CHAPTER 9

Properties and reactions of organic compounds

Organic reactions are chemical reactions that take place between organic compounds, and these reactions depend on the properties of the compounds. The number of all the possible organic reactions that can occur is essentially infinite because of the myriad combinations of compounds. However, there are certain general patterns that can be observed to describe many common and useful reactions. It is not unusual to find that different pathways can be taken to produce the same organic substance.

YOU WILL EXAMINE:

- bonding in organic compounds
- structural isomers and stereoisomers
- the effect of different structures on properties
- physical properties of hydrocarbons
- physical properties of alcohols, aldehydes, ketones, carboxylic acids and esters
- reactions of hydrocarbons
- reactions of haloalkanes, alcohols, carboxylic acids, esters and amines
- organic pathways
- yield and atom economy.

Which flavour of jellybean is your favourite? Is it peach, apple, bubblegum or one of the newer, more unusual taste sensations? Chemistry plays an essential part in creating the extensive variety of aromas and flavours in jellybeans and numerous other foods. Most flavours are actually quite complicated, with contributions from several chemicals, many of which are esters. For example, the taste and aroma of apple is provided by the ester methyl pentanoate. Food chemists perform many experiments to produce a taste that is as close as possible to the original. Changing even a small part of a molecule can provide quite a different result. Esters are derived from the reaction of an alcohol and a carboxylic acid. This reaction and more are explored in this chapter.
Physical and chemical properties of organic compounds

The physical and chemical properties of organic compounds provide information that helps us understand and evaluate the interactions between organic chemicals. Depending on the types of atoms present in compounds, these interactions determine how organic molecules react to produce important chemicals for fuels, pharmaceuticals, manufacturing, industry and biological processes. The number of all the possible organic reactions that can occur is essentially infinite because there are so many combinations of organic compounds. However, certain general patterns involving addition, decomposition, combination, substitution or rearrangement of atoms or groups of atoms can be used to describe many common and useful reactions. It is not unusual to find that different pathways can produce the same organic substance.

Properties and bonding

The trends in physical properties of organic compounds, such as melting point, boiling point, viscosity, flashpoint and solubility, can be deduced from their structure, including size, shape and any functional groups. These factors depend on the strength of the intermolecular forces present. In molecules (where atoms are connected by intramolecular covalent bonds), intermolecular forces may be of three types: dispersion forces, dipole–dipole attractions and hydrogen bonding.

Bonding in and between organic molecules

The millions of organic compounds known to chemists are mainly covalent molecules. These molecules could be simple molecules, such as methane and ethanol, or macromolecules, such as polyethylene and proteins. The physical properties and behaviours of organic molecules are influenced by their size, shape, structure and degree of polarisation of their covalent bonds. In general, simple organic compounds are gases, volatile liquids, or solids with low melting and boiling temperatures. This is because the intermolecular forces between these organic molecules are weak. These intermolecular forces include:

- **dispersion forces** (also called van der Waals forces): In non-polar molecules such as methane, CH₄, wax and oils, electrons may momentarily be distributed unevenly within the molecules, inducing a temporary dipole. Neighbouring molecules with similar temporary dipoles are attracted weakly to each other. This results in weak dispersion forces between the molecules. The strength of the dispersion forces is affected by the size and shape of molecules.
Dipole–dipole interactions are the result of permanent dipoles.

Hydrogen bonding occurs between a molecule that contains an H atom and a molecule that contains an F, O or N atom.

• **dipole–dipole attractions**: Molecules such as HCl, HBr and CH₃Cl are polar and have permanent dipoles. The partial positive charge on one molecule is electrostatically attracted to the partial negative charge on a neighbouring molecule. Dipole–dipole attractions are stronger intermolecular forces than dispersion forces.

• **hydrogen bonding**: This takes place between a molecule containing hydrogen atoms bonded to one of the three highly electronegative elements F, O and N, and another molecule that must also contain an electronegative atom, such as oxygen and nitrogen. Hydrogen bonds are stronger intermolecular forces than both dispersion forces and dipole–dipole attractions. Hydrogen bonding occurs between water molecules and also between organic compounds such as alcohols (e.g. methanol, CH₃OH), carboxylic acids (e.g. ethanoic acid, CH₃COOH) and organic amines (e.g. methylvamine, CH₃NH₂).

Hydrogen bonding is stronger than dipole–dipole attractions due to the larger dipole moment that exists within these molecules as well as to the small size of the hydrogen atom involved. This allows the molecules to get closer to each other than in dipole–dipole attractions, thus increasing the force of attraction.

**Revision questions**

1. State whether the intermolecular forces acting between molecules of the following compounds are dispersion forces, dipole–dipole attraction or hydrogen bonding.
   (a) CH₃OH   (b) CH₄
   (c) CH₃CH₂Cl   (d) CH₃NH₂

2. Which one of each of the following pairs would have the stronger intermolecular forces?
   (a) CH₄ and CH₃CH₃
   (b) CH₃OH and CH₂Cl
   (c) CH₃CH₂Cl and CH₃CH₂CH₃

**Isomers — same but different**

Another reason for the enormous number of organic compounds is the existence of isomers, as was briefly discussed in chapter 8. Two or more compounds with the same molecular formula but different arrangements of atoms are known as isomers. The effect on the properties of the substances depends on the type of isomerism present. If the atoms are arranged in different orders, then they are **structural isomers**. If the atoms are connected in the same order but are oriented differently in space, they are **stereoisomers**. In many cases, three-dimensional structural formulas (using wedges and dashes) are used to...
represent three-dimensional molecular structures. They were described in chapter 8.

Boiling points provide a good indication of the strength of the intermolecular forces that hold the molecules of a substance together, so it is useful to compare the boiling points of related compounds to see how structural differences account for the differences in intermolecular attractions.

**Structural isomerism**

Structural isomers can have different physical and chemical properties if they contain different functional groups. Three types of structural isomers are chain, positional and functional isomers. The physical properties of chain isomers show a difference in boiling point, with more branched isomers having lower boiling points. For example, the boiling point of butane is -0.5 °C, and the boiling point of methylpropane is -11.7 °C. The second molecule is more spherical and has less surface area for the dispersion forces to act.

In positional isomers, the position of the functional group may affect not only the compactness of the molecule but also its polarity.

If isomers have functional isomerism, then they have different functional groups, and this affects their intermolecular forces, resulting in significantly distinct properties.

Examples of structural isomers can be found in table 9.1.

### TABLE 9.1 Types of isomers

<table>
<thead>
<tr>
<th>Isomer</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Structural isomers</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Chain isomers</strong></td>
<td></td>
</tr>
<tr>
<td>different branching in carbon chain</td>
<td>H H H H</td>
</tr>
<tr>
<td></td>
<td>H - C - C - C - C - H</td>
</tr>
<tr>
<td></td>
<td>H H H H</td>
</tr>
<tr>
<td></td>
<td>butane</td>
</tr>
<tr>
<td><strong>Positional isomers</strong></td>
<td></td>
</tr>
<tr>
<td>different positions of the functional group, which is usually indicated by a number in the name</td>
<td>OH H H</td>
</tr>
<tr>
<td></td>
<td>H - C - C - C - H</td>
</tr>
<tr>
<td></td>
<td>H H H</td>
</tr>
<tr>
<td></td>
<td>propan-1-ol</td>
</tr>
<tr>
<td><strong>Functional isomers</strong></td>
<td></td>
</tr>
<tr>
<td>same atoms but different functional groups</td>
<td>H H</td>
</tr>
<tr>
<td></td>
<td>H - C - C - C - O</td>
</tr>
<tr>
<td></td>
<td>H H H</td>
</tr>
<tr>
<td></td>
<td>propanal</td>
</tr>
<tr>
<td><strong>Stereoisomers</strong></td>
<td></td>
</tr>
<tr>
<td><strong>cis and trans isomers</strong></td>
<td></td>
</tr>
<tr>
<td>different arrangements of atoms around a double bond or in a ring, which restricts rotation. If the groups on each carbon atom are on the same side of the molecule, that molecule is the cis isomer. If they are on opposite sites, it is the trans isomer.</td>
<td>CH3</td>
</tr>
<tr>
<td></td>
<td>C - C</td>
</tr>
<tr>
<td></td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>cis-but-2-ene</td>
</tr>
<tr>
<td><strong>Enantiomers or optical isomers</strong></td>
<td></td>
</tr>
<tr>
<td>non-superimposable mirror images containing an asymmetric carbon atom. These molecules are referred to as chiral.</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>H C - F</td>
</tr>
<tr>
<td></td>
<td>Br</td>
</tr>
<tr>
<td></td>
<td>Cl</td>
</tr>
</tbody>
</table>
Stereoisomerism

Stereoisomers include cis and trans isomers and enantiomers. cis–trans isomers have different physical and chemical properties. These isomers are formed when there are two different groups on each of the carbon atoms in a carbon–carbon double bond. A cis isomer has both of the groups on the same side of the double bond, and a trans isomer has the groups on different sides of the double bond. Boiling points are affected by the polarity of the molecules, but the arrangements of the molecules in the solids affects their melting points. For example, in cis-1,2-dichloroethene, each C—Cl bond is polar, so the overall molecule is polar. However, in trans-1,2-dichloroethene, the individual dipoles in the bonds cancel out, and so the molecule is non-polar. The result is that the boiling point of the cis isomer (60.2 °C) is higher than that of the trans isomer (48.5 °C).

<table>
<thead>
<tr>
<th>Isomer</th>
<th>Melting point (°C)</th>
<th>Boiling point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>cis</td>
<td>-81.5</td>
<td>60.2</td>
</tr>
<tr>
<td>trans</td>
<td>-49.4</td>
<td>48.5</td>
</tr>
</tbody>
</table>

It is interesting to note that the melting points do not follow the same pattern as the boiling points. In the solid state, the trans isomers can pack more closely than the cis isomers, making the intermolecular forces more effective. cis and trans isomers can also occur in ring structures. cis–trans isomers belong to a larger group of stereoisomers called diastereomers, which includes other stereoisomers that are not mirror images of each other.

