La-Net

CHM102

GENERAL CHEMISTRY II

Course Code: CHM 102
Course Title: General Chemistry II
Course Unit: 2 Units

Series 1: Foundations and Development of Organic Chemistry
Series 2: Carbon Allotropes and Fullerenes in Modern Chemistry
Series 3: Electronic Theory, Structure Determination, and Stereochemistry
Series 4: Organic Functional Groups, Nomenclature, and Reaction Mechanisms
Series 5: Comparative and Transition Metal Chemistry

Series 1: Foundations and Development of Organic Chemistry

Series Outline

Part 1: Historical Survey of Organic Chemistry

- Origins and early discoveries
- Milestones in organic chemistry development
- Importance of organic chemistry in science and industry

Part 2: Significance of Organic Chemistry

- Role in pharmaceuticals and medicine
- Applications in agriculture and food chemistry
- Contributions to materials science and everyday life

Part 3: Organic Chemistry in Modern Context

- Relationship with biochemistry and nanochemistry
- Emerging trends and innovations
- Future directions and global impact

Introduction

Organic chemistry is often described as the chemistry of life because it underpins the structure and behaviour of countless compounds that form the basis of living systems, medicines, fuels, and materials. Understanding its foundations provides learners with the historical context and appreciation of how the discipline has evolved, while also highlighting its relevance to modern science and technology. This Series sets the stage for deeper exploration of organic chemistry throughout the course.

The aim of this Series is to introduce you to the historical development and importance of organic chemistry, while equipping you with an understanding of its significance in both scientific progress and everyday applications.

We shall commence this Series by examining the historical survey of organic chemistry, tracing its origins, early discoveries, and milestones that shaped the discipline. Next, we will explore the significance of organic chemistry, considering its role in medicine, agriculture, and materials science. Finally, we will conclude with an examination of organic chemistry in the modern context, where we will connect its foundations to biochemistry, nanochemistry, and emerging innovations that continue to transform the world.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **2.1** define the origins and early discoveries that shaped the foundations of organic chemistry,
- **2.2** explain key milestones in the historical development of organic chemistry and their scientific significance,
- **2.3** analyse the importance of organic chemistry in fields such as medicine, agriculture, and materials science,
- **2.4** evaluate the modern relevance of organic chemistry by linking it to biochemistry, nanochemistry, and emerging innovations.

2.1 Historical Survey Of Organic Chemistry

2.1.1 Origins and early discoveries

Organic chemistry began as the study of compounds derived from living organisms. The term **organic compounds** refers to chemical substances containing carbon, often combined with hydrogen, oxygen, nitrogen, and other elements. Early chemists believed that these compounds could only be produced by living systems, a theory known as **vitalism**, which suggested that a special "vital force" was required. This belief was challenged in 1828 when Friedrich Wöhler synthesised **urea**, an organic compound, from ammonium cyanate, an inorganic salt. This landmark experiment demonstrated that organic compounds could be created artificially, marking the beginning of modern organic chemistry.
Fill in the blank: The theory that organic compounds could only be produced by living organisms was called __________.

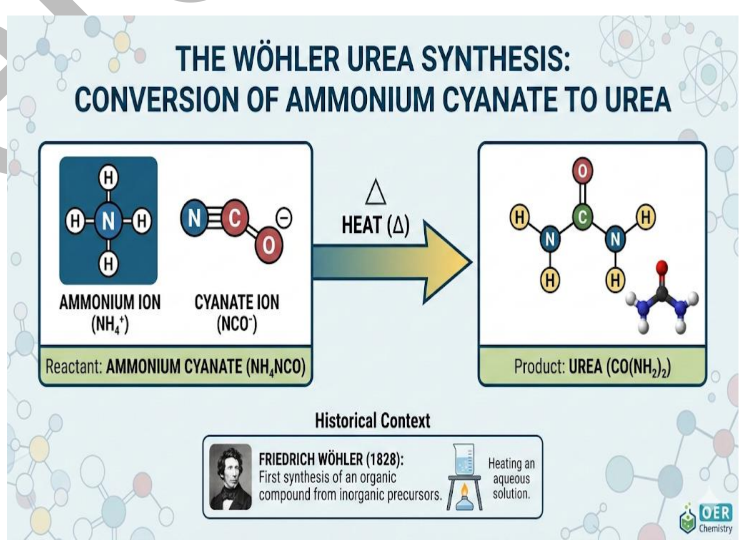

Figure 2.1 Wöhler's experiment disproving vitalism.

2.1.2 Milestones in organic chemistry development

Following Wöhler's discovery, organic chemistry advanced rapidly. Chemists began to isolate and identify compounds such as **alkanes** (saturated hydrocarbons), **alkenes** (unsaturated hydrocarbons with double bonds), and **alkynes** (unsaturated hydrocarbons with triple bonds). The development of structural theory by August Kekulé, who proposed the ring structure of **benzene**, was another milestone. Later, advances in spectroscopy and chromatography allowed scientists to determine the structures and properties of organic molecules with greater precision.
Fill in the blank: August Kekulé is credited with proposing the ring structure of __________.

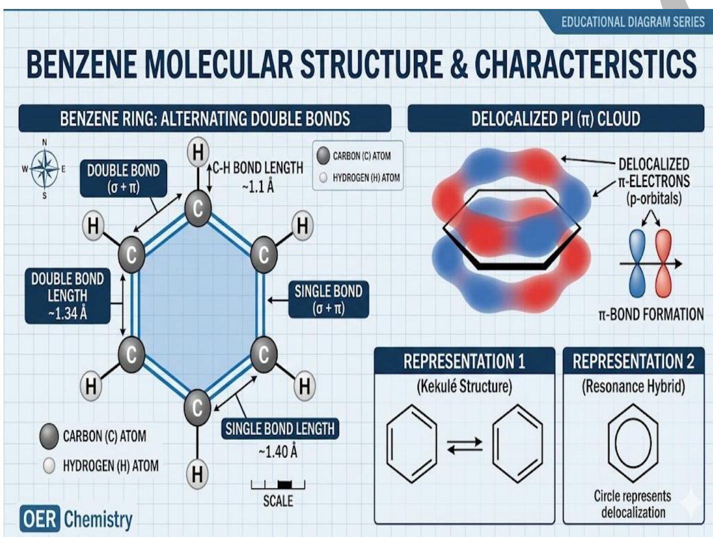

Plate 2.1 Structural representation of benzene.

2.1.3 Importance of organic chemistry in science and industry

Organic chemistry is central to many industries and scientific fields. In **pharmaceuticals**, it provides the basis for drug design and synthesis. In **agriculture**, organic compounds are used in fertilisers, pesticides, and herbicides. In **materials science**, organic chemistry contributes to the development of plastics, dyes, and synthetic fibres. The ability to design and manipulate organic molecules has transformed modern life, making organic chemistry a cornerstone of technological progress.
Fill in the blank: Organic chemistry contributes to materials science through the development of __________, dyes, and synthetic fibres.

Field	Key Applications	Examples
Medicine	Drug discovery, vaccine development, and diagnostic tools.	Antibiotics (Penicillin), Ibuprofen, and mRNA lipid nanoparticles.
Agriculture	Enhancing crop yields and protecting plants from pests.	Synthetic fertilizers, biodegradable pesticides, and pheromones.
Materials Science	Creation of polymers, fibers, and electronic components.	Polyethylene plastics, Kevlar, and Organic LEDs (OLEDs).

Box 2.1 Selected applications of organic chemistry

Pilot Questions:

1. What was the central belief of vitalism, and how did Wöhler's experiment challenge it?
2. How did the discovery of benzene's ring structure contribute to the development of structural theory in organic chemistry?
3. Why is the ability to artificially synthesise organic compounds considered a turning point in chemistry?

