH}_3\text{CH}_2\text{OH} & \text{ethanol} \\
\hline
\text{CH}_3\text{CH}_2\text{CH}_2\text{OH} & \text{propan-1-ol} \\
& This time, the locant appears near the end of the name, but, as before, it appears directly before the letters representing the group. \\
\hline
\text{CH}_3\text{CH}_2\text{CH}_3\text{CH}_2\text{OH} & \text{3-methylbutan-2-ol} \\
& This example illustrates the use of both a prefix and a suffix. This is not called 2-methylbutan-3-ol the lowest number locant should be used for the suffix functional group (-2-ol not -3-ol). \\
\hline
\text{CH}_3\text{CH}_2\text{CH}_3\text{CH}_2\text{OH} & \text{3,3-dimethylbutan-1-ol} \\
& This example shows the use of prefixes, a suffix, locants and a comma! As with alkanes, the name uses locants that add up to the smallest possible number. \\
\end{tabular}
\caption{Naming alcohols from structural formulae using the rules of IUPAC nomenclature.}
\end{table}
APPLYING THE RULES TO WRITE FORMULAE

Here are some examples of applying the rules to write a structural formula for a compound from its IUPAC name.

<table>
<thead>
<tr>
<th>NAME</th>
<th>STRUCTURAL FORMULA</th>
</tr>
</thead>
<tbody>
<tr>
<td>dimethylpropane</td>
<td>prop indicates a chain of three carbon atoms dimethyl indicates two methyl groups attached to the chain No locants are needed, so the two methyl groups must be attached to the carbon chain in a way that does not make the longest carbon chain any longer than three carbon atoms. So the structural formula is:</td>
</tr>
<tr>
<td></td>
<td>CH₃</td>
</tr>
<tr>
<td></td>
<td>CH₃—C—CH₃</td>
</tr>
<tr>
<td></td>
<td>CH₃</td>
</tr>
<tr>
<td>3-methylbutan-1-ol</td>
<td>but indicates a chain of four carbon atoms methyl indicates a CH₃ group 1- and 3- indicate attachments to the first and third carbon atoms in the chain. So the structural formula is:</td>
</tr>
<tr>
<td></td>
<td>CH₂—CH₂—CH—CH₃</td>
</tr>
<tr>
<td></td>
<td>OH</td>
</tr>
<tr>
<td></td>
<td>CH₃</td>
</tr>
</tbody>
</table>

LEARNING TIP

When you practise writing names from structural formulae, always check that the code you have used for the longest carbon chain is for the longest chain. This may not be the one shown horizontally. When you practise writing structural formulae from names, always check that each carbon has only four bonds. Showing three or five bonds is a common error.

CHECKPOINT

1 Write IUPAC names for the compounds with these structural formulae.
   \[
   \begin{align*}
   &CH₂—CH—CH₃ \quad CH₂—CH—CH₃ \\
   &Br \quad Br \quad Br \quad OH
   \end{align*}
   \]

2 Write structural formulae for the compounds with these IUPAC names.
   2,2-dimethylpentane 2,3-dimethylbutan-2-ol

SUBJECT VOCABULARY

locant a number used to indicate which carbon atom in the chain an atom or group is attached to
prefix a set of letters written at the beginning of a name
suffix a set of letters written at the end of a name
1. An organic compound is shown by this formula:

\[
\begin{align*}
&\text{CH}_3 \\
&\text{CH}_3 - C - \text{CH}_3 \\
&\text{CH}_3
\end{align*}
\]

What type of formula is this?
A. displayed formula
B. general formula
C. molecular formula
D. structural formula

[Total: 1]

2. Which statement is correct for the members of a homologous series?
A. They have similar boiling points.
B. Their molecular formulae differ by CH₃.
C. They contain the same functional group.
D. Their chemical properties are different.

[Total: 1]

3. What is the IUPAC name for this compound?
A. 3,4-dichlorobutene
B. 1,2-dichlorobutane
C. 3,4-dichlorobutane
D. 1,2-dichlorobutene

[Total: 1]

4. Which fuel is carbon-neutral?
A. ethanol
B. natural gas
C. petrol
D. wood

[Total: 1]

5. Which equation represents a substitution reaction?
A. \(\text{C}_2\text{H}_4 + \text{H}_2\text{O} \rightarrow \text{C}_2\text{H}_5\text{OH}\)
B. \(\text{C}_2\text{H}_4 + \text{Br}_2 \rightarrow \text{C}_2\text{H}_4\text{Br}_2\)
C. \(\text{C}_2\text{H}_6 + \text{F}_2 \rightarrow \text{C}_2\text{H}_5\text{F} + \text{HF}\)
D. \(\text{C}_2\text{H}_4 \rightarrow \text{C}_2\text{H}_4 + \text{H}_2\)

[Total: 1]