Some molecules can be described as chiral. They have what is known as an asymmetric carbon atom or chiral centre; this means that they cannot be superimposed on their mirror images. We are familiar with many chiral objects. For example, seashells, scissors, gloves, hands and feet cannot be matched directly with their mirror images, whereas mittens and socks can fit on either hand or foot. Chiral molecules that are non-superimposable mirror images of one another are called enantiomers. These molecules are not symmetrical and can be recognised because the chiral carbon atom is bonded to four different atoms or groups. The physical properties of enantiomers are identical (except for optical activity), and their chemical properties are generally the same, but they react differently with other molecules that have optical properties. The significant implications of this in biological systems will be discussed in chapter 11.
Enantiomers can be distinguished by their ability to rotate plane-polarised light in equal but opposite directions. This optical activity is the reason why they are also called optical isomers. When optically active substances are synthesised in the laboratory, they are often a 50/50 mixture of the two enantiomers. This is known as a racemic mixture or racemate. A racemic mixture does not affect plane-polarised light. Stereoisomers formed in biological systems consist of the one enantiomer.

Normally, a light wave is made up of a mixture of waves vibrating in every direction perpendicular to its direction of movement. Unpolarised light can be converted into a single polarised beam by passing it through a polarising filter. Sunglasses use a polarising filter to limit glare. Optically active molecules can rotate the plane of polarisation of plane-polarised light. An instrument called a polarimeter can be used to analyse this rotation. If it is rotated clockwise it is the (+) enantiomer; if it is rotated anticlockwise, it is the (−) enantiomer.

**Identifying chiral molecules**

Building models of molecules and trying to superimpose them is a good way of determining whether a molecule is chiral or achiral. Chiral molecules are not
Chiral molecules have four different groups attached to a carbon atom. If two or more groups attached to the tetrahedral atoms in a molecule are the same, then the molecule is achiral (not chiral). If the molecule has a plane of symmetry, as shown in the diagram below, it is achiral. And, as mentioned previously, if four different groups are attached to a carbon atom, then it is a chiral molecule. The carbon atom in CH₂ or CH₃ groups is not a chiral centre.

(a) The chloropropane molecule is achiral as it has a plane of symmetry. (b) The chlorobutane molecule does not have a plane of symmetry and so is chiral.

**Sample problem 9.1**

Explain why the molecule CH₃CH(OH)CH₂CH₃ is described as a chiral molecule.

**Solution:** Draw the structure.

The second carbon atom has four different groups attached — a hydroxyl group, a hydrogen, a methyl group and an ethyl group — so is a chiral molecule. This means that it cannot be superimposed on its mirror image, and so it is an enantiomer.

**Revision questions**

3. Classify each of the following objects as chiral or achiral.
   (a) Nail
   (b) Baseball bat
   (c) Golf club
   (d) Tennis racquet
   (e) Ear
   (f) Mug
   (g) Car
   (h) Scissors
   (i) Socks

4. How many chain isomers of the molecular formula C₅H₁₂ are there?

5. Draw the structure of the molecule CH₃CH₂CH₂CH₂OH, and name a positional isomer of it.
6. Draw the structure of a functional group isomer of ethanol, C₂H₅OH.
7. Draw and label the *cis* and *trans* isomer forms of pent-2-ene.
8. Describe the type of isomerism that exists in these two molecules.

![Structure of functional group isomer of ethanol and pent-2-ene isomers](image)

**Examples of chiral molecules**

From 1957, the drug thalidomide was used to treat morning sickness in pregnant women. Over 10,000 children were born with horrific birth defects as a result of this drug. Eventually, investigations found that thalidomide was a racemic mix of two enantiomers due to the presence of one chiral carbon atom. While one enantiomer did indeed cure morning sickness, the other enantiomer caused deformities in organs and limbs. The chiral carbon atom is unstable, and enzymes in the liver can convert (racemise) the therapeutic form into the harmful form, so it is very difficult to isolate the beneficial enantiomer. Thalidomide is currently used, under strict regulations, to treat some cancers and other conditions including leprosy.

![Structures of Enantiomers of Thalidomide](image)

Ibuprofen, which is used for pain relief and reducing fever and inflammation, is another familiar example of an enantiomer. Again, one enantiomer is effective, whereas the other is inactive. As a large proportion of the inactive molecule is converted into the active molecule in the body, it is sold as a racemic mixture; there is not enough advantage to warrant the expense of manufacturing the active isomer alone.

The pharmaceutical industry is now much more aware of the possibility of the effects of different enantiomers when developing new medications. Most pharmaceuticals under development are chiral. Therefore, either pure samples of the active isomer are produced or the two isomers in a racemic mixture are separated. Separation can be achieved using chromatography with a single-enantiomer stationary phase.

**Physical properties of hydrocarbons**

The physical properties of compounds depend on their structures.

**Alkanes**

Alkanes are colourless compounds that are less dense than water and have weaker intermolecular attractive forces. Alkanes consist of non-polar molecules. The first four in the series are gases. As the size of the molecule increases, so does the influence of the dispersion forces; therefore, the melting and boiling points increase, as can be seen in table 9.3. Another factor that
affects the boiling point is the degree of branching; as the amount of branching increases, the boiling point decreases. This is due to the inability of molecules to get closer to each other; as the dispersion forces operate over a small distance only, the attraction is diminished. Alkanes are insoluble in water because of their non-polar structures, but they are soluble in organic solvents because dispersion forces between the alkane molecules and the solvent replace the dispersion forces between the alkane molecules.

**TABLE 9.3 Melting and boiling points of alkanes**

<table>
<thead>
<tr>
<th>Alkane</th>
<th>Formula</th>
<th>Semi-structural formula</th>
<th>Melting point (°C)</th>
<th>Boiling point (°C)</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>methane</td>
<td>CH₄</td>
<td>CH₄</td>
<td>−183</td>
<td>−164</td>
<td>gas</td>
</tr>
<tr>
<td>ethane</td>
<td>C₂H₆</td>
<td>CH₃CH₃</td>
<td>−182</td>
<td>−87</td>
<td>gas</td>
</tr>
<tr>
<td>propane</td>
<td>C₃H₈</td>
<td>CH₃CH₂CH₃</td>
<td>−190</td>
<td>−42</td>
<td>gas</td>
</tr>
<tr>
<td>butane</td>
<td>C₄H₁₀</td>
<td>CH₃(CH₂)₂CH₃</td>
<td>−135</td>
<td>−1</td>
<td>gas</td>
</tr>
<tr>
<td>pentane</td>
<td>C₅H₁₂</td>
<td>CH₃(CH₂)₃CH₃</td>
<td>−130</td>
<td>36</td>
<td>liquid</td>
</tr>
<tr>
<td>hexane</td>
<td>C₆H₁₄</td>
<td>CH₃(CH₂)₄CH₃</td>
<td>−94</td>
<td>68</td>
<td>liquid</td>
</tr>
<tr>
<td>heptane</td>
<td>C₇H₁₆</td>
<td>CH₃(CH₂)₅CH₃</td>
<td>−90</td>
<td>98</td>
<td>liquid</td>
</tr>
<tr>
<td>octane</td>
<td>C₈H₁₈</td>
<td>CH₃(CH₂)₆CH₃</td>
<td>−57</td>
<td>126</td>
<td>liquid</td>
</tr>
</tbody>
</table>

The **viscosity** of liquid alkanes also increases with the number of carbon atoms. Viscosity is the resistance to flow of a liquid, and it is affected by intermolecular forces and the shapes of the molecules; honey has high viscosity and water has low viscosity. The increased number of intermolecular forces in larger molecules, together with the possibility of branched molecules becoming tangled, results in higher viscosity. Viscosity decreases as the temperature increases because the molecules attain enough energy to overcome the forces holding the molecules together.

**Flashpoint**

Organic chemicals can be classified as flammable or combustible according to their flashpoints. The **flashpoint** of a volatile liquid is the lowest temperature at which the liquid gives off enough vapour to start burning at its surface on application of an ignition source. Below the flashpoint, there is not enough vapour available to support combustion. A flammable liquid is any liquid with a flashpoint below 37.8 °C. Liquids classified as combustible are harder to ignite and have a flashpoint of 37.8 °C and above. Flammable liquids ignite and burn easily at lower temperatures. Combustible liquids can burn at temperatures that are usually above room temperature. It is not actually the liquid that burns; it is the mixture of its vapours that burns in the oxygen in the air. Smaller hydrocarbons have weaker intermolecular forces and are more easily vaporised; therefore, they have lower flashpoints and are more flammable. The vaporisation rate increases as the temperature increases. Therefore, flammable and combustible liquids are more hazardous at temperatures higher than room temperature. If a fuel has a flashpoint below room temperature, such as petrol and alcohol, it is a safety hazard, as a spark could cause immediate ignition.
TABLE 9.4  Flashpoints of some organic compounds

<table>
<thead>
<tr>
<th>Substance</th>
<th>Flashpoint (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pentane</td>
<td>−40</td>
</tr>
<tr>
<td>hexane</td>
<td>−22</td>
</tr>
<tr>
<td>propanone</td>
<td>−19</td>
</tr>
<tr>
<td>methyl acetate</td>
<td>−10</td>
</tr>
<tr>
<td>ethyl ethanoate</td>
<td>−4</td>
</tr>
<tr>
<td>heptane</td>
<td>−4</td>
</tr>
<tr>
<td>1,1,1-trichloroethane</td>
<td>−1</td>
</tr>
<tr>
<td>methanol</td>
<td>11</td>
</tr>
<tr>
<td>ethanol</td>
<td>12</td>
</tr>
<tr>
<td>propan-2-ol</td>
<td>12</td>
</tr>
<tr>
<td>octane</td>
<td>13</td>
</tr>
<tr>
<td>propyl ethanoate</td>
<td>13</td>
</tr>
<tr>
<td>propan-1-ol</td>
<td>25</td>
</tr>
<tr>
<td>2-methylpropan-1-ol</td>
<td>28</td>
</tr>
<tr>
<td>butanol</td>
<td>29</td>
</tr>
<tr>
<td>trichloroethene</td>
<td>32</td>
</tr>
</tbody>
</table>

Alkenes and alkynes

Alkenes generally have similar physical properties to alkanes, except that the double bond limits rotation, resulting in some compounds forming cis–trans isomers, as discussed earlier in the chapter. Alkenes are more reactive than alkanes due to the high electron density available within their bonds and because the electrons in the carbon–carbon double bond are more accessible. Alkynes are compounds with low polarity, and they have physical properties that are essentially the same as those of the alkanes and alkenes. Many are highly flammable.