2.2 Significance Of Organic Chemistry

2.2.1 Role in pharmaceuticals and medicine

Organic chemistry plays a crucial role in the design and synthesis of **pharmaceuticals**, which are chemical substances used to diagnose, treat, or prevent diseases. Many life-saving drugs, such as antibiotics, antivirals, and anticancer agents, are organic compounds. The ability to manipulate molecular structures allows chemists to improve drug effectiveness and reduce side effects. For example, the development of aspirin from salicylic acid illustrates how organic chemistry transforms natural compounds into safer and more effective medicines.
Fill in the blank: Aspirin was developed from __________ acid to reduce side effects and improve patient safety.

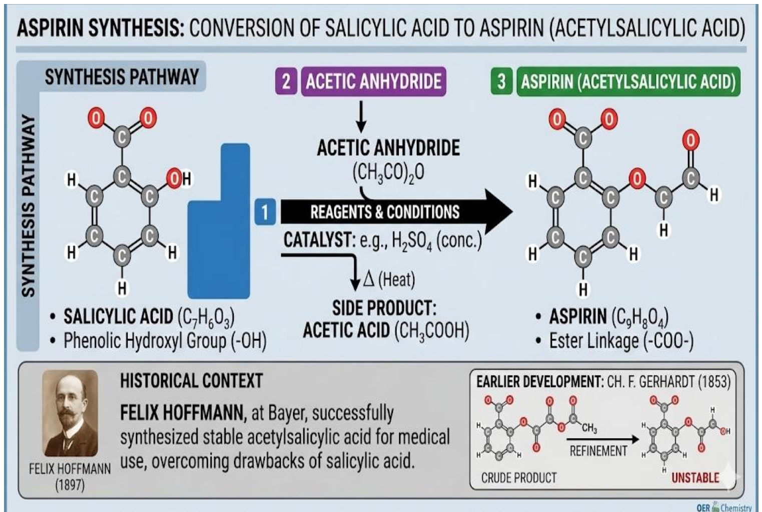

Figure 2.2 Synthesis of aspirin from salicylic acid.

2.2.2 Applications in agriculture and food chemistry

In agriculture, organic chemistry provides the foundation for **fertilisers**, **pesticides**, and **herbicides**, which enhance crop yield and protect plants from pests and diseases. Organic compounds are also used in food chemistry, where they contribute to flavour, preservation, and nutritional value. For instance, organic preservatives help extend the shelf life of packaged foods, while flavouring agents improve taste. These applications demonstrate how organic chemistry supports global food security and quality.

Fill in the blank: Organic chemistry contributes to agriculture through the development of fertilisers, __________, and herbicides.

Plate 2.2 Application of organic compounds in agriculture.

2.2.3 Contributions to materials science and everyday life

Organic chemistry is central to **materials science**, which involves the design and production of new materials. Organic compounds are used to create plastics, synthetic fibres, dyes, and polymers that shape modern industries. Everyday items such as clothing, packaging, paints, and electronic devices rely heavily on organic materials. The versatility of carbon-based compounds makes organic chemistry indispensable in developing products that are durable, lightweight, and adaptable to diverse needs.

Fill in the blank: Organic chemistry contributes to materials science through the development of plastics, __________, and synthetic fibres.

Material Category	Contribution of Organic Chemistry	Common Examples
Polymers & Plastics	Synthesis of long-chain hydrocarbons through polymerization.	Polyethylene (bottles), PVC (pipes), Teflon (non-stick coating).
Synthetic Fibres	Creation of high-tensile organic chains for textiles and industry.	Nylon (clothing), Polyester, Kevlar (body armor).
Dyes & Pigments	Engineering chromophores (parts of molecules that absorb light).	Indigo (denim dye), Azo dyes, Fluorescein (medical tracing).
Advanced Materials	Development of organic semiconductors and "smart" materials.	OLED screens, Conductive polymers, Hydrogels for medicine.

Box 2.2 Selected contributions of organic chemistry to materials science

Pilot Questions:

1. In what ways does organic chemistry contribute to the development of pharmaceuticals?
2. How do organic compounds improve agricultural productivity and food preservation?
3. Which everyday materials demonstrate the importance of organic chemistry in modern life?

2.3 Organic Chemistry In Modern Context

2.3.1 Relationship with biochemistry and nanochemistry

Organic chemistry forms the backbone of **biochemistry**, which is the study of chemical processes within living organisms. Biomolecules such as proteins, carbohydrates, lipids, and nucleic acids are all organic compounds, and their behaviour can only be understood through organic chemistry principles. Similarly, **nanochemistry** refers to the application of chemistry at the nanoscale, where organic molecules are used to build nanostructures with unique properties. These connections show how organic chemistry bridges life sciences and advanced technology. Fill in the blank: Biomolecules such as proteins, carbohydrates, lipids, and __________ are all organic compounds studied in biochemistry.

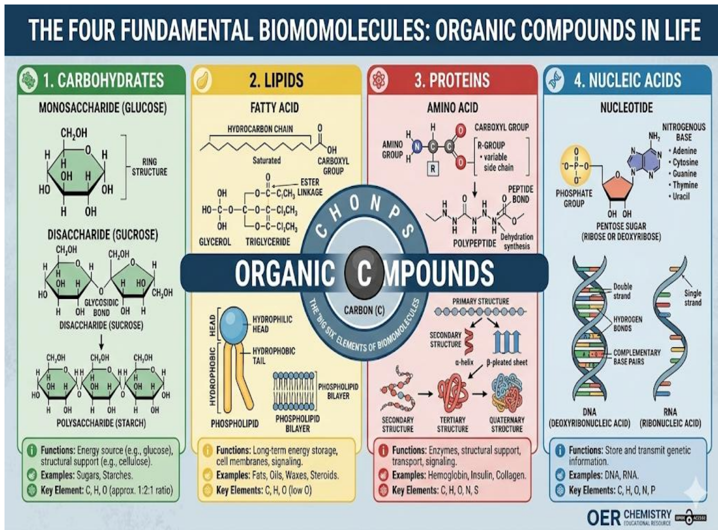

Figure 2.3 Organic chemistry as the foundation of biomolecules.

2.3.2 Emerging trends and innovations

Modern organic chemistry is constantly evolving to meet global challenges. Innovations such as **green chemistry**, which focuses on designing chemical processes that reduce waste and environmental impact, are reshaping the discipline. Advances in **synthetic chemistry** allow scientists to create complex molecules for pharmaceuticals and materials. Additionally, organic chemistry contributes to renewable energy through the development of biofuels and organic solar cells. These trends highlight how organic chemistry adapts to societal needs.
Fill in the blank: The branch of chemistry that focuses on reducing waste and environmental impact is called __________ chemistry.

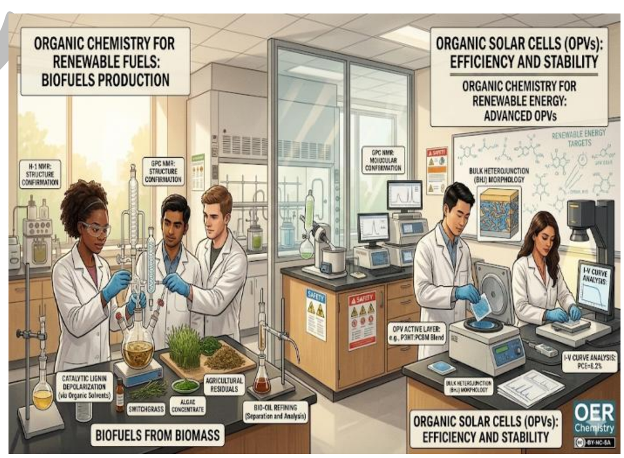

Plate 2.3 Organic chemistry innovations in renewable energy.