6. Which equation represents a substitution reaction?
A. \(\cdot\text{CH}_2\text{Cl} + \text{Cl}^- \rightarrow \text{CH}_2\text{Cl}_2\)
B. \(\text{H}^- + \text{Cl} \rightarrow \text{HCl}\)
C. \(\cdot\text{CH}_3 + \text{Cl}_2 \rightarrow \text{CH}_3\text{Cl} + \text{Cl}^-\)
D. \(\text{CH}_3\text{Cl} + \text{Cl}_2 \rightarrow \text{CH}_2\text{Cl}_3 + \text{HCl}\)

[Total: 1]

7. The table lists the boiling temperatures of some alkanes.

<table>
<thead>
<tr>
<th>Alkane</th>
<th>Molecular formula</th>
<th>Boiling temperature/K</th>
</tr>
</thead>
<tbody>
<tr>
<td>butane</td>
<td>(\text{C}<em>4\text{H}</em>{10})</td>
<td>273</td>
</tr>
<tr>
<td>pentane</td>
<td>(\text{C}<em>5\text{H}</em>{12})</td>
<td>309</td>
</tr>
<tr>
<td>hexane</td>
<td>(\text{C}<em>6\text{H}</em>{14})</td>
<td>342</td>
</tr>
<tr>
<td>heptane</td>
<td>(\text{C}<em>7\text{H}</em>{16})</td>
<td>372</td>
</tr>
<tr>
<td>octane</td>
<td>(\text{C}<em>8\text{H}</em>{18})</td>
<td>399</td>
</tr>
<tr>
<td>nonane</td>
<td>(\text{C}<em>9\text{H}</em>{20})</td>
<td></td>
</tr>
<tr>
<td>decane</td>
<td>(\text{C}<em>{10}\text{H}</em>{22})</td>
<td>447</td>
</tr>
</tbody>
</table>

(a) Give the molecular formula of octane.

(b) (i) Explain the trend in boiling temperature of the alkanes.
(ii) Predict a value for the boiling temperature of nonane.
(c) Long chain alkanes, such as decane, can be cracked into shorter chain alkanes and alkenes.
(i) Write an equation for the cracking of decane into octane and ethene.
(ii) The ethene produced can be converted into ethanol by direct hydration with steam. Write an equation for this reaction and state the conditions that are used in industry.
(d) Reforming is a process used in the production of petrol. Unbranched-chain alkanes can be reformed to produce either branched-chain alkanes or cycloalkanes.
(i) Using skeletal formulae, write an equation for the reforming of decane into 2,3-dimethyloctane.
(ii) Using skeletal formulae, write an equation for the reforming of heptane into methylcyclohexane.
(iii) State why reforming is used in the production of petrol.

[Total: 13]
8 Compound Y is a hydrocarbon containing 85.7% of carbon by mass.

(a) (i) Calculate the empirical formula of Y. [2]
(ii) The molar mass of Y is 56 g mol\(^{-1}\). Show that the molecular formula of Y is \(\text{C}_4\text{H}_8\). [1]

(b) There are six isomers for compound Y: four unsaturated molecules and two saturated molecules. Draw a displayed formula for each of the five isomers and name each compound. [6]

[Total: 9]

9 The structural formulae of four hydrocarbons, A, B, C and D, are shown.

A \[ \text{CH}_3 \quad \text{CH}_2 \quad \text{CH}_2 \quad \text{CH}_3 \]

B \[ \text{CH}_3 \quad \text{CH}_2 \quad \text{CH}_2 \quad \text{CH}_2 \quad \text{CH}_3 \]

C \[ \text{CH}_3 \quad \text{CH}_2 \quad \text{CH}_2 \quad \text{CH}_2 \]

D \[ \text{CH}_3 \quad \text{CH}_2 \quad \text{CH}_2 \quad \text{CH}_2 \quad \text{CH}_3 \]

(a) Identify the homologous series to which all these hydrocarbons belong. Give a reason for your answer. [2]

(b) Explain which structural formulae represent only one compound. [2]

(c) Give the structural formulae for the two isomers of B. Give the IUPAC name for each isomer. [4]

[Total: 8]

10 Halogenoalkanes undergo both substitution reactions with aqueous KOH and elimination reactions with ethanolic KOH.

(a) Draw the mechanism for the substitution reaction between 1-chlorobutane and aqueous potassium hydroxide. [3]

(b) Explain why substitution reactions are faster with 1-bromobutane than with 1-chlorobutane. [3]

(c) Which pair of chlorobutanes would both give a hydrocarbon of formula C\(_4\)H\(_6\) when separately treated with hot ethanolic KOH? [1]

A \(\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{Cl}\) and \(\text{CH}_3\text{CH}_2\text{CH}_2\text{CHCl}_2\)

B \(\text{CH}_3\text{CHClCHClCH}_3\) and \(\text{ClCH}_2\text{CH}_2\text{CH}_2\text{Cl}\)

C \(\text{CH}_3\text{CH}_2\text{CH}_2\text{Cl}\) and \(\text{ClCH}_2\text{CH}_2\text{CH}_2\text{Cl}\)

D \(\text{CH}_3\text{CH}_2\text{CH}_2\text{Cl}\) and \(\text{CH}_3\text{CH}_2\text{CHClCH}_3\)

(d) Which chlorobutane is classified as a tertiary halogenoalkane? [1]