Revision questions

9. Describe the intramolecular and intermolecular bonding that exists in hydrocarbons.

10. Methane, CH₄, and candle wax, C₂₅H₅₂, are alkanes, but methane is a gas and candle wax is a solid. Explain why this occurs.

11. (a) Explain why the flashpoint of propan-1-ol is higher than the flashpoint of propan-2-ol.
    (b) Predict which of the compounds in (a) has the higher boiling point.

How do functional groups affect physical properties?

The presence of functional groups containing atoms other than hydrogen affects the properties of organic compounds. For example, the existence of a halogen in an organic molecule may result in a polar molecule. This would increase the strength of the intermolecular forces because dipole–dipole attractions would be present in addition to dispersion forces. When oxygen or nitrogen is involved, hydrogen bonding will be present.

Functional groups affect the properties of organic compounds.
Alcohols

The hydroxyl group in alcohols has a significant effect on properties. It can form hydrogen bonds with other alcohol or water molecules. Consequently, alcohols have a higher boiling point than corresponding alkanes, and smaller alcohols (three or fewer carbon atoms) are soluble in water. The boiling point of primary alcohols increases with increasing chain length due to the increasing number of dispersion forces, whereas the solubility decreases with increasing chain length due to the increasing length of the non-polar (hydrophobic) section of the molecules. The effect of the increased number of dispersion forces explains why volatility (tendency to vaporise) decreases with molecular size whereas viscosity increases.

Alcohols can form hydrogen bonds with other alcohol molecules or water.

This bar is made almost entirely of ice. The alcoholic drinks do not freeze even though they are served in ice vessels. Alcohol has a lower freezing point than water.

Many alcohols are highly flammable (with flashpoints below 37.8 °C), especially methanol (11 °C) and ethanol (17 °C). The flammability of alcohols decreases as the molecules increase in size and mass due to the increased strength of attraction between the molecules. Volatility also decreases as the size of the molecule increases.

You may have experienced the low flashpoint of ethanol at Christmas dinner when a flaming pudding has been ceremoniously delivered from the kitchen. The alcohol needs to be warmed because, if the temperature is too far below its flashpoint, it does not ignite as there are not enough vapours. It is interesting that the pudding is not burned in this process because the alcohol used
is about half water, and the evaporating water keeps the temperature low. Another aspect of Christmas chemistry is that the oxygen in the alcohol causes it to completely combust with a blue flame, as distinct from the yellow flame observed when burning hydrocarbons in candle wax, which produces a cooler, sooty and yellow flame.

**Carboxylic acids**

Like the alcohols, the first few members of the carboxylic acid homologous series are very soluble in water due to their capacity for strong hydrogen bonding with water molecules. Carboxylic acids have much higher boiling points than the previously discussed homologous series because carboxylic acid molecules can form two hydrogen bonds with each other.

Carboxylic acids are weak acids that only partially ionise in water. They are still stronger acids than their corresponding alcohols because the —OH group is more polarised in the —COOH group by the presence of the highly electronegative O atom of C=O. This double-bonded O atom attracts the electrons away from the —OH group. Therefore, the H (from the hydroxyl group) is more weakly bonded to O and is more easily donated.

Alcohols and carboxylic acids with a small number of carbon atoms are soluble in water. As the number of carbon atoms increases, they tend to be more insoluble.

Aldehydes, ketones and esters

Aldehydes and ketones are volatile compounds and are commonly found in perfumes and flavourings. Smaller molecules of these compounds are soluble
Aldehydes, ketones and esters are volatile compounds with distinctive odours because they can form hydrogen bonds with water, but solubility decreases with increasing length of the non-polar chain. These molecules cannot hydrogen bond with each other, but the polarity of the molecule means that the boiling point is higher than for similar-sized alkanes but lower than for alcohols and carboxylic acids, which have hydrogen bonding between hydroxyl groups.

Esters are very commonly found in plants and are responsible for many distinctive odours and flavours. Esters have lower boiling points than carboxylic acids. This is because esters cannot form hydrogen bonds with each other since they do not have an O—H bond. Esters with very short carbon chains are soluble in water, whereas those with longer chains are less soluble.

**Amines and amides**

Amines are very stable compounds that generally have strong or unpleasant odours, similar to rotting fish. They are weak bases because they can accept a proton. For example:

\[ \text{R—N:} + \text{H—O—H} \rightleftharpoons \text{R—N—H} + \text{OH}^- \]

Hydrogen bonding is possible in amines (due to the presence of N—H bonds) but their boiling points are lower than the corresponding alcohols. The first two members of the homologous series are gases at room temperature, whereas the larger members are liquids. As with the other polar compounds containing hydrogen bonding, the solubility decreases with chain length.

Amides have higher melting and boiling temperatures than similar-sized organic compounds due to their capacity to form multiple hydrogen bonds between molecules. Methanamide is a liquid at room temperature, but larger amides are solids because of the increased number of dispersion forces. Smaller amides are soluble but less soluble than comparable amines and carboxylic acids; their solubility is similar to that of esters.

**Revision questions**

12. Arrange the following compounds in order of increasing boiling point, and give reasons for your answer.

   - pentane, propane, propan-1-ol, pentan-1-ol

13. Explain why methane and ethane are insoluble in water whereas methanol and ethanol are soluble.

14. Use examples to explain whether replacing one or more hydrogens in methane with chlorine would always result in a polar molecule.

15. Explain which has the higher boiling point: butanamide, \( \text{CH}_3\text{CH}_2\text{CH}_2\text{CONH}_2 \), or ethyl ethanoate, \( \text{CH}_3\text{COOCH}_2\text{CH}_3 \).

**Reactions of organic compounds**

We are surrounded by organic reactions occurring both outside and inside our bodies. They include combustion of fuels for heating, transport and providing energy for our bodies to function. Most of the materials that we see around us have been produced as a result of reactions involving organic compounds. Can you name some of these products?
Reactions of alkanes and alkenes

Ethane and ethene can be used as starting materials in chemical reactions that lead to the production of many other organic substances, such as alcohols and carboxylic acids. The remainder of this chapter will look at some of the more common chemical reactions of organic compounds.

Combustion of alkanes and alkenes

Alkanes are saturated compounds with strong covalent C—C and C—H bonds, making them stable and fairly unreactive with many of the common laboratory reagents. They do not dissolve in water and do not react with acids, bases or strong oxidising agents in standard laboratory conditions. Their inert chemical behaviours make larger alkanes useful as non-polar solvents and lubricating oils. They do, however, undergo combustion with oxygen and react with the halogens.

Another important use of alkanes is as fuels. Although alkanes are kinetically stable in the presence of oxygen, combustion occurs when they are supplied with the necessary activation energy such as during ignition. The oxidation of alkanes is an exothermic reaction and the combustion products are carbon dioxide and water if a plentiful supply of oxygen is available and complete combustion occurs. For example:

\[
\text{C}_7\text{H}_{16}(g) + 11\text{O}_2(g) \rightarrow 7\text{CO}_2(g) + 8\text{H}_2\text{O}(g)
\]

Like the alkanes, alkenes burn in air to form carbon dioxide and water. For example, ethene combuts with oxygen according to the equation:

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

If the supply of oxygen is limited, carbon monoxide is formed instead of carbon dioxide.

The combustion of hydrocarbons and the alkanes in particular is of immense importance as this process is used in power stations, furnaces, domestic heaters, candles, internal combustion engines and many other devices that are essential for living in a technological society. An understanding of the nature of the combustion process is critical to the design of such devices. An important and familiar example is the petrol engine in cars.

Substitution reactions of alkanes

The alkanes undergo substitution reactions with the halogens in which the halogen atoms replace hydrogen. For example, the successive chlorination of methane to form chloromethanes occurs as follows:

\[
\text{CH}_4 + \text{Cl}_2 \xrightarrow{\text{UV light}} \text{CH}_3\text{Cl} + \text{HCl} \quad \text{(chloromethane)}
\]

\[
\text{CH}_3\text{Cl} + \text{Cl}_2 \xrightarrow{\text{UV light}} \text{CH}_2\text{Cl}_2 + \text{HCl} \quad \text{(dichloromethane)}
\]

\[
\text{CH}_2\text{Cl}_2 + \text{Cl}_2 \xrightarrow{\text{UV light}} \text{CHCl}_3 + \text{HCl} \quad \text{(trichloromethane)}
\]

\[
\text{CHCl}_3 + \text{Cl}_2 \xrightarrow{\text{UV light}} \text{CCl}_4 + \text{HCl} \quad \text{(tetrachloromethane)}
\]

Alkanes can undergo substitution reactions in which an atom or group of atoms replaces a hydrogen atom.
In the reactions at the bottom of the previous page, ultraviolet light is the source of energy to break the Cl—Cl bond to produce chlorine free radicals:

$$\text{Cl}_2 \rightarrow \text{Cl}^\cdot + \text{Cl}^\cdot$$

The small dot indicates an unpaired electron in the chlorine free radical, which makes it very reactive and able to attack the C—H bond.