2.3.3 Future directions and global impact

The future of organic chemistry lies in its ability to address pressing issues such as health, sustainability, and technology. Research into personalised medicine, biodegradable plastics, and advanced nanomaterials demonstrates its potential to transform industries and improve quality of life. As organic chemistry continues to expand, its global impact will be felt in healthcare, environmental protection, and technological innovation.

Fill in the blank: One promising future direction of organic chemistry is the development of __________ plastics to reduce environmental pollution.

Direction	Description	Key Applications
Personalized Medicine	Tailoring medical treatment to the individual characteristics (genetic, environmental, lifestyle) of each patient.	Targeted drug delivery systems, pharmacogenomics, and patient-specific synthetic antibodies.
Biodegradable Plastics	Developing polymers from renewable resources that break down into non-toxic components in the environment.	Compostable packaging (e.g., PLA), "green" electronics, and temporary medical implants/stents.
Nanomaterials	Designing organic molecules that self-assemble into nanostructures with specific physical or chemical properties.	Organic LEDs (OLEDs), carbon nanotubes for drug delivery, and high-efficiency organic photovoltaics (solar cells).
Green & Sustainable Chemistry	Redesigning chemical processes to minimize waste, use safer solvents (like water), and maximize atom economy.	Solvent-free synthesis (mechanochemistry), biocatalysis using enzymes, and CO_2 capture/utilization.
AI & Automated Synthesis	Using artificial intelligence and robotics to predict reaction outcomes and perform complex molecular synthesis autonomously.	High-throughput drug discovery, automated retrosynthesis, and "self-driving" laboratories.

Box 2.3 Selected future directions of organic chemistry

Pilot Questions:

1. How does organic chemistry form the foundation of biochemistry and nanochemistry?
2. What role does green chemistry play in addressing environmental challenges?
3. Which future directions of organic chemistry could have the greatest global impact, and why?

Series Summary

This Series has introduced you to the foundations and development of organic chemistry, highlighting its historical roots, practical importance, and modern relevance. We began with a historical survey, tracing the origins of organic chemistry and the key discoveries that shaped its growth. We then examined its significance in medicine, agriculture, and materials science, showing how organic compounds underpin many aspects of daily life. Finally, we explored organic chemistry in the modern context, linking it to biochemistry, nanochemistry, and emerging innovations that continue to transform science and society.

By working through this Series, you should now be able to define the origins and early discoveries of organic chemistry, explain important milestones in its development, analyse its role in medicine, agriculture, and materials science, and evaluate its modern relevance and future directions. These abilities directly align with the Series Learning Outcomes (SLOs), equipping you with a strong foundation to progress into more advanced areas of the course.

Glossary of Terms

- **Agriculture:** The practice of cultivating plants and raising animals, where organic chemistry contributes through fertilisers, pesticides, and herbicides.
- **Alkanes:** Saturated hydrocarbons containing only single bonds between carbon atoms.
- **Alkenes:** Unsaturated hydrocarbons containing at least one double bond between carbon atoms.
- **Alkynes:** Unsaturated hydrocarbons containing at least one triple bond between carbon atoms.
- **Biochemistry:** The branch of science that studies chemical processes within living organisms, built upon principles of organic chemistry.
- **Fertilisers:** Chemical substances, often containing organic compounds, used to enhance plant growth and crop yield.
- **Green chemistry:** An approach to chemical design and processes that aims to reduce waste and minimise environmental impact.
- **Nanochemistry:** The study and application of chemistry at the nanoscale, often using organic molecules to build nanostructures.
- **Organic compound:** Chemical substances containing carbon, usually combined with hydrogen, oxygen, nitrogen, or other elements.
- **Pharmaceuticals:** Organic chemical substances designed and synthesised to diagnose, treat, or prevent diseases.

- **Spectroscopy:** A scientific technique used to study the interaction of matter with electromagnetic radiation, helping to determine the structure of organic compounds.
- **Urea:** An organic compound first synthesised artificially by Friedrich Wöhler in 1828, disproving the vitalism theory.
- **Vitalism:** The early belief that organic compounds could only be produced by living organisms through a special "vital force."

Concept Check Questions [Series 1: Foundations and Development of Organic Chemistry]

Objective Questions

1. Define the term **organic compounds**. (Linked to SLO 2.1)

A. Compounds containing oxygen only
B. Compounds containing carbon, often with hydrogen and other elements
C. Compounds produced only by living organisms
D. Compounds made exclusively of metals

2. Who disproved the theory of **vitalism** by synthesising urea? (Linked to SLO 2.1)

A. August Kekulé
B. Friedrich Wöhler
C. Antoine Lavoisier
D. Robert Boyle

3. August Kekulé is credited with proposing the structure of which compound? (Linked to SLO 2.2)

A. Methane
B. Benzene
C. . Ethanol
D. Acetylene

4. Which branch of chemistry focuses on reducing waste and environmental impact? (Linked to SLO 2.4)

A. Physical chemistry
B. Analytical chemistry
C. Green chemistry
D. Inorganic chemistry

Short-Answer Questions

1. Explain why Wöhler's synthesis of urea was a turning point in organic chemistry. (Linked to SLO 2.1)

2. Describe one way organic chemistry contributes to agriculture. (Linked to SLO 2.3)
3. Identify two everyday products that rely on organic chemistry. (Linked to SLO 2.3)
4. State one emerging innovation in organic chemistry that addresses sustainability. (Linked to SLO 2.4)

Long-Answer Questions

1. Analyse the importance of organic chemistry in medicine, agriculture, and materials science, giving examples from each field. (Linked to SLO 2.3)
2. Evaluate the modern relevance of organic chemistry by discussing its relationship with biochemistry, nanochemistry, and future directions. (Linked to SLO 2.4)

Answers to Concept Check Questions [Series 1]

Objective Questions

1. B. Compounds containing carbon, often with hydrogen and other elements.
2. B. Friedrich Wöhler.
3. B. Benzene.
4. C. Green chemistry.

Short-Answer Questions

1. Wöhler's synthesis of urea showed that organic compounds could be created artificially, disproving vitalism and marking the beginning of modern organic chemistry.
2. Organic chemistry contributes to agriculture through fertilisers, pesticides, and herbicides that improve crop yield and protect plants.
3. Examples include plastics, synthetic fibres, dyes, and pharmaceuticals.
4. Green chemistry innovations such as biodegradable plastics or organic solar cells.

Long-Answer Questions

1. **Basic response:** Organic chemistry is important in medicine through drug design, in agriculture through fertilisers and pesticides, and in materials science through plastics and synthetic fibres.
   Value-added response: Beyond these, organic chemistry enables advanced drug synthesis for targeted therapies, supports global food security through improved crop protection, and drives innovation in lightweight polymers used in aerospace and electronics.
2. **Basic response:** Organic chemistry remains relevant today through its role in biochemistry, nanochemistry, and innovations such as green chemistry.
   Value-added response: Its modern relevance extends to global challenges, including personalised medicine, renewable energy, and sustainable materials. By linking molecular design to cutting-edge technologies, organic chemistry continues to shape healthcare, environmental protection, and industrial progress.

Answers to Pilot Questions [Series 1]

Part 1: Historical Survey of Organic Chemistry

1. Vitalism was the belief that organic compounds could only be produced by living organisms through a special "vital force." Wöhler's synthesis of urea disproved this idea.
2. Kekulé's proposal of the benzene ring structure introduced the concept of cyclic compounds and advanced structural theory in organic chemistry.
3. Artificial synthesis of organic compounds marked a turning point because it showed that organic chemistry could be studied and expanded beyond natural sources.

Part 2: Significance of Organic Chemistry

1. Organic chemistry contributes to pharmaceuticals by enabling the design and synthesis of drugs such as antibiotics, antivirals, and pain relievers.
2. In agriculture, organic compounds improve productivity through fertilisers, pesticides, and herbicides, while also supporting food preservation.
3. Everyday materials such as plastics, synthetic fibres, and dyes demonstrate the importance of organic chemistry in modern life.