A \(\text{H}_3\text{CCH}_2\text{CH}_2\text{Cl}\)

B \(\text{CH}_3\text{CH}_2\text{CHClCH}_3\)

C \(\text{(CH}_3)_3\text{CCl}\)

D \(\text{(CH}_3)_2\text{CHCH}_2\text{Cl}\)

[Total: 8]

11 Lavandulol is a compound that is found in lavender oil. The skeletal formula of lavandulol is

(a) (i) Give the molecular formula of lavandulol. [1]
(ii) Give the names of the two functional groups that are present in lavandulol. [2]

(b) Lavandulol can be oxidised by acidified potassium dichromate(VI) solution to produce either compound X or compound Y.

\[ \begin{array}{c}
\text{CH}_2\text{OH} \\
\text{compound X} \\
\text{CHO} \\
\text{COOH} \\
\text{compound Y} \\
\end{array} \]

(i) State the conditions required to produce compound X. [2]
(ii) State the conditions required to produce compound Y. [2]
(iii) Describe a chemical test that could be performed to show that the compound formed was X and not Y. [2]

[Total: 9]
A JOURNAL ARTICLE

CATALYSTS FOR A GREEN INDUSTRY

Important catalytic reactions

Today, the industrial world relies upon an enormous number of chemical reactions and an even greater number of catalysts. A selection of important reactions reveals the scope of modern catalysis and demonstrates how crucial it will be for chemists to achieve their environmental objectives.

A sacrifice: worst case catalyst

A sacrificial, or stoichiometric, catalyst is used once and discarded. The amount of waste produced is not insignificant since these catalysts are used in stoichiometric amounts. For example, the catalyst may typically be in a 1:1 mole ratio with the main reactant.

In the manufacture of anthraquinone for the dyestuffs industry, for example, aluminium chloride is the sacrificial catalyst in the initial step, the acylation of benzene, see Fig A. This is a type of Friedel–Crafts reaction in which the spent catalyst is discarded along with waste from the process. Fresh catalyst is required for the next batch of reactants.

The problem is that the aluminium chloride complexes strongly with the products, i.e. Cl–, forming [AlCl₄]⁻ and cannot be economically recycled, resulting in large quantities of corrosive waste.

New catalysts, with better environmental credentials, are now being tried out. Compounds, such as the highly acidic dysprosium(III) triflate (trifluoromethane sulfonate, see Fig A) offer the possibility of breaking away from the sacrificial catalyst by enabling the catalyst to be recycled.

Low sulfur fuels: desulphurisation catalysis

Petroleum-derived fuels contain a small amount of sulfur. Unless removed this sulfur persists throughout the refining processes and ends up in the petrol or diesel. Pressure to decrease atmospheric sulfur has driven the development of catalytic desulphurisation. One of the problems was that much of the sulfur present was in compounds such as the thiophenes, which are stable and resistant to breakdown.

The catalyst molybdenum disulfide coated on an alumina support provided one solution. Cobalt is added as a promoter, suggesting that the active site is a molybdenum-cobalt sulfide arrangement. In the catalytic reaction (see Fig B), which is essentially a hydrogenation sequence, the adsorbed thioene molecule is hydrogenated and its aromatic stability destroyed. This enables the C–S bond to break and release the sulfur as hydrogen sulfide. This is an interesting example of a catalyst performing different types of reactions: hydrogenation, elimination and isomerisation.

Based on an article in Education in Chemistry magazine, published by the Royal Society of Chemistry
SCIENCE COMMUNICATIONS

1 A lot of scientific literacy is required to read this extract. Imagine that you need to convince the general public that we must try to remove the sulfur from fuels although it is expensive. Design a pamphlet to present a strong argument.

CHEMISTRY IN DETAIL

2 a Work out the molecular formula of thiophene (shown below).

2 b Calculate the percentage by mass of sulfur in the molecule.

2 c Write a balanced equation for the complete combustion of thiophene. (You can assume the oxidised product of sulfur is SO₂ only.)

3 a During the elimination (fig B) part of the reaction sequence, butan-1-thiol is converted into two products. Name them.

3 b The isomerisation process gives rise to two stereo isomers. Explain what is meant by a geometric isomer and name both.

3 c Why can the double bond hydrogenation reaction be considered to have 100% atom economy?

ACTIVITY

You may wonder why sulfur appears in fossil fuels at all! The chemistry of sulfur gives it some special properties. Apart from carbon, hydrogen, oxygen and nitrogen, it is the only other element present in amino acids, which are the building blocks of all proteins. Prepare a 5-minute presentation to the class about the importance of sulfur in proteins: Your presentation should include:

- which amino acids contain sulfur
- what properties of sulfur make it so important in protein structure
- what the consequences of a diet low in sulfur can be

DID YOU KNOW?

Hydrogen sulfide (H₂S) is highly toxic. Luckily, most humans can detect it at concentrations of less than 0.5 parts per billion (or ppb; that’s 1 molecule in 2 × 10⁹ air molecules). H₂S smells like rotten eggs so we get plenty of warning before the potentially fatal concentration level of 800 000 ppb, which can be fatal, is reached.