Chloromethane (also known as methyl chloride) is used as a refrigerant and as a local anaesthetic (it acts by freezing the skin). Dichloromethane (also known as methylene dichloride) and tetrachloromethane (also known as carbon tetrachloride) are used as solvents.

Other alkanes react similarly with chlorine except that a larger number of chloroalkanes are formed. For example, ethane, C\textsubscript{2}H\textsubscript{6}, reacts with chlorine to form six chloroethanes and their isomers, as shown in the figure below.

Alkanes react with other halogens in a similar manner.
Cracking

Cracking is a process that uses heat and pressure, and sometimes a catalyst, to break larger hydrocarbon molecules into smaller molecules, including an alkene and hydrogen, or an alkane.

Sample problem 9.2

Write a semi-structural equation for each of the following.
(a) Ethene is produced from the cracking of propane.
(b) Carbon monoxide is produced by incomplete combustion of ethene in limited air.

\[
\begin{align*}
\text{(a) } & \text{CH}_3\text{CH}_2\text{CH}_3(g) \rightarrow \text{CH}_2\text{CH}_2(g) + \text{CH}_4(g) \\
\text{(b) } & \text{CH}_2\text{CH}_2(g) + 2\text{O}_2 \rightarrow 2\text{CO}(g) + 2\text{H}_2\text{O}(g)
\end{align*}
\]

Revision questions

16. Write an equation for the complete combustion of octane, C\textsubscript{8}H\textsubscript{18}.
17. The alkenes burn in a similar way to alkanes. Write an equation for the complete combustion of propene.
18. How many possible products are there when ethane reacts with bromine?
Write the name of each of these products.

Addition reactions of alkenes

Alkenes are more reactive than alkanes. They are unsaturated hydrocarbons and undergo addition reactions in which the C=C bond is broken and new single bonds are formed. This is because the energy required to break the double bond is less than the energy released in the formation of two single bonds. For example, hydrogenation of ethene produces ethane and releases energy.

\[
\text{H}_2\text{C} = \text{CH}_2(g) + \text{H}_2(g) \xrightarrow{\text{catalyst}} \text{H}_3\text{C} - \text{CH}_3(g)
\]

Substances that undergo addition reactions with alkenes include H\textsubscript{2}, Cl\textsubscript{2}, Br\textsubscript{2}, HCl, HBr, and HI. Addition of H\textsubscript{2} requires the presence of a catalyst, such as finely divided Pt, Pd or Ni. The others react without the need for catalysis. The equations below are examples of addition reactions with alkenes. Note that the reactants Br\textsubscript{2}, HCl and H\textsubscript{2} in these reactions add across the double bond. Therefore, 1,2-dibromopropane is the only product.

\[
\begin{align*}
\text{H}_2\text{C} = \text{CHCH}_3 & \text{ (propene)} + \text{Br}_2 \rightarrow \text{CH}_2\text{BrCHBrCH}_3 \\
\text{H}_2\text{C} = \text{CH}_2 & \text{ (ethene)} + \text{HCl} \rightarrow \text{CH}_3\text{CH}_2\text{Cl} \\
\text{H}_2\text{C} - \text{CH} = \text{CH}_2 & \text{ (but1-ene)} + \text{H}_2 \xrightarrow{\text{Pd}} \text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_3
\end{align*}
\]

The reaction of an alkene with bromine is used as a test for unsaturation. When red-brown bromine water is shaken with an unsaturated hydrocarbon, the reaction mixture becomes colourless due to the formation of the dibromo derivative.

Ethene is used as a raw material in a fast method to produce the large amounts of ethanol needed for industrial use. Ethene is mixed with steam and passed over a phosphoric acid catalyst at 330 °C. The reaction of the direct
Ethanol can be produced by hydration of ethene or a substitution reaction of a haloalkane.

The catalytic hydration of ethene in the vapour phase is an addition reaction and is shown below.

\[ \text{H}_2\text{C} = \text{CH}_2(g) + \text{H}_2\text{O}(g) \xrightarrow{\text{H}_3\text{PO}_4} \text{CH}_3\text{CH}_2\text{OH}(g) \]

**Addition polymerisation**

Another important reaction of some unsaturated hydrocarbons is **polymerisation**, a process in which many small molecules (monomers) are joined together to form a large molecule (polymer).

The **monomer** ethene, containing a double bond, undergoes **addition polymerisation** readily to form polyethene (also known as polyethylene or polythene). This product is one of the most commonly used synthetic polymers. Low-density (melting at lower temperature) polyethene is used for making film, garbage bags and plastic wrappers and for making moulded items such as squeeze bottles. High-density (containing linear rather than branched chains and melting at a higher temperature) polyethene is more rigid and is used for moulding items such as bread and drink crates.

This pie chart shows Australia’s consumption of different types of polymers.
A number of other useful plastics can be produced by making minor alterations to the ethene molecule.

(a) ethene  
\[
\text{\begin{tikzpicture}
\node[draw, circle, fill=white] (c) at (0,0) {\text{C}};
\node[draw, circle, fill=white] (c) at (1,0) {\text{C}};
\node[draw, circle, fill=white] (c) at (2,0) {\text{C}};
\node (h) at (0,0) {\text{H}};
\node (h) at (1,0) {\text{H}};
\node (h) at (2,0) {\text{H}};
\end{tikzpicture}}
\]

(b) vinyl chloride  
\[
\text{\begin{tikzpicture}
\node[draw, circle, fill=white] (c) at (0,0) {\text{C}};
\node[draw, circle, fill=white] (c) at (1,0) {\text{C}};
\node[draw, circle, fill=white] (c) at (2,0) {\text{C}};
\node (h) at (0,0) {\text{H}};
\node (h) at (1,0) {\text{H}};
\node (h) at (2,0) {\text{Cl}};
\end{tikzpicture}}
\]

(c) styrene  
\[
\text{\begin{tikzpicture}
\node[draw, circle, fill=white] (c) at (0,0) {\text{C}};
\node[draw, circle, fill=white] (c) at (1,0) {\text{C}};
\node[draw, circle, fill=white] (c) at (2,0) {\text{C}};
\node[draw, circle, fill=white] (c) at (2,1) {\text{C}};
\node[draw, circle, fill=white] (c) at (2,2) {\text{C}};
\node (h) at (0,0) {\text{H}};
\node (h) at (1,0) {\text{H}};
\node (h) at (2,0) {\text{H}};
\end{tikzpicture}}
\]

(d) tetrafluoroethene  
\[
\text{\begin{tikzpicture}
\node[draw, circle, fill=white] (c) at (0,0) {\text{C}};
\node[draw, circle, fill=white] (c) at (1,0) {\text{C}};
\node[draw, circle, fill=white] (c) at (2,0) {\text{C}};
\node[draw, circle, fill=white] (c) at (2,1) {\text{C}};
\node[draw, circle, fill=white] (c) at (2,2) {\text{C}};
\node (h) at (0,0) {\text{H}};
\node (h) at (1,0) {\text{H}};
\node (h) at (2,0) {\text{H}};
\end{tikzpicture}}
\]

(e) vinyl acetate  
\[
\text{\begin{tikzpicture}
\node[draw, circle, fill=white] (c) at (0,0) {\text{C}};
\node[draw, circle, fill=white] (c) at (1,0) {\text{C}};
\node[draw, circle, fill=white] (c) at (2,0) {\text{C}};
\node[draw, circle, fill=white] (c) at (2,1) {\text{C}};
\node[draw, circle, fill=white] (c) at (2,2) {\text{C}};
\node (h) at (0,0) {\text{H}};
\node (h) at (1,0) {\text{H}};
\node (h) at (2,0) {\text{COOCH}_3};
\end{tikzpicture}}
\]

(f) methyl methacrylate  
\[
\text{\begin{tikzpicture}
\node[draw, circle, fill=white] (c) at (0,0) {\text{C}};
\node[draw, circle, fill=white] (c) at (1,0) {\text{C}};
\node[draw, circle, fill=white] (c) at (2,0) {\text{C}};
\node[draw, circle, fill=white] (c) at (2,1) {\text{C}};
\node[draw, circle, fill=white] (c) at (2,2) {\text{C}};
\node (h) at (0,0) {\text{H}};
\node (h) at (1,0) {\text{H}};
\node (h) at (2,0) {\text{COOCH}_3};
\end{tikzpicture}}
\]

The structural formulas for (a) ethene, (b) vinyl chloride, (c) styrene, (d) tetrafluoroethene, (e) vinyl acetate and (f) methyl methacrylate. These monomers make, respectively, polyethene, PVC, polystyrene, Teflon, PVA and perspex. Note their obvious similarity to the structure of ethene.