Part 3: Organic Chemistry in Modern Context

1. Organic chemistry underpins biochemistry by explaining the behaviour of biomolecules, and it supports nanochemistry by enabling the design of nanoscale structures.
2. Green chemistry reduces waste and environmental impact by promoting sustainable chemical processes.
3. Future directions such as personalised medicine, biodegradable plastics, and nanomaterials could have significant global impact by improving healthcare, sustainability, and technology.

References and Attributions [Series 1: Foundations and Development of Organic Chemistry]

Figures

- Figure 2.1 Wöhler's experiment disproving vitalism.
  Attribution: AI-generated using the prompt *"Generate a simple chemical reaction diagram showing ammonium cyanate converting to urea."*
- Figure 2.2 Synthesis of aspirin from salicylic acid.
  Attribution: AI-generated using the prompt *"Generate a labelled chemical reaction diagram showing salicylic acid converting to aspirin."*
- Figure 2.3 Organic chemistry as the foundation of biomolecules.
  Attribution: AI-generated using the prompt *"Generate a labelled diagram showing proteins, carbohydrates, lipids, and nucleic acids as organic compounds."*

Plates

- Plate 2.1 Structural representation of benzene.
  Attribution: AI-generated using the prompt *"Create a labelled diagram of benzene showing alternating double bonds in a hexagonal ring."*
- Plate 2.2 Application of organic compounds in agriculture.
  Attribution: AI-generated using the prompt *"Create an illustration of a farmer applying fertilisers and pesticides to crops."*
- Plate 2.3 Organic chemistry innovations in renewable energy.
  Attribution: AI-generated using the prompt *"Create an illustration of scientists working on biofuels and organic solar cells in a laboratory."*

Boxes and Tables

- Box 2.1 Selected applications of organic chemistry.
  Attribution: AI-generated using the prompt *"Generate a simple table listing applications of organic chemistry in medicine, agriculture, and materials science."*
- Box 2.2 Selected contributions of organic chemistry to materials science.
  Attribution: AI-generated using the prompt *"Generate a simple table listing contributions of organic chemistry to materials science such as plastics, dyes, fibres, and polymers."*
- Box 2.3 Selected future directions of organic chemistry.
  Attribution: AI-generated using the prompt *"Generate a simple table listing future directions of organic chemistry such as personalised medicine, biodegradable plastics, and nanomaterials."*

Open Educational Resources (OER) Search Strings Suggested

- "Wöhler urea synthesis diagram OER chemistry"
- "benzene structure diagram OER chemistry"
- "aspirin synthesis diagram OER chemistry"
- "applications of organic chemistry OER teaching resource"
- "agriculture pesticides fertilisers OER image"
- "applications of organic chemistry in materials science OER resource"
- "biomolecules organic chemistry diagram OER"
- "organic chemistry renewable energy OER image"
- "future directions organic chemistry OER resource"

General References

- Historical context and definitions adapted from standard organic chemistry textbooks and teaching resources.
- Key terms such as *organic compounds*, *vitalism*, *urea*, *biochemistry*, and *green chemistry* were defined within the Series content for clarity.

Course Code: CHM 102
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Series 2: Carbon Allotropes and Fullerenes in Modern Chemistry
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Series 2: Carbon Allotropes and Fullerenes in Modern Chemistry
Series Outline

Part 1: Carbon allotropes and their properties

- Definition of allotropes
- Overview of carbon allotropes (diamond, graphite, graphene, fullerenes)
- Comparative properties and significance

Part 2: Fullerenes as the fourth allotrope of carbon

- Discovery and structure of fullerenes
- Unique features of fullerenes compared to other allotropes
- Types of fullerenes (C60, C70, nanotubes)

Part 3: Applications of fullerenes in modern science

- Uses in nanostructures and nanochemistry
- Role in electronics and materials science
- Potential applications in medicine and energy

Part 4: Future directions and challenges

- Emerging research trends in fullerene chemistry
- Limitations and challenges in practical applications
- Prospects for fullerene-based technologies

Introduction

Carbon is one of the most versatile elements in the periodic table, capable of forming a wide range of structures with remarkable properties. From the hardness of diamond to the conductivity of graphite, carbon allotropes have fascinated scientists for centuries. The discovery of fullerenes as the fourth allotrope of carbon opened new frontiers in nanoscience and materials chemistry, making this topic central to understanding modern applications of organic and inorganic chemistry.

The aim of this Series is to introduce you to the unique structures and properties of carbon allotropes, with a particular focus on fullerenes, and to explore their applications in science, technology, and future innovations.
We shall commence this Series by examining the different carbon allotropes and their properties, highlighting how each form contributes to science and industry. Next, we will focus on fullerenes as the fourth allotrope of carbon, exploring their discovery, structure, and distinctive features. Following that, we will consider the wide-ranging applications of fullerenes in nanochemistry, electronics, medicine, and energy. Finally, we will conclude by discussing future directions and challenges in fullerene research, considering both limitations and the exciting prospects for fullerene-based technologies.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **2.1** define the concept of allotropy and describe the major carbon allotropes, including diamond, graphite, graphene, and fullerenes.
- **2.2** compare the structural and physical properties of carbon allotropes, highlighting their scientific and industrial significance.
- **2.3** explain the discovery and structural features of fullerenes, including C60, C70, and carbon nanotubes.
- **2.4** analyse the unique chemical behaviour of fullerenes in relation to other carbon allotropes.
- **2.5** evaluate the applications of fullerenes in nanochemistry, electronics, medicine, and energy technologies.
- **2.6** assess current challenges and future directions in fullerene research, including limitations and prospects for technological innovation.

2.1 Carbon Allotropes And Their Properties

2.1.1 Definition of allotropes

An **allotrope** is a different structural form of the same element, where atoms are arranged in distinct ways that give rise to unique physical and chemical properties. Carbon is particularly notable for its allotropy, as it can exist in several forms including diamond, graphite, graphene, and fullerenes. These variations arise because carbon atoms can bond in multiple configurations, such as tetrahedral, planar, or spherical arrangements.
Fill in the blank: The ability of an element to exist in different structural forms is called __________.

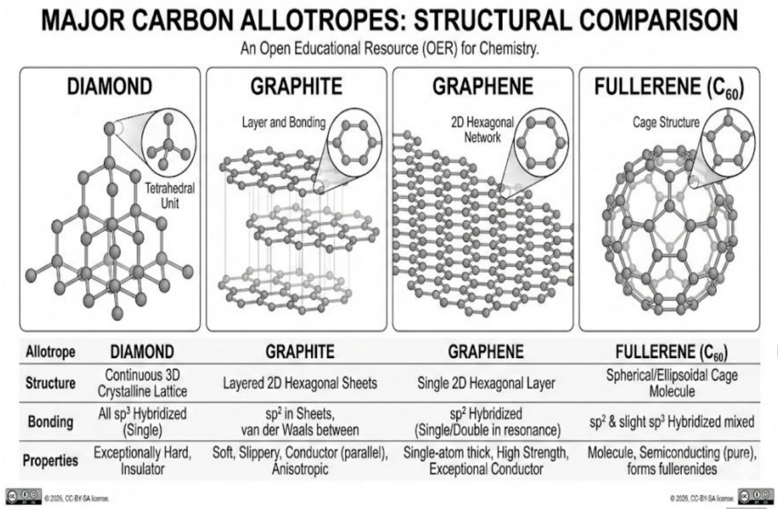


Figure 2.1 Structural forms of carbon allotropes.

2.1.2 Overview of carbon allotropes

Carbon allotropes differ widely in their properties due to variations in bonding and structure. **Diamond** is a three-dimensional tetrahedral network where each carbon atom bonds to four others, making it extremely hard. **Graphite** consists of layers of carbon atoms arranged in hexagonal sheets, with weak forces between layers, giving it lubricating properties and electrical conductivity. **Graphene** is a single layer of graphite, notable for its strength and conductivity. **Fullerenes** are spherical or tubular molecules composed of carbon atoms arranged in pentagons and hexagons, discovered in the late 20th century.

