Organic Chemistry: Reactions of Organic Compounds

1 Reactions of Organic Compounds

Organic compounds undergo a wide variety of chemical reactions. Understanding these allows us to synthesize new molecules, analyze natural compounds, and explain biological and industrial processes.

1.1 1. Combustion

Definition: Combustion is a reaction in which an organic compound reacts with oxygen (O_2), typically producing carbon dioxide (CO_2), water (H_2O), and energy (heat/light).

1.1 Complete Combustion

Occurs with an excess of oxygen.
General equation for a hydrocarbon:

$$C_xH_y + O_2 \longrightarrow CO_2 + H_2O$$

Example: Combustion of propane

$$C_3H_8 + 5\,O_2 \longrightarrow 3\,CO_2 + 4\,H_2O$$

Characteristics:

- Blue, non-sooty flame
- Maximum energy released
- Products: CO_2 and H_2O

1.2 Incomplete Combustion

Occurs when oxygen is limited. Produces carbon monoxide (CO), carbon (soot), water, and less energy.

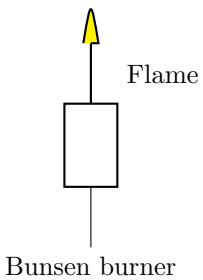
$$2\,CH_4 + 3\,O_2 \longrightarrow 2\,CO + 4\,H_2O$$

or

$$CH_4 + O_2 \longrightarrow C + 2\,H_2O$$

Hazards: Carbon monoxide is toxic; soot can cause respiratory problems.

1.3 Diagram: Combustion Apparatus



1.2 2. Substitution Reactions

Definition: In substitution reactions, an atom or group in a molecule is replaced by another atom or group.
Common in: Saturated hydrocarbons (alkanes) and aromatic compounds.

2.1 Example: Halogenation of Methane

$$\mathrm{CH_4 + Cl_2 \xrightarrow{hv} CH_3Cl + HCl}$$

Where light (hv) initiates the reaction.
Mechanism: Free radical substitution (initiation, propagation, termination).
Stages:

- **Initiation:** Formation of free radicals
$$\mathrm{Cl_2 \xrightarrow{hv} 2\,Cl\cdot}$$
- **Propagation:**
$$\mathrm{Cl\cdot + CH_4 \longrightarrow HCl + CH_3\cdot}$$
$$\mathrm{CH_3\cdot + Cl_2 \longrightarrow CH_3Cl + Cl\cdot}$$
- **Termination:** Combination of free radicals
$$\mathrm{Cl\cdot + Cl\cdot \longrightarrow}$$
$$\mathrm{CH_3\cdot + Cl\cdot \longrightarrow}$$

2.2 Diagram: Substitution Mechanism

$$\mathrm{CH_4 \xrightarrow{+\ Cl_2,\ UV} CH_3Cl}$$

2.3 Further Substitution: Multiple Products

Example: Bromination of Propane

$$\mathrm{C_3H_8 + Br_2 \longrightarrow C_3H_7Br + HBr}$$

Possible Products:

- 1-bromopropane ($\mathrm{CH_3CH_2CH_2Br}$)
- 2-bromopropane ($\mathrm{CH_3CHBrCH_3}$)

Question: Why are two different products possible?
Answer: Because the Br atom can substitute a hydrogen on either the terminal or central carbon atom.

1.3 3. Addition Reactions

Definition: Atoms or groups are added to a molecule, breaking multiple bonds (double/triple).
Common in: Alkenes and alkynes.

3.1 Example: Bromination of Ethene

$$\mathrm{CH_2{=}CH_2 + Br_2 \longrightarrow CH_2Br{-}CH_2Br}$$

3.2 Mechanism: Electrophilic Addition

1. The double bond acts as a nucleophile attacking Br_2.
2. A cyclic bromonium ion intermediate forms.
3. Br^- attacks, opening the ring.

3.3 Diagram: Addition

$$H_2C{=\!=}CH_2 + Br_2 \rightarrow Br{-}CH_2{-}CH_2{-}Br$$

3.4 Markovnikov's Rule

In addition of HX to asymmetric alkenes, H attaches to the carbon with more hydrogens.

$$CH_3CH{=}CH_2 + HBr \longrightarrow CH_3CHBrCH_3$$

Major product: 2-bromopropane

3.5 Other Addition Reactions

Hydrogenation: Addition of hydrogen to unsaturated compounds (alkenes/alkynes), usually with a metal catalyst (Ni, Pt, or Pd).

$$CH_2{=}CH_2 + H_2 \xrightarrow{Ni} CH_3CH_3$$

Hydration: Addition of water to alkenes to form alcohols.

$$CH_2{=}CH_2 + H_2O \xrightarrow{H_2SO_4} CH_3CH_2OH$$

Hydrohalogenation: Addition of HX (X = Cl, Br, I) to alkenes.

$$CH_2{=}CH_2 + HBr \longrightarrow CH_3CH_2Br$$

1.4 3.6 Testing for Unsaturation

Bromine Water Test:
Alkenes/alkynes decolorize orange bromine water (addition), while alkanes do not (no reaction).

1.5 4. Elimination Reactions

Definition: Atoms or groups are removed from a molecule, usually forming double or triple bonds.