This leads to a larger range of other useful plastics and polymers. Polyvinylchloride (PVC or ‘vinyl’) is a good example. The following represents the polymerisation of vinyl chloride to polyvinylchloride.

\[
\text{\begin{tikzpicture}
\node[draw, circle, fill=white] (c) at (0,0) {\text{C}};
\node[draw, circle, fill=white] (c) at (1,0) {\text{C}};
\node[draw, circle, fill=white] (c) at (2,0) {\text{C}};
\node[draw, circle, fill=white] (c) at (2,1) {\text{C}};
\node[draw, circle, fill=white] (c) at (2,2) {\text{C}};
\node (h) at (0,0) {\text{H}};
\node (h) at (1,0) {\text{H}};
\node (h) at (2,0) {\text{Cl}};
\end{tikzpicture}}
\]

or

\[
\text{\begin{tikzpicture}
\node[draw, circle, fill=white] (c) at (0,0) {\text{C}};
\node[draw, circle, fill=white] (c) at (1,0) {\text{C}};
\node[draw, circle, fill=white] (c) at (2,0) {\text{C}};
\node[draw, circle, fill=white] (c) at (2,1) {\text{C}};
\node[draw, circle, fill=white] (c) at (2,2) {\text{C}};
\node (h) at (0,0) {\text{H}};
\node (h) at (1,0) {\text{H}};
\node (h) at (2,0) {\text{Cl}};
\end{tikzpicture}}
\]

Sample problem 9.3

How many products are produced from the reaction between hydrogen chloride and but-2-ene? Write semi-structural equations to show the reaction.

\[
\text{\begin{tikzpicture}
\node[draw, circle, fill=white] (c) at (0,0) {\text{H}};
\node[draw, circle, fill=white] (c) at (1,0) {\text{C}};
\node[draw, circle, fill=white] (c) at (2,0) {\text{CH}_3};
\node[draw, circle, fill=white] (c) at (3,0) {\text{CH}_3};
\node (h) at (0,0) {\text{H}};
\node (h) at (1,0) {\text{H}};
\node (h) at (2,0) {\text{H}};
\node (h) at (3,0) {\text{H}};
\end{tikzpicture}}
\]

\[
\text{\begin{tikzpicture}
\node[draw, circle, fill=white] (c) at (0,0) {\text{H}};
\node[draw, circle, fill=white] (c) at (1,0) {\text{C}};
\node[draw, circle, fill=white] (c) at (2,0) {\text{H}};
\node[draw, circle, fill=white] (c) at (3,0) {\text{Cl}};
\node (h) at (0,0) {\text{H}};
\node (h) at (1,0) {\text{H}};
\node (h) at (2,0) {\text{Cl}};
\node (h) at (3,0) {\text{Cl}};
\end{tikzpicture}}
\]

However, the formulas for these potential products represent the same structure, so there is only one product.

Revision questions

19. Write the structural equations for the reactions of chlorine, hydrogen and hydrogen chloride with propene. Name the compounds formed.

20. Red bromine, Br₂, liquid is decolourised in an addition reaction with an alkene. Explain, with reference to ethane and ethene, how this reaction could demonstrate which substance is unsaturated.

21. Write the addition reaction for five monomers of tetrafluoroethene. The tetrafluoroethane monomer has the structural formula F₂C═CF₂.
Reactions of haloalkanes

As discussed earlier, haloalkanes can be prepared from alkanes using substitution reactions, or from alkenes using addition reactions. Haloalkanes are widely used but most do not occur naturally and must be produced synthetically. One of the first used was chloroform in the American Civil War (1861) where it was used as an anaesthetic for amputations and treatment of soldiers. Haloalkanes are now widely used in medicine, agriculture and production of polymers.

Although haloalkanes have a number of uses in their own right, they are particularly useful as precursors to the preparation of further substances. Alcohols can be prepared from haloalkanes in substitution reactions by reacting them with dilute solutions of either sodium or potassium hydroxide. For example, propan-2-ol can be made by reacting either 2-chloropropane or 2-bromopropane with dilute sodium hydroxide.

$$\text{CH}_3\text{CHCH}_3 + \text{NaOH} \rightarrow \text{CH}_3\text{CHCH}_3 + \text{NaBr}$$

Either 1-chloropropane or 1-bromopropane could be used to make propan-1-ol.

$$\text{CH}_3\text{CH}_2\text{CH}_2\text{Cl} + \text{NaOH} \rightarrow \text{CH}_3\text{CH}_2\text{CH}_2\text{OH} + \text{NaCl}$$

Reactions of alcohols

Alcohols undergo oxidation (as in combustion with oxygen from the air), substitution and more general types of oxidation reactions.

All alcohols are flammable and burn in air to produce carbon dioxide and water. For this reason, ethanol is added to petrol to produce various ethanol blends.

$$\text{CH}_3\text{CH}_2\text{OH}(l) + 3\text{O}_2(g) \rightarrow 2\text{CO}_2(g) + 3\text{H}_2\text{O}(g)$$

It is also possible to remove the $-\text{OH}$ functional group and substitute it with a different group. For example, the amine group, $-\text{NH}_2$, can be added by passing the appropriate alcohol and ammonia over an alumina, $\text{Al}_2\text{O}_3$, catalyst at high temperatures. The production of ethanamine from ethanol is an example of such a reaction.

$$\text{CH}_3\text{CH}_2\text{OH}(g) + \text{NH}_3(g) \xrightarrow{\text{alumina, high temperature}} \text{CH}_3\text{CH}_2\text{NH}_2(g) + \text{H}_2\text{O}(g)$$

Primary alcohols are easily oxidised in the laboratory, first to aldehydes and then to carboxylic acids, using either acidified permanganate, $\text{H}^+$/MnO$_4^-$aq, or acidified dichromate, $\text{H}^+$/Cr$_2$O$_7^{2-}$(aq), solution (or another oxidising agent). $[\text{O}]$ is the symbol for oxidising agent.
In these oxidation reactions, there is an increase in the oxygen to hydrogen ratio; that is, there is more oxygen and less hydrogen. The product of these reactions is a carboxylic acid. For example, propan-1-ol can be converted into propanoic acid as shown below.

\[ CH_3CH_2CH_2OH \xrightarrow{H^+/Cr_2O_7^{2-}} CH_3CH_2COOH \]

The oxidation of ethanol in wine takes place when it is left exposed to air for some time. Such wine has a sour taste of ethanoic acid, commonly known as acetic acid. The oxidation reaction that takes place is:

\[ C_2H_5OH(aq) + O_2(g) \rightarrow CH_3COOH(aq) + H_2O(l) \]

The reaction is catalysed by the presence of the micro-organism Acetobacter aceti in the exposed wine.

**Secondary alcohols** are oxidised to ketones, which do not undergo further oxidation. For example, propan-2-ol is oxidised to propanone.

\[ CH_3CHOHCH_3 \xrightarrow{H^+/Cr_2O_7^{2-}} (CH_3)_2CO \]

### Reactions of alcohols — summary

- **Substitution**
  - **Alkaline alcoholysis**: Ethanol reacts with hydrogen chloride to form ethyl chloride.
  - **Ester**: Ethanol reacts with acetic anhydride to form ethyl acetate.
- **Dehydration**
  - **Chloral**: Ethanol reacts with phosphorus pentachloride to form chloral.
  - **Ethereal ether**: Ethanol reacts with phosphorus oxychloride to form diethyl ether.
- **Oxidation**
  - **Acetone**: Ethanol reacts with potassium permanganate to form acetone.
  - **Aldehyde**: Ethanol reacts with chromium(VI) oxide to form acetaldehyde.
  - **Carboxylic acid**: Ethanol reacts with acidified potassium dichromate to form acetic acid.

### Revision questions

22. What type of reaction is involved in the conversion of a haloalkane to an alcohol?

23. Alcohols make good fuels. For example, ethanol is used as an additive in petrol. Write an equation for the combustion of ethanol (in a plentiful supply of oxygen).

24. (a) Name the alcohol on the right.
   (b) Give the name and structure of the product formed by the complete oxidation of this alcohol by acidified potassium dichromate.
Reactions of carboxylic acids

Carboxylic acids contain the carboxyl (—COOH) functional group. They are weak acids because they hydrolyse to a small extent in water according to the following general equation.

\[ \text{RCOOH} + \text{H}_2\text{O} \rightleftharpoons \text{RCOO}^- + \text{H}_2\text{O}^+ \]

(where \( R \) represents either a single H atom or an alkyl group such as —CH\(_3\) or —CH\(_2\)CH\(_3\)).

As expected, carboxylic acids show typical reactions of acids. For example, they react readily with bases, magnesium metal and metal carbonates. Due to the reaction shown above, solutions of carboxylic acids all have a pH less than 7.

An important subgroup of carboxylic acids are the fatty acids. A typical fatty acid may contain from 16 to 22 carbon atoms and is therefore insoluble. Fatty acids are also called long-chain carboxylic acids.

Another important reaction of carboxylic acids is their reaction with alcohols to form esters.

Formation of esters

Esters are products of condensation reactions between alcohols and carboxylic acids. A typical esterification (process of ester formation) reaction is the formation of ethyl ethanoate, \( \text{CH}_3\text{COOCH}_2\text{CH}_3 \), by heating ethanol, \( \text{C}_2\text{H}_5\text{OH} \), and ethanoic acid, \( \text{CH}_3\text{COOH} \), in the presence of an acid such as concentrated sulfuric acid. During the condensation reaction, a water molecule is produced. The ester formed is partially insoluble in water and can be purified by mixing it with cold water. The ester forms a sweet-smelling insoluble layer on top of the water, while sulfuric acid and unreacted ethanol and ethanoic acid dissolve in the water.

A typical esterification reaction

This process is called a condensation reaction because a small molecule (water) is split off as the two molecules join together. In general:

\[ \text{RCOOH} + \text{R}’\text{OH} \rightarrow \text{RCOOR’} + \text{H}_2\text{O} \]

carboxylic acid + alcohol \( \rightarrow \) ester + water

Esters can be converted back into their respective carboxylic acid and alcohol. This reaction is called hydrolysis, because water is used to split the ester molecule. Dilute acid or alkali is used as a catalyst and the mixture is heated.

\[ \text{ester} + \text{water} \xrightarrow{\text{catalyst}} \text{carboxylic acid} + \text{alcohol} \]
For example:

\[ \text{C}_4\text{H}_9\text{COOCH}_3 + \text{H}_2\text{O} \xrightarrow{\text{catalyst}} \text{C}_4\text{H}_9\text{COOH} + \text{CH}_3\text{OH} \]

- methyl butanoate
- butanoic acid
- methanol

**Sample problem 9.4**

Name the carboxylic acid and alcohol that have been reacted together to produce the ester \( \text{CH}_3\text{CH}_2\text{COOCH}_2\text{CH}_3 \).