Fill in the blank: The carbon allotrope that consists of a single layer of graphite is called __________.

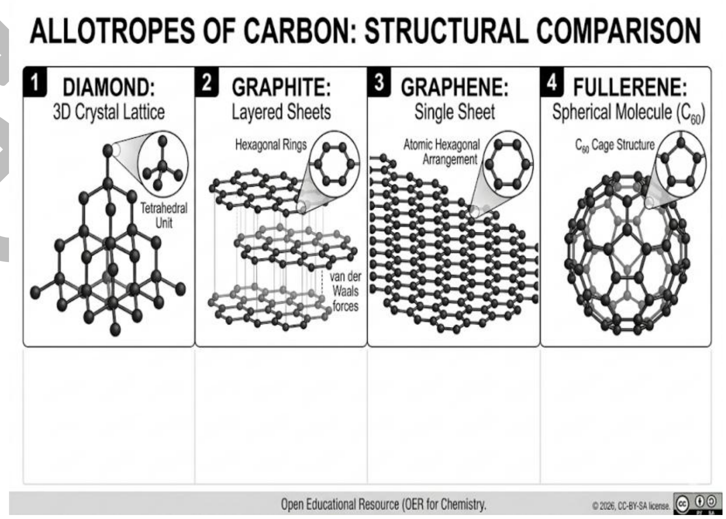


Plate 2.1 Visual comparison of carbon allotropes.

2.1.3 Comparative properties and significance

The properties of carbon allotropes make them valuable in different contexts. Diamond is prized for its hardness and optical clarity, used in cutting tools and jewellery. Graphite is used in pencils, lubricants, and electrodes due to its softness and conductivity. Graphene has potential in electronics and materials science because of its strength and flexibility. Fullerenes, with their unique molecular structures, are being explored for applications in nanotechnology, medicine, and energy storage.

Fill in the blank: The carbon allotrope used in pencils and electrodes due to its conductivity is __________.

Allotrope	Structure	Key Properties	Common Applications
Diamond	3D Tetrahedral Lattice (sp^3)	Extremely hard, transparent, high thermal conductivity, electrical insulator.	Jewelry, industrial cutting/drilling tools, heat sinks in electronics.
Graphite	Layered Hexagonal Sheets (sp^2)	Soft/slippery (layers slide), high melting point, conducts electricity.	Lubricants, pencil "lead," electrodes in batteries, crucibles.
Graphene	Single 2D Atomic Layer (sp^2)	Incredibly strong, flexible, transparent, world-class electrical/thermal conductor.	Next-gen electronics, transparent touchscreens, high-capacity capacitors.
Fullerenes (C_{60})	Spherical Cage (Buckyball)	High surface area, semi-conducting, can "trap" other molecules inside.	Drug delivery systems, antioxidants, organic photovoltaics (solar cells).

Box 2.1 Comparative properties of carbon allotropes

Pilot Questions

1. What is meant by the term allotrope, and why is carbon especially known for its allotropy?
2. How do the structures of diamond and graphite differ, and how do these differences explain their contrasting properties?
3. Why is graphene considered a revolutionary material in modern science and technology?

2.2 Fullerenes As The Fourth Allotrope Of Carbon

2.2.1 Discovery and structure of fullerenes

Fullerenes are spherical or tubular molecules composed entirely of carbon atoms arranged in pentagons and hexagons. They were discovered in 1985 by Harold Kroto, Richard Smalley, and Robert Curl, who identified the C60 molecule, also known as the "buckyball." This structure resembles a football, with 60 carbon atoms forming a hollow sphere. The discovery of fullerenes marked the identification of the fourth allotrope of carbon, alongside diamond, graphite, and graphene.

Fill in the blank: The C60 fullerene molecule is commonly called a __________ because of its football-like shape.

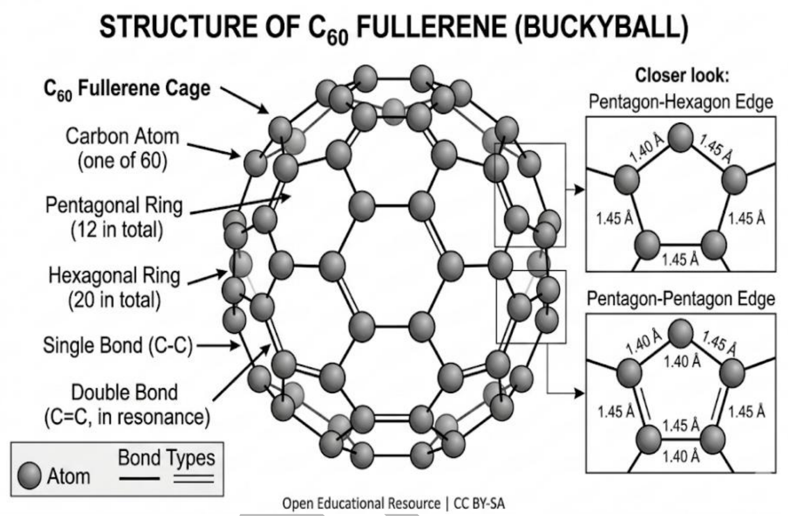


Figure 2.2 Structure of C60 fullerene ("buckyball").

2.2.2 Unique features of fullerenes compared to other allotropes

Fullerenes differ from other carbon allotropes in several ways. Unlike diamond and graphite, which form extended networks, fullerenes are discrete molecules. Their hollow, cage-like structure gives them unique chemical reactivity and the ability to encapsulate other atoms or molecules. This property makes them useful in nanotechnology and medicine. Fullerenes also exhibit interesting electrical and optical behaviours, making them candidates for advanced materials.

Fill in the blank: Unlike diamond and graphite, fullerenes exist as __________ molecules rather than extended networks.

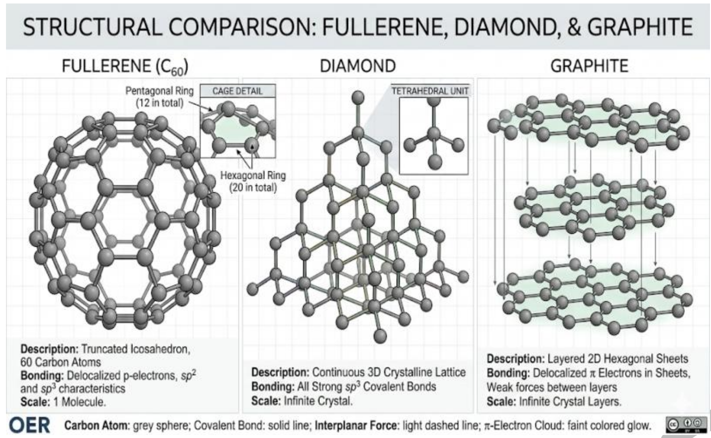


Plate 2.2 Comparison of fullerene molecular structure with other carbon allotropes.

2.2.3 Types of fullerenes

There are several types of fullerenes, each with distinct structures. **C60** is the most famous, but larger molecules such as **C70** exist with elongated shapes. **Carbon nanotubes** are cylindrical fullerenes with remarkable strength and conductivity, widely studied for applications in electronics and materials science. The diversity of fullerene structures demonstrates the versatility of carbon bonding and opens up possibilities for innovative uses.

Fill in the blank: Cylindrical fullerenes with exceptional strength and conductivity are called __________ nanotubes.