Example: Dehydration of Ethanol

$$CH_3CH_2OH \xrightarrow{H_2SO_4,\ \Delta} CH_2{=}CH_2 + H_2O$$

Example: Dehydrohalogenation

$$CH_3CH_2Br + KOH\ (alc) \longrightarrow CH_2{=}CH_2 + KBr + H_2O$$

4.3 Mechanistic Details of Elimination

E1 and E2 Mechanisms:

- **E1 (Unimolecular):** Two steps (formation of carbocation, then elimination)
- **E2 (Bimolecular):** One-step, concerted elimination (base removes H, leaving group leaves)

Example: E2 Elimination

$$CH_3CH_2Br + OH^- \longrightarrow CH_2{=}CH_2 + Br^- + H_2O$$

1.6 5. Polymerization

Definition: Many small molecules (monomers) join to form a large molecule (polymer).

5.1 Addition Polymerization

Monomers with double bonds form addition polymers.

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

Polyethene

5.2 Condensation Polymerization

Monomers with two functional groups join, releasing small molecules (e.g., water).

$$\mathrm{nHO{-}CH_2{-}CH_2{-}OH + nHOOC{-}COOH \longrightarrow [-O{-}CH_2{-}CH_2{-}OOC{-}CO-]_n + 2\,nH_2O}$$

Polyester formation

1.7 5.3 Biological Polymerization

Example: Protein Synthesis (Polypeptide Formation)

$$n\ \underset{\text{amino acid}}{H_2N{-}CHR{-}COOH} \longrightarrow \underset{\text{polypeptide}}{[-NH{-}CHR{-}CO-]_n} + (n\text{-}1)\ H_2O$$

Peptide Bond Formation:

$$H_2N\text{-}CHR\text{-}COOH + H_2N\text{-}CHR \longrightarrow H_2N\text{-}CHR\text{-}CO\text{-}NH\text{-}CHR + H_2O$$

1.8 6. Oxidation and Reduction (Redox) Reactions

Oxidation: Gain of oxygen, loss of hydrogen, or increase in oxidation state
Reduction: Loss of oxygen, gain of hydrogen, or decrease in oxidation state

6.1 Oxidation Examples

- Primary alcohol → Aldehyde → Carboxylic acid

$$CH_3CH_2OH + [O] \longrightarrow CH_3CHO + H_2O$$

$$CH_3CHO + [O] \longrightarrow CH_3COOH$$

- Secondary alcohol → Ketone

$$(CH_3)_2CHOH + [O] \longrightarrow (CH_3)_2CO + H_2O$$

6.2 Reduction Examples

- Aldehyde → Primary alcohol

$$CH_3CHO + 2\,[H] \longrightarrow CH_3CH_2OH$$

- Ketone → Secondary alcohol

$$CH_3COCH_3 + 2\,[H] \longrightarrow CH_3CHOHCH_3$$

6.3 Oxidation States and Organic Redox

Oxidation State Table:

Functional Group	Relative Oxidation State
Alkane	Lowest
Alcohol	Higher
Aldehyde/Ketone	Higher
Carboxylic Acid	Highest

Summary:

- *Oxidation:* Alkane → Alcohol → Aldehyde/Ketone → Carboxylic Acid
- *Reduction:* Carboxylic Acid → Aldehyde/Ketone → Alcohol → Alkane

Worked Example:

Oxidation of Ethanol (Lab Test for Alcohols):

$$CH_3CH_2OH + 2\,[O] \xrightarrow{K_2Cr_2O_7/H_2SO_4} CH_3COOH + 2\,H_2O$$

Observation: Orange $K_2Cr_2O_7$ turns green.

7. Summary Diagrams

Addition vs. Substitution vs. Elimination:

Addition:

$$CH_2{=}CH_2 \xrightarrow{H_2/Ni} CH_3{-}CH_3$$

$$CH_4 \xrightarrow[Cl_2/UV]{} CH_3Cl$$

Substitution:

$$CH_3CH_2OH \xrightarrow[\text{conc}\cdot H_2SO_4/\Delta]{} CH_2{=}CH_2$$

Elimination:

8. Practice/Cognitive Challenge (Extended)

1. Write the balanced equation for the bromination of propane and identify the possible products.
2. Explain, using electron movement, why alkenes undergo addition while alkanes undergo substitution.
3. Draw and describe the mechanism for the addition of HBr to propene (show Markovnikov product).
4. Predict the major organic product when 2-methylpropene reacts with HCl and explain (Markovnikov's rule).
5. Compare addition and elimination reactions using equations and diagrams.
6. Draw the full mechanism for the free radical bromination of methane.

7. Describe how you could distinguish between an alkene and an alkane experimentally.
8. Given the compound 2-methylbut-2-ene, predict the major product when it undergoes acid-catalyzed hydration.
9. Explain, with equations, how polyamides (e.g., nylon) are formed.
10. Design an experiment to oxidize a secondary alcohol to a ketone and describe the observations.

9. Summary Table

Reaction	**Typical Substrate**	**Key Reagent/Condition**	**Product**
Combustion	Alkane	O_2, heat	$CO_2 + H_2O$
Substitution	Alkane	Halogen, UV	Haloalkane
Addition	Alkene	Br_2, H_2, HX	Alkane/haloalkane
Elimination	Alcohol/Haloalkane	Conc. H_2SO_4/base	Alkene
Polymerization	Alkene/diol/dicarboxylic acid	Initiator/condensation	Polymer
Redox	Alcohols	[O], [H]	Aldehyde, acid, ketone, alcohol