**Solution:**

Since the ester link \(-\text{COO}\) is formed from the carboxylic acid reactant, the carboxylic acid must be propanoic acid, \( \text{CH}_3\text{CH}_2\text{COOH} \). The other reactant, the alcohol, must have \(-\text{OH}\) attached; therefore, the alcohol must be ethanol, \( \text{CH}_3\text{CH}_2\text{OH} \). The ester is called ethyl propanoate.

**Polyesters**

Polyesters are synthetic fibres used as a substitute for cotton and wool and are formed as a result of ester linkages between monomers to form the polymer. A common polyester is terylene, which is \( \text{poly} (\text{ethane-1,2-diyldibenzyene-1,4-dicarboxylate}) \). This polyester is made by the esterification of ethane-1,2-diol (also known as ethylene glycol) and benzene-1,4-dicarboxylic acid (also known as terephthalic acid). The structures of these molecules are shown in the figure below. These monomer units are joined together to form polyester.

Polyesters have great tensile strength and are used as the bonding resin in glass fibre plastics. They have a wide variety of uses in the textile industry. Many yachts have sails made of polyester as it is stronger than natural fibres and does not rot. Polyesters are mixed with cotton to make fabric for clothing. They are crease resistant and do not shrink or stretch. The oven bags that you use for roasting are also made of polyester as it can withstand high temperatures.
Reaction of carboxylic acids with amines

Small amines react in a similar manner to ammonia, which is a weak base. Therefore, carboxylic acids can donate a proton to a primary amine. An example is the acid-base reaction of ethanoic acid with methanamine to produce the salt methylammonium ethanoate. This salt is heated to over 100 °C, water is removed, and an amide is formed.

\[ \text{carboxylic acid} + \text{amine} \rightarrow \text{ammonium salt} \]

Reactions of carboxylic acids – summary

Revision questions

25. Write the equation representing the reaction between aqueous solutions of ethanoic acid and potassium hydroxide.

26. Name and draw the structures of two esters that are structural isomers of ethyl ethanoate.

27. Write an equation showing the reaction between methanol and propanoic acid.

28. Write an equation for the hydrolysis of butyl methanoate.
Organic pathways

There are often different pathways that organic reactions can follow to arrive at the same product. For instance, ethanol can be produced industrially in three ways: from ethene, from chloroethane and from ethane.

\[\text{ethene} \rightarrow \text{polyethene} \]
\[\text{H}_2(\text{g}) \quad \text{HCl}(\text{g}) \quad \text{H}_3\text{PO}_4(\text{aq}) \quad \text{H}_2(\text{g}) \quad \text{Cl}_2(\text{g}) \]
\[\text{Catalyst} \]
\[\text{ethane} \quad \text{chloroethane} + \text{HCl} \quad \text{ethanol} (\text{+ NaCl}) \quad \text{ethanoic acid} \]
\[\text{UV light} \quad \text{NaOH} \quad \text{Cr}_2\text{O}_7^{2-} \quad \text{NH}_3\text{CH}_3 \quad \text{CH}_3\text{CONHCH}_3, \text{H}_2\text{O} \]

**Revision questions**

29. Ethanol is used in alcoholic drinks and as a fuel and a solvent. Write the structural equations for the chemical reactions involved in the three ways that ethanol can be produced.

30. Describe the steps involved in producing the flavouring ethyl ethanoate, commencing with ethane.

**Measuring the efficiency of reactions**

There are a number of ways of evaluating the efficiency of a chemical process. Factors that could be considered include energy consumption, cost of chemicals and equipment, and environmental impact. Traditionally, the efficiency of a reaction has been determined by calculating the percentage yield.

**Percentage yield**

Sometimes when chemical reactions are performed, not all of the reactants are converted into the desired products. This could be due to many factors including:
1. the reaction being an equilibrium reaction and not going to completion
2. losses when transferring liquids between containers
3. losses when filtering
4. losses when heating
5. presence of unreactive impurities
6. decomposition of product
7. some liquid lost due to evaporation
8. other side reactions.

Chemical processes have been designed to manufacture the maximum amount of product from a given amount of raw materials. This is called the yield of a reaction and can be calculated using the following formula.

\[
\text{% yield} = \frac{\text{mass of product actually made}}{\text{theoretical mass of product that could be made}} \times 100
\]

The theoretical mass of the product is calculated using the given amount of the limiting reactant in the reaction.

**Sample problem 9.5**

2.18 g of ethanol, C₂H₅OH, is reacted with excess oxygen to produce 3.63 g of carbon dioxide according to the equation:

\[
\text{C}_2\text{H}_5\text{OH}(l) + 3\text{O}_2(g) \rightarrow 3\text{H}_2\text{O}(g) + 2\text{CO}_2(g)
\]

What is the percentage yield of this reaction?

**Solution:**

\[
\begin{align*}
n(\text{C}_2\text{H}_5\text{OH}) &= \frac{2.18 \text{ g}}{46.0 \text{ g mol}^{-1}} = 0.0474 \text{ mol} \\
\text{theoretical } n(\text{CO}_2) &= 2 \times 0.0474 = 0.0948 \text{ mol} \\
m(\text{CO}_2) &= 0.0948 \text{ mol} \times 44.0 \text{ g mol}^{-1} = 4.17 \text{ g} \\
\text{% yield (CO}_2) &= \frac{3.63 \text{ g}}{4.17 \text{ g}} \times 100 = 87.0\%
\end{align*}
\]

**Atom economy**

Calculating the yield, however, does not give an indication of how effectively the reactants have been used to generate the product with minimal waste. Atom economy is another method for measuring the efficiency of a reaction that takes into account the amount of waste produced.

\[
\text{reactant(s)} \rightleftharpoons \text{desired product} + \text{waste products}
\]

The atom economy of a reaction considers the amount of useful product produced from a particular amount of reactants. Measuring atom economy enables sustainable development by using less natural resources and minimizing waste. The optimal situation is where the yield of a reaction is maximized, and as many atoms as possible of the reactants are incorporated into the final product. It is preferable to decrease the amount of waste produced rather than have to deal with it at the end of the process.

Atom economy of a reaction can be calculated as:

\[
\text{% atom economy} = \frac{\text{mass of atoms in desired product}}{\text{mass of atoms in reactants}} \times 100
\]

**Sample problem 9.6**

Ethanol can be produced through the process of the fermentation of glucose in the absence of air.

\[
\text{C}_6\text{H}_12\text{O}_6(\text{aq}) \rightarrow 2\text{C}_2\text{H}_5\text{OH}(\text{aq}) + 2\text{CO}_2(\text{g})
\]

What is the atom economy of this reaction?
The desired product is ethanol. From the equation, 1 mole of glucose produces
2 moles of ethanol.

\[ M(\text{CH}_3\text{CH}_2\text{OH}) = 2 \times (2 \times 12.0 + 6 \times 1.0 + 1 \times 16.0) = 92.0 \text{ g mol}^{-1} \]

\[ M(\text{C}_6\text{H}_12\text{O}_6) = (6 \times 12.0 + 12 \times 1.0 + 6 \times 16.0) = 180 \text{ g mol}^{-1} \]

% atom economy = \( \frac{92.0}{180} \times 100 = 51.1\% \)

**Revision questions**

31. 30.3 g of ethanoic acid, CH₃COOH, is obtained from the oxidation of 26.8 g
of ethanol, C₂H₅OH. What is the percentage yield?

32. The complete combustion of 82.2 grams of propane produces a 73.2% yield.
How many grams of CO₂ would be produced?

33. Ethanol is manufactured industrially by reacting ethene with steam.

\[ \text{H}_2\text{C}--\text{CH}_2(\text{g}) + \text{H}_2\text{O}(\text{g}) \rightarrow \text{CH}_3\text{CH}_2\text{OH}(\text{g}) \]

(a) What is the % atom economy for this reaction?
(b) How does your answer to (a) compare with the calculated value in
sample problem 9.6?
(c) Which is the more efficient process?
(d) What other factors need to be considered when choosing which process
to use?

34. Two methods of producing hydrogen are shown below. Which has the
higher % atom economy?

Method 1: \( \text{CH}_4(\text{g}) + \text{H}_2\text{O}(\text{g}) \rightarrow \text{CO}(\text{g}) + 3\text{H}_2(\text{g}) \)

Method 2: \( \text{C}(\text{s}) + \text{H}_2\text{O} (\text{g}) \rightarrow \text{CO}(\text{g}) + \text{H}_2(\text{g}) \)

35. Methane and chlorine react to produce the solvent dichloromethane
according to the following equation.

\[ \text{CH}_4(\text{g}) + 2\text{Cl}_2(\text{g}) \rightarrow \text{CH}_2\text{Cl}_2(\text{g}) + 2\text{HCl}(\text{g}) \]

Calculate the % atom economy for the formation of \( \text{CH}_2\text{Cl}_2 \) in this reaction.
Summary