Type	Molecular Formula	Structure Description	Key Properties
Buckminsterfullerene	C_{60}	A "buckyball" consisting of 12 pentagons and 20 hexagons.	Highly stable, behaves like an electron-deficient alkene, and is superconducting when doped with alkali metals.
C70 Fullerene	C_{70}	Rugby-ball shaped (prolate spheroid) with 12 pentagons and 25 hexagons.	Slightly more reactive than C_{60} due to higher curvature at the poles; used in organic photovoltaics.
Carbon Nanotubes (CNTs)	$(C_{n})_x$	Cylindrical tubes of graphene sheets; can be Single-Walled (SWCNT) or Multi-Walled (MWCNT).	Extraordinary tensile strength, high thermal conductivity, and can be metallic or semiconducting depending on "chirality."

Type	Molecular Formula	Structure Description	Key Properties
Endohedral Fullerenes	$M@C_{n}$	A fullerene cage with an atom or small molecule trapped inside.	Unique electronic properties influenced by the internal guest; used in medical imaging (MRI) and quantum computing.

Box 2.2 Selected types of fullerenes

Pilot Questions

1. Who discovered fullerenes, and what is the common name given to the C60 molecule?
2. How do fullerenes differ structurally from diamond and graphite?
3. What are carbon nanotubes, and why are they considered important in modern science?

2.3 Applications Of Fullerenes In Modern Science

2.3.1 Uses in nanostructures and nanochemistry

Fullerenes are central to **nanochemistry**, which is the study and manipulation of chemical structures at the nanoscale. Their hollow, cage-like structure allows them to act as building blocks for nanostructures. They can encapsulate atoms or molecules, making them useful in designing nanoscale delivery systems. Their ability to self-assemble into larger frameworks also makes them valuable in the development of advanced materials.

Fill in the blank: The branch of chemistry that focuses on structures and processes at the nanoscale is called ___________.

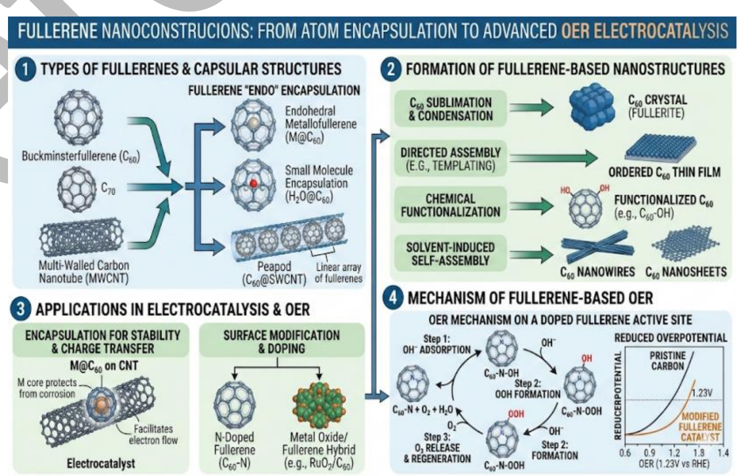


Figure 2.3 Fullerenes as building blocks in nanochemistry.

2.3.2 Role in electronics and materials science

Fullerenes exhibit unique electrical and optical properties, making them promising in **electronics** and **materials science**. They can act as semiconductors, superconductors, and light-absorbing materials. In solar cells, fullerenes are used as electron acceptors to improve efficiency. Their strength and flexibility also make them suitable for creating lightweight, durable materials.

Fill in the blank: In solar cells, fullerenes are used as __________ acceptors to improve efficiency.

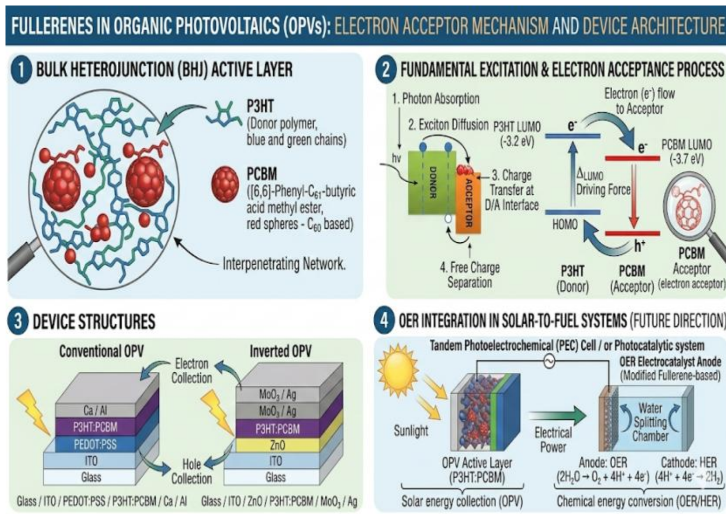
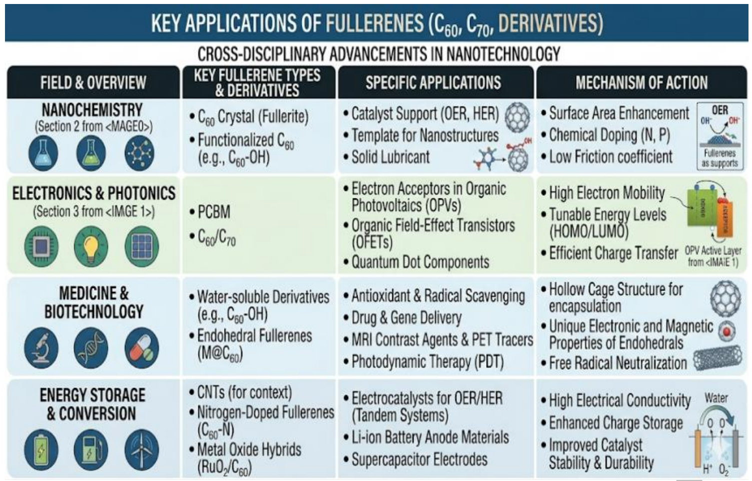


Plate 2.3 Application of fullerenes in solar cells.

2.3.3 Potential applications in medicine and energy

In **medicine**, fullerenes are studied for drug delivery, as their hollow structure can carry therapeutic molecules to targeted cells. They also show potential as antioxidants, neutralising harmful free radicals in the body. In **energy**, fullerenes are explored for use in hydrogen storage and advanced battery technologies, due to their ability to trap and release molecules efficiently. These applications highlight the versatility of fullerenes in addressing global challenges.

Fill in the blank: Fullerenes are being studied in medicine for their ability to act as __________, neutralising harmful free radicals.



KEY APPLICATIONS OF FULLERENES (C_{60}, C_{70}, DERIVATIVES)

CROSS-DISCIPLINARY ADVANCEMENTS IN NANOTECHNOLOGY

FIELD & OVERVIEW	KEY FULLERENE TYPES & DERIVATIVES	SPECIFIC APPLICATIONS	MECHANISM OF ACTION
NANOCHEMISTRY (Section 2 from <MAGEO>)	• C_{60} Crystal (Fullerite) • Functionalized C_{60} (e.g., C_{60}-OH)	• Catalyst Support (OER, HER) • Template for Nanostructures • Solid Lubricant	• Surface Area Enhancement • Chemical Doping (N, P) • Low Friction coefficient OER OH^- OH^- Fullerenes as supports
ELECTRONICS & PHOTONICS (Section 3 from <IMGE 1>)	• PCBM • C_{60}/C_{70}	• Electron Acceptors in Organic Photovoltaics (OPVs) • Organic Field-Effect Transistors (OFETs) • Quantum Dot Components	• High Electron Mobility • Tunable Energy Levels (HOMO/LUMO) • Efficient Charge Transfer OPV Active Layer from <IMAiE 1)
MEDICINE & BIOTECHNOLOGY	• Water-soluble Derivatives (e.g., C_{60}-OH) • Endohedral Fullerenes (M@C_{60})	• Antioxidant & Radical Scavenging • Drug & Gene Delivery • MRI Contrast Agents & PET Tracers • Photodynamic Therapy (PDT)	• Hollow Cage Structure for encapsulation • Unique Electronic and Magnetic Properties of Endohedrals • Free Radical Neutralization
ENERGY STORAGE & CONVERSION	• CNTs (for context) • Nitrogen-Doped Fullerenes (C_{60}-N) • Metal Oxide Hybrids (RuO_2/C_{60})	• Electrocatalysts for OER/HER (Tandem Systems) • Li-ion Battery Anode Materials • Supercapacitor Electrodes	• High Electrical Conductivity • Enhanced Charge Storage • Improved Catalyst Stability & Durability Water H^+ O_2^-

Box 2.3 Selected applications of fullerenes in modern science

Pilot Questions

1. How does the hollow structure of fullerenes make them useful in nanochemistry?
2. Why are fullerenes considered important in solar cell technology?
3. What potential roles could fullerenes play in medicine and energy storage?