- The boiling points and other physical properties of organic compounds are influenced by the size, shape, structure and degree of polarisation of their covalent bonds. The intermolecular forces involved are dispersion forces, dipole–dipole attractions and hydrogen bonding.
- Isomers are compounds with the same molecular formula but different arrangements of atoms.
- In structural isomers, the atoms are arranged in different ways. Therefore, the chemical bonding is different. Structural isomers have different physical properties and, if different functional groups, chemical reactivities.
  - Chain isomers have different branching in the carbon chain.
  - Positional isomers show different positions of the particular functional group, which is usually indicated by a number in the name.
  - Functional isomers have the same atoms but different functional groups.
- Stereoisomers have the same sequence of bonded atoms, but the spatial arrangement of atoms differs.
  - cis–trans isomers are non-mirror-image molecules that have the same chemical bonding but different spatial arrangements of atoms. cis–trans isomers involve atoms or groups that can be either next to each other (cis isomer) or on opposite sides of the molecule (trans isomer) in restricted bonded compounds.
  - Enantiomers, or optical isomers, are mirror-image molecules that cannot be superimposed on each other. These molecules are described as chiral. Enantiomers have identical physical properties. Their chemical properties are also generally the same (except interactions with other molecules with optical properties). A chiral molecule rotates the plane of polarised light passing through the solution. Optical isomers can have radically different biological effects.
- Alkanes, alkenes and alkynes consist of non-polar molecules. Smaller molecular mass hydrocarbons are gases, and their boiling points increase with size due to the increased effect of dispersion forces. They are also insoluble in water but soluble in organic solvents. They are colourless and have low density.
- Alcohols are flammable and form hydrogen bonds with adjacent molecules. As a result, the smaller alcohols are liquids at room temperature and soluble in water. Solubility decreases with increasing chain length, whereas boiling point increases.
- Carboxylic acids form stronger hydrogen bonds than alcohols because their —OH group is more polarised due to the presence of the electron-withdrawing group C=O. The —COOH group is more acidic than the —OH group of alcohols, but carboxylic acids are much weaker acids than inorganic acids such as sulfuric acid.
- Smaller aldehydes have an unpleasant smell, but those with higher molar mass have a pleasant smell. Aldehydes and ketones have lower boiling points than alcohols because, although the C=O (carbonyl group) is polar, they do not have a hydroxyl group and do not form hydrogen bonds between molecules.
- Esters are volatile liquids at room temperature. Smaller molecules are polar and soluble in water, but their solubility decreases with increased size.
- All alkanes and alkenes undergo complete combustion with excess oxygen (air) to produce carbon dioxide and water. The exothermic nature of these reactions is the reason for the use of these hydrocarbons as fuels.
- Alkanes undergo substitution reactions with halogens to produce a range of haloalkanes.
- Alkenes are more reactive than alkanes (because of the C=C double bond) and undergo addition reactions with a wide range of substances.
- A number of monomers of alkenes can undergo addition polymerisation reactions to form large molecules called polymers.
- Alcohols burn in air to form carbon dioxide and water. They undergo substitution reactions, for example, with ammonia to form amines. Primary alcohols are oxidised to aldehydes and then to carboxylic acids using acidified dichromate or permanganate ions. Secondary aldehydes are oxidised to ketones but do not undergo further oxidation. Tertiary alcohols cannot be oxidised.
- Carboxylic acids are weak acids that undergo reactions with metals, bases and metal carbonates. Carboxylic acids react with amines in acid-base reactions, followed by dehydration to form amides.
- Esters are formed by condensation reactions between alcohols and carboxylic acids in the presence of heat and an acid catalyst. A water molecule is eliminated in the process.
- Polyesters are synthetic fibres manufactured from a diol and a dicarboxylic acid monomer.
- In some chemical reactions, not all of the reactants are converted into the desired products. The percentage
yield is the amount of product produced from a given amount of raw materials. It is calculated as:
\[
\text{% yield} = \frac{\text{mass of product actually made}}{\text{theoretical mass of product that could be made}} \times 100
\]

Atom economy is another method of measuring the efficiency of a reaction that takes into account the amount of waste produced. It is a measure of the amount of reactants that become useful products. It is calculated as:
\[
\text{% atom economy} = \frac{\text{mass of atoms in desired product}}{\text{mass of atoms in reactants}} \times 100
\]

Multiple choice questions

1. Which of the following compounds are isomers?
   A propanoic acid and ethanoic acid
   B propanol and propanal
   C propan-1-ol and propan-2-ol
   D propane and propan-1-ol

2. The two molecules shown below are best described as:
   A optical isomers
   B structural isomers
   C cis-trans isomers
   D stereoisomers.

3. Identify the chiral carbon atom in this molecule.
   A a
   B b
   C c
   D d

4. Enantiomers are:
   A stereoisomers with superimposable mirror images
   B stereoisomers that contain no chiral carbon atoms
   C stereoisomers with non-superimposable mirror images
   D stereoisomers with cis-trans isomerism.

5. Which properties are generally characteristic of hydrocarbons?
   A Low melting point and soluble in polar solvents
   B High melting point and soluble in polar solvents
   C Low melting point and insoluble in polar solvents
   D High melting point and insoluble in nonpolar solvents

6. Which of the following alkanes would you expect to have the lowest melting point?
   A octane
   B propane
   C pentane
   D butane

7. The lowest temperature at which a material produces a flammable vapour describes:
   A auto ignition temperature
   B flashpoint
   C fire point
   D ignition temperature.

8. Which of the following compounds is likely to have the lowest flashpoint?
   A cooking oil
   B pentane
   C ethanol
   D carbon dioxide

9. Which of the following is the most soluble in water?
   A \(\text{CH}_3\text{CH}_2\text{CH}_2\text{OH}\)
   B \(\text{CH}_3\text{CH}_2\text{OH}\)
   C \(\text{CH}_3\text{CH}_2\text{Cl}\)
   D ethanoic acid

10. Which of the following has the lowest boiling point?
    A 2,3-dimethylbutane
    B hexane
    C 2,3-dimethylpentane
    D 3-methylpentane

11. Which of the following compounds can form hydrogen bonds between its molecules?
    A \(\text{CH}_3\text{CH}_2\text{OCH}_2\text{CH}_3\)
    B \(\text{CH}_3\text{CH}_2\text{OH}\)
    C \(\text{CH}_3\text{CH}=\text{N(CH}_3\text{)}_2\)
    D \(\text{CH}_3\text{CH}_2\text{OH}\)

12. Which of the following has the greatest solubility in octane?
    A octanol
    B propylamine
    C pentane
    D ethanoic acid

13. Which of the following is an incorrect statement about amino groups?
    A They form aqueous solutions with a pH greater than 7.
    B They are found in amino acids.
    C They contain nitrogen.
    D They are non-polar.

14. When comparing the boiling points of aldehydes and ketones with compounds of similar molecular mass, it can be observed that their boiling points are:
    A higher than those of alcohols and alkanes
    B lower than those of alcohols and alkanes
    C higher than those of alcohols but lower than those of alkanes
    D higher than those of alkanes but lower than those of alcohols.
15. Which of the following is an incorrect statement about the properties of carboxylic acids?
A The boiling points of carboxylic acids are higher than alcohols of similar size.
B The smaller carboxylic acids are liquids at room temperature.
C Carboxylic acids cannot form hydrogen bonds with water.
D Carboxylic acids ionise only partially in water.

16. The following reaction is an example of:
\[ CH_2CH_2 + HCl \rightarrow CH_3CH_2Cl \]
A an addition reaction
B a substitution reaction
C a condensation reaction
D a combustion reaction.

17. Which of the following can be used to convert an alkene to an alkane?
A H₂O
B CO₂
C HCl
D H₂

18. 2-bromobutane reacts with KOH in ethanol to produce two products. The type of reaction involved is:
A addition
B acid–base
C oxidation
D substitution.

19. Which compound is converted to pentanal by acidified potassium dichromate solution?
A pentan-1-ol
B pentan-2-ol
C pentanone
D pentanoic acid

20. The polymer polymethylmethacrylate:
\[ \begin{array}{cccccc}
  & CH_3 & CH_3 & CH_3 & CH_3 \\
C & CH_2 & C & CH_2 & C & CH_2 & C & CH_2 \\
 & CO_2CH_3 & CO_2CH_3 & CO_2CH_3 & CO_2CH_3 \\
\end{array} \]
is formed from the monomer:
A \[ \begin{array}{c}
  & \text{CH}_3 \\
C & H_3C \rightarrow \text{CH} \\
 & \text{CO}_2\text{CH}_3 \\
\end{array} \]
B \[ \begin{array}{c}
  & \text{CH}_3 \\
C & H_3C = \text{CH} \\
 & \text{CO}_2\text{CH}_3 \\
\end{array} \]
C \[ \begin{array}{c}
  & \text{CH}_3 \\
C & H_2C = \text{CH} \\
 & \text{CO}_2\text{CH}_3 \\
\end{array} \]
D \[ \begin{array}{c}
  & \text{CH}_3 \\
C & \text{H}_2C = \text{C} \\
 & \text{CO}_2\text{CH}_3 \\
\end{array} \]

21. If a secondary alcohol is oxidised it produces:
A a ketone
B an aldehyde
C a carboxylic acid
D initially an aldehyde that reacts further to form a carboxylic acid.

22. Which of the following statements is incorrect?
A Ethanoic acid reacts with magnesium to form magnesium ethanoate and hydrogen.
B Oxidation of ethanol results in ethanoic acid.
C Ethanol dissociates in water to form the ethoxide ion and hydronium ion.
D Ethanoic acid does not dissolve in water.

23. The synthesis of polyester is:
A a condensation reaction where water molecules are used up
B a hydrolysis reaction where water molecules are eliminated
C the result of monomers of alcohol and carboxylic acid molecules joined together to form a long chain of ester
D the result of monomers of ringed alcohol and unsaturated hydrocarbon molecules joined together to form a long chain of ester.

24. Complete this sentence by selecting the correct option.
Carboxylic acids may be prepared by the oxidation of ...
I: primary alcohols II: secondary alcohols III: aldehydes IV: ketones.
A I only
B II and III
C I and III
D II and IV

25. If the theoretical yield for a reaction to produce propanoic acid is 126 grams and 95.0 grams of the product is actually made, what is the percentage yield?
A 132%
B 75.4%
C 32.6%
D 24.6%

Review questions

Properties and bonding
1. Describe the main intermolecular forces acting in the following compounds.
(a) CH₃Cl (e) H₂C═CH₂
(b) CH₃OCH₃ (f) CH₃CH₂CH₂CH₂CH₂CHO
(c) CBr₄ (g) cis-CH₂Cl₂
(d) CH₃CH₂NH₂ (h) HCOOH

2. The molar masses of propan-1-ol and butane are similar. Which would you expect to have the higher boiling point? Explain your answer.

3. Use a labelled diagram to explain why methanol, CH₃OH, is soluble in water.

4. Describe the trends in the following properties as the molar mass of a hydrocarbon increases.
(a) Volatility (c) Flashpoint
(b) Viscosity (d) Boiling point
Isomerism

5. Draw and label the cis and trans isomers with the molecular formula C₂H₂F₂.

6. Draw each of the following structures and place an asterisk (*) at the chiral carbon atom.
   (a) 2-chlorobutane
   (b) 2-methylbutan-1-ol
   (c) butan-2-ol
   (d) 3-methylhexane

7. but-2-ene reacts with HCl to form a pair of optically active isomers.
   (a) Draw diagrams to show the relationship between the two isomers.
   (b) State the structural requirement for a molecule to be able to exist as enantiomers.

8. Describe the type of isomerism present in each of the following pairs of compounds:
   (a)  
   (b)  
   (c)  

9. This compound has three structural isomers: X, Y and Z.

   Isomer X is a ketone.
   Isomer Y is an ester.
   Isomer Z reacts with sodium carbonate to produce carbon dioxide.

   Draw the structures of these isomers.

10. The enantiomers for the pain-relief medication ibuprofen are shown below.
    (a) List the functional groups present.
    (b) Identify and state the chiral carbon atom.

    (S)-ibuprofen (effective)
    (R)-ibuprofen (ineffective)

11. Name the molecule below, and explain why it can be described as being chiral.
    \[\text{CH}_3\text{CHClCH}_2\text{CH}_3\]

12. Explain why H₂NCH₂COOH can react with both an acid and a base.

Cracking

13. In a sample of natural gas coming ashore for processing, the ethane content is found to be 2.5%. This ethane may be subsequently separated and sold for cracking to produce ethene. This ethene may then be converted into ethanol — an important industrial solvent.
   (a) Write an equation for the production of ethanol from ethene.
   (b) Calculate the theoretical mass of ethanol that may ultimately be made from 10000 L of natural gas, collected at 10 atm and 15 °C.

Reactions of organic compounds

14. What is a substitution reaction? Write the equations of methane reacting with bromine and all the possible products formed.

15. Under what conditions can substitution reactions with alkanes occur?

16. Write equations for the reactions between:
   (a) ethene + HI
   (b) propene and H₂ (Pt catalyst)
   (c) ethene + Br₂
   (d) but-1-ene + Cl₂
   (e) methane + excess O₂
   (f) ethane + Cl₂
   (g) ethene + H₂O
   (h) but-2-ene + H₂.

17. For each of the following polymer backbones, identify the individual monomer.
   (a)  
   (b)  
   (c)  
   (d)  

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18. Write the formula of each of the substances X, Y and Z that are shown in the diagram below.

\[ \text{X} \quad \text{H}_2\text{O} \quad \text{Y} \]

\[ \text{Z} \quad \text{CH}_2\text{BrCH}_2\text{Br} \]

19. Write structural formulas for the products formed when the following substances are reacted together under appropriate conditions.
(a) \( \text{H}_2\text{C}==\text{CH}_2 \) and \( \text{H}_2\text{O} \)
(b) \( \text{H}_3\text{C}==\text{CH}==\text{CH}_2 \) and \( \text{H}_2\text{O} \)
(c) \( \text{H}_3\text{C}==\text{CH}_2 \) and \( \text{Br}_2 \)
(d) \( \text{H}_2\text{C}==\text{CH}_2 \) and \( \text{HCl} \)
(e) \( \text{H}_3\text{C}==\text{CH}==\text{CH}_2 \) with itself

20. (a) Name the following ester.

(b) Name and draw the structures of the reactants required to produce this ester.

21. Describe a simple chemical test that could be used to distinguish an unsaturated hydrocarbon from a saturated one.

22. Ethene is an important material not only for the production of polymers but also for the manufacture of many other chemicals. Write equations to show the production of three such chemicals from ethene.

23. (a) Draw and name the two possible products formed from the reaction between \( \text{HCl} \) and propene.

(b) Why is only one product formed in the reaction of \( \text{HCl} \) and but-2-ene?

24. Calculate the volume of ethene required to produce 100 kg of polyethylene at 25 °C and 250 atm pressure.

25. Polypropene is produced by the polymerisation of a particular monomer.
(a) What is meant by the term ‘monomer’?
(b) What is the name of the monomer used in the above process?
(c) What is the source of this monomer in industry?
(d) Which other very important substance, which can also act as a monomer, is also formed by catalytic cracking?

26. Synthetic rubber uses buta-1, 3-diene and styrene to make styrene-butadiene rubber (SBR).
(a) Draw the structures of buta-1, 3-diene and styrene, and hence explain why both these substances are suitable monomers for this process.
(b) What is the main industrial source of buta-1,3-diene?
(c) From what important chemical is styrene made?

27. (a) Draw sections of the polymers that are formed from the following monomers.

(i) \( \text{CH}_3\text{COOCH_3} \)

(ii) \( \text{CH_3COOCH_3} \)

(iii) \( \text{CF_2CF_2} \)

(b) Suggest a name for each of the polymers above. Try to find out their common names and some uses for each one.

28. One way of manufacturing vinyl chloride (chloro-ethene) is initially to produce ethyne (acetylene, \( \text{C}_2\text{H}_2 \)) and then to react this with hydrogen chloride. The equations are:

\[ \text{CaC}_2(s) + 2\text{H}_2\text{O}(l) \rightarrow \text{C}_2\text{H}_2(g) + \text{Ca(OH)}_2(s) \]

\[ \text{C}_2\text{H}_2(g) + \text{HCl}(g) \rightarrow \text{C}_2\text{H}_3\text{Cl}(g) \]

(a) Draw the structural formulas for acetylene and vinyl chloride.

(b) Calculate the mass of calcium carbide required to make 500 g of vinyl chloride.

(c) What type of reaction is represented by the second equation above?

(d) Draw a section of the polymer that vinyl chloride makes.

29. Shown below is a small section of a polymer that is made from two different monomers.

\[ \text{A} \quad \text{B} \quad \text{H} \quad \text{H} \quad \text{A} \quad \text{B} \quad \text{H} \quad \text{H} \]

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

\[ \text{D} \quad \text{E} \quad \text{H} \quad \text{H} \quad \text{D} \quad \text{E} \quad \text{H} \quad \text{H} \]
(a) Could the monomers DAC=CBE and H₂C=CH₂ have been used to make this polymer?
(b) Could the monomers H₂C=CBE and H₂C=CAD have been used to make this polymer?

30. What type of reaction is the esterification process? What are the reactants and products?

31. Carboxylic acids can be made from alkanes. Describe the stages and products formed in the conversion of ethane to ethanoic acid. Draw structures and name the products at each stage.

Efficiency of reactions

32. When 11.5 g of methanol was treated with excess potassium permanganate, 13.2 g of methanoic acid was obtained. Balance the following equation by first balancing the relevant half-equations, and then calculate the percentage yield.

\[ \text{CH}_3\text{OH} + \text{MnO}_4^- \rightarrow \text{HCOOH} + \text{MnO}_2 \]

33. Explain why the atom economy of this reaction is 100%.

\[ \text{H}_2\text{C}=\text{CH}_2 + \text{H}_2\text{O} \rightarrow \text{CH}_3\text{CH}_2\text{OH} \]

34. 2-methylpropan-1-ol can be used to manufacture diesel and jet fuel. The first step in the process is the production of 2-methylpropene.

\[ \text{C}_4\text{H}_{10}\text{O}(l) \rightarrow \text{C}_4\text{H}_8(g) + \text{H}_2\text{O}(g) \]

Calculate the % atom economy for this reaction.
Exam practice questions

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

Multiple choice questions
1. Which of the following statements correctly describes cis-trans isomers?
   A They have different arrangements around a double bond.
   B They have an asymmetric carbon atom that makes them mirror images.
   C They have the same physical properties.
   D They have different molecular formulas.
   1 mark

2. Burning ethane in excess oxygen produces carbon dioxide and water in the ratio:
   A 1 : 3  
   B 1 : 1  
   C 2 : 3  
   D 2 : 1.
   1 mark

3. The ester with the formula CH₃COOC₂H₅ is made from:
   A propanol and ethanoic acid
   B ethanol and methanoic acid
   C methanol and ethanoic acid
   D ethanol and ethanoic acid.
   1 mark

4. An unknown reactant, X, is oxidised by acidified potassium dichromate solution to produce a substance that does not react with solid sodium carbonate. Which of the following molecules could represent the structure of X?
   A CH₃CH₂CH₂OH
   B CH₃CH(OH)CH₃
   C CH₃OCH₃
   D CH₃COOH
   1 mark

Extended response questions
1. (a) For each of the following monomers, draw the structure of part of a chain comprised of three monomers.
   (i) CHClCHCl
   (ii) CH₂CHCN
   1 mark

   (b) What type of polymerisation is this?
   2 marks

2. Pentyl ethanoate has the sweet-smelling aroma of banana. Its semi-structural formula is CH₃COOCH₂CH₂CH₂CH₂CH₃.
   (a) In which organic group does this compound belong?
   1 mark

   (b) Apart from flavourings, what is another use for this type of compound?
   1 mark

   (c) Reacting ethanoic acid with what other substance can produce pentyl ethanoate?
   1 mark

   (d) Name the type of reaction that takes place.
   1 mark

3. Consider the following reaction pathway.
   but-2-ene $\xrightarrow{\text{Step 1}}$ CH₃CHCICH₂CH₃ $\xrightarrow{\text{Step 2}}$ substance X $\xrightarrow{\text{Step 3}}$ butanone
   (a) Name substance X and draw its structure.
   2 marks

   (b) Why does but-2-ene show cis-trans isomerism but but-1-ene does not?
   2 marks

   (c) To which group of compounds does but-2-ene belong?
   1 mark

   (d) Name the type of reaction occurring in step 1.
   1 mark