2.4 Future Directions And Challenges

2.4.1 Emerging research trends in fullerene chemistry

Research into **fullerene chemistry** continues to expand, with scientists exploring new ways to harness their unique properties. Current trends include the design of functionalised fullerenes, where chemical groups are attached to the carbon cage to enhance reactivity and broaden applications. Another area of interest is the integration of fullerenes into nanocomposites, combining them with other materials to create advanced systems with improved strength, conductivity, or biocompatibility.

Fill in the blank: Fullerenes that have chemical groups attached to their carbon cages are called __________ fullerenes.

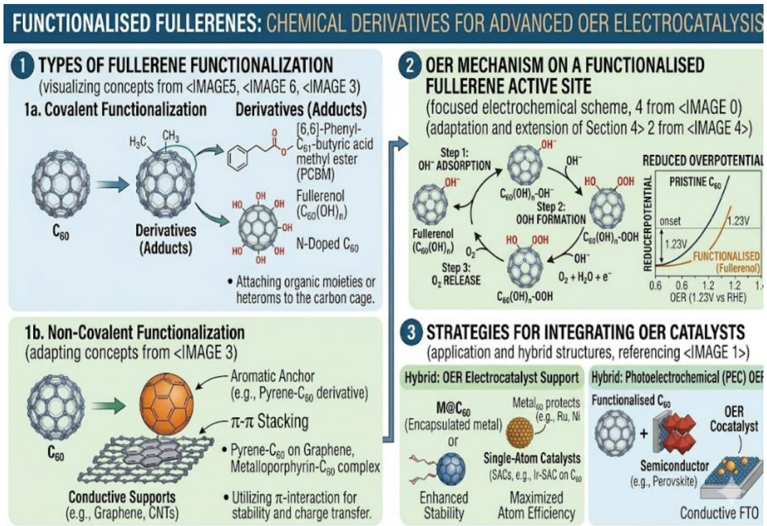


Figure 2.4 Functionalised fullerene structures.

2.4.2 Limitations and challenges in practical applications

Despite their promise, fullerenes face several challenges. Their production can be costly and complex, limiting large-scale use. Stability under certain conditions is another issue, as fullerenes may degrade or lose effectiveness. Additionally, concerns about toxicity and environmental impact must be addressed before widespread adoption in medicine or consumer products. These challenges highlight the need for further research and careful regulation.
Fill in the blank: One major challenge in fullerene applications is their potential __________, which raises safety concerns in medicine and industry.

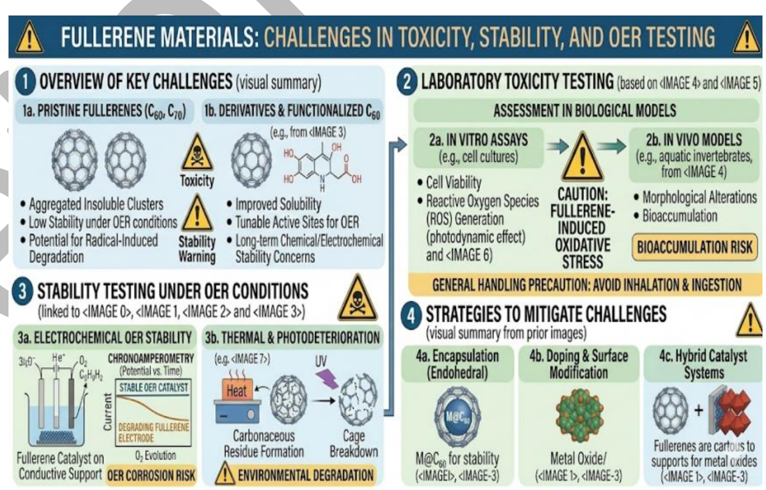


Plate 2.4 Challenges in fullerene applications.

2.4.3 Prospects for fullerene-based technologies

Looking ahead, fullerenes hold promise in several cutting-edge fields. In **energy**, they may contribute to more efficient solar cells and hydrogen storage systems. In **medicine**, fullerene-based drug delivery and antioxidant therapies could revolutionise treatment approaches. In **electronics**, their unique conductivity and optical properties may lead to faster, smaller, and more efficient devices. These prospects suggest that fullerenes could play a transformative role in addressing global challenges.

Fill in the blank: Fullerenes are being explored in energy research for their potential role in __________ storage systems.

Field	Emerging Application	Future Outlook & Mechanisms
Energy	**Tandem Water Splitting**	Use of N-doped fullerenes as supports for single-atom catalysts (SACs) to achieve ultra-low overpotentials in OER/HER systems.
	EV Battery Anodes	Integration into Silicon-carbon composite anodes to buffer volume expansion and improve cycle life in next-gen electric vehicle batteries.
Medicine	**Quantum-Dot Therapeutics**	Using endohedral fullerenes ($M@C_{60}$) as precise, non-toxic contrast agents for real-time, molecular-level MRI and PET imaging.
	"Smart" Drug Delivery	Surface-functionalized fullerenes designed to trigger drug release only in acidic tumor environments, reducing systemic toxicity.
Electronics	**Quantum Computing**	Endohedral fullerenes serving as stable "qubits" (spin-based) for room-temperature quantum processors, currently in pilot testing phases.
	Wearable Photovoltaics	C_{70} and PCBM derivatives used in flexible, transparent organic solar cells integrated into clothing and smart windows.

Box 2.4 Future prospects of fullerene-based technologies

Pilot Questions

1. What are functionalised fullerenes, and why are they important in current research?
2. What challenges limit the widespread use of fullerenes in industry and medicine?
3. Which future applications of fullerenes could have the greatest impact on global challenges?

Series Summary

This Series has introduced you to the fascinating world of carbon allotropes, with a particular focus on fullerenes as the fourth allotrope of carbon. We began by examining the definition and properties of carbon allotropes, then explored the discovery and unique features of fullerenes, followed by their diverse applications in nanochemistry, electronics, medicine, and energy. Finally, we considered future directions and challenges, including functionalisation, production limitations, and prospects for fullerene-based technologies.

By working through this Series, you should now be able to define and compare carbon allotropes (SLO 2.1 and SLO 2.2), describe the discovery and structural features of fullerenes (SLO 2.3), analyse their chemical behaviour and applications (SLO 2.4 and SLO 2.5), and evaluate both the challenges and future opportunities in fullerene research (SLO 2.6). These outcomes provide you with a solid foundation for understanding how carbon's versatility continues to shape modern science and technology.

Glossary of Terms

- **Allotrope**
  A different structural form of the same element, where atoms are arranged in distinct ways that result in unique physical and chemical properties.
- **Carbon nanotube**
  A cylindrical form of fullerene with exceptional strength and conductivity, widely studied for applications in electronics and materials science.
- **Diamond**
  A carbon allotrope where each atom is bonded to four others in a three-dimensional tetrahedral network, making it extremely hard and optically clear.
- **Fullerenes**
  Spherical or tubular molecules composed entirely of carbon atoms arranged in pentagons and hexagons, discovered in 1985 and recognised as the fourth allotrope of carbon.
- **Functionalised fullerenes**
  Fullerenes that have chemical groups attached to their carbon cages to enhance reactivity and broaden their applications.
- **Graphene**
  A single layer of carbon atoms arranged in a hexagonal lattice, known for its strength, flexibility, and electrical conductivity.
- **Graphite**
  A carbon allotrope consisting of layers of carbon atoms arranged in hexagonal sheets, with weak forces between layers, giving it lubricating properties and electrical conductivity.

- **Nanochemistry**
  The branch of chemistry that focuses on structures and processes at the nanoscale, often involving materials such as fullerenes and nanoparticles.
- **Vitalism**
  A historical belief that organic compounds could only be produced by living organisms through a special "vital force," later disproved by Wöhler's synthesis of urea.
- **C60 (Buckyball)**
  A spherical fullerene molecule composed of 60 carbon atoms arranged in a football-like structure of pentagons and hexagons.

Concept Check Questions [Series 2: Carbon Allotropes and Fullerenes in Modern Chemistry]

Objective Questions

1. Which carbon allotrope consists of a three-dimensional tetrahedral network, making it extremely hard? (Linked to SLO 2.1)

A. Graphite
B. Diamond
C. Graphene
D. Fullerene

2. The C60 molecule is commonly called a __________. (Linked to SLO 2.3)

A. Nanotube
B. Buckyball
C. Graphene sheet
D. Carbon cage

3. In solar cells, fullerenes are used as __________. (Linked to SLO 2.5)

A. Electron acceptors
B. Proton donors
C. Conductivity enhancers
D. Optical filters

4. Which of the following is a major challenge in fullerene applications? (Linked to SLO 2.6)

A. Low hardness
B. High toxicity concerns
C. Poor conductivity
D. Lack of optical properties

Short-Answer Questions

1. Define the term allotrope and give one example from carbon. (Linked to SLO 2.1)
2. Explain why graphene is considered revolutionary in modern science. (Linked to SLO 2.2)
3. Describe one unique structural feature of fullerenes compared to diamond and graphite. (Linked to SLO 2.3)
4. Identify one potential medical application of fullerenes. (Linked to SLO 2.5)
5. State one limitation that restricts the widespread use of fullerenes. (Linked to SLO 2.6)

Long-Answer Questions

1. Analyse the applications of fullerenes in nanochemistry, electronics, medicine, and energy, giving examples from each field. (Linked to SLO 2.5)
2. Evaluate the future directions and challenges of fullerene research, considering both limitations and prospects. (Linked to SLO 2.6)

Answers to Concept Check Questions [Series 2: Carbon Allotropes and Fullerenes in Modern Chemistry]

Objective Questions

1. B. Diamond
2. B. Buckyball
3. A. Electron acceptors
4. B. High toxicity concerns

Short-Answer Questions

1. An allotrope is a different structural form of the same element. Example: diamond is an allotrope of carbon.
2. Graphene is revolutionary because it is a single layer of carbon atoms with exceptional strength, flexibility, and conductivity, making it valuable in electronics and materials science.
3. Fullerenes are discrete, hollow molecules rather than extended networks, unlike diamond and graphite.
4. Fullerenes can be used in medicine for drug delivery or as antioxidants.
5. Limitations include high production costs, stability issues, and potential toxicity.

Long-Answer Questions

1. **Basic response:** Fullerenes are applied in nanochemistry as building blocks, in electronics as electron acceptors in solar cells, in medicine for drug delivery and antioxidant therapies, and in energy for hydrogen storage and advanced batteries.
   Value-added response: Beyond these, fullerenes are being integrated into nanocomposites for stronger materials, explored in superconductivity research, tested

for targeted cancer therapies, and investigated for next-generation renewable energy systems.

2. **Basic response:** Future directions include functionalised fullerenes, improved applications in medicine and energy, and advanced electronics. Challenges include high production costs, stability issues, and toxicity concerns.
   Value-added response: Outstanding learners may note that fullerene research is also tied to global sustainability goals, with potential breakthroughs in clean energy, biocompatible nanomedicine, and eco-friendly materials. Addressing toxicity and scalability will be critical for fullerene technologies to move from laboratory research to widespread industrial use.

Answers to Pilot Questions

Part 1: Carbon allotropes and their properties

1. An allotrope is a different structural form of the same element, and carbon is especially known for its allotropy because it can form diamond, graphite, graphene, and fullerenes.
2. Diamond has a three-dimensional tetrahedral structure, while graphite has layered hexagonal sheets. These structural differences explain why diamond is extremely hard and graphite is soft and conductive.
3. Graphene is considered revolutionary because it is a single layer of carbon atoms with exceptional strength, flexibility, and electrical conductivity, making it highly valuable in modern science and technology.

Part 2: Fullerenes as the fourth allotrope of carbon

1. Fullerenes were discovered in 1985 by Harold Kroto, Richard Smalley, and Robert Curl, and the C60 molecule is commonly called the buckyball.
2. Fullerenes differ structurally from diamond and graphite because they are discrete, hollow molecules rather than extended networks.
3. Carbon nanotubes are cylindrical fullerenes with remarkable strength and conductivity, making them important in electronics and materials science.

Part 3: Applications of fullerenes in modern science

1. The hollow structure of fullerenes allows them to encapsulate atoms or molecules, making them useful in nanochemistry.
2. Fullerenes are important in solar cell technology because they act as electron acceptors, improving efficiency.
3. In medicine, fullerenes can be used for drug delivery and as antioxidants, while in energy they are explored for hydrogen storage and advanced batteries.

Part 4: Future directions and challenges

1. Functionalised fullerenes are molecules with chemical groups attached to their carbon cages, making them more reactive and versatile.
2. Challenges include high production costs, stability issues, and concerns about toxicity and environmental impact.
3. Future applications could include more efficient solar cells, hydrogen storage systems, advanced electronics, and innovative medical therapies.

References and Attributions [Series 2: Carbon Allotropes and Fullerenes in Modern Chemistry]

Figures

- Figure 2.1 Structural forms of carbon allotropes.
  Attribution: AI-generated using the prompt *"Generate a labelled diagram showing diamond, graphite, graphene, and fullerene structures side by side."*
- Figure 2.2 Structure of C60 fullerene ("buckyball").
  Attribution: AI-generated using the prompt *"Generate a labelled diagram of C60 fullerene showing carbon atoms arranged in pentagons and hexagons."*
- Figure 2.3 Fullerenes as building blocks in nanochemistry.
  Attribution: AI-generated using the prompt *"Generate a labelled diagram showing fullerene molecules forming nanostructures and encapsulating atoms."*
- Figure 2.4 Functionalised fullerene structures.
  Attribution: AI-generated using the prompt *"Generate a labelled diagram showing functionalised fullerenes with chemical groups attached to the carbon cage."*

Plates

- Plate 2.1 Visual comparison of carbon allotropes.
  Attribution: AI-generated using the prompt *"Create an illustration showing diamond crystal lattice, graphite layered sheets, graphene single sheet, and fullerene spherical molecule."*
- Plate 2.2 Comparison of fullerene molecular structure with other carbon allotropes.
  Attribution: AI-generated using the prompt *"Create an illustration comparing fullerene cage structure with diamond lattice and graphite layered sheets."*
- Plate 2.3 Application of fullerenes in solar cells.
  Attribution: AI-generated using the prompt *"Create an illustration showing fullerene molecules being used in solar cells as electron acceptors."*
- Plate 2.4 Challenges in fullerene applications.
  Attribution: AI-generated using the prompt *"Create an illustration showing laboratory testing of fullerene materials with caution signs for toxicity and stability."*

Boxes and Tables

- Box 2.1 Comparative properties of carbon allotropes.
  Attribution: AI-generated using the prompt *"Generate a simple table comparing diamond, graphite, graphene, and fullerenes with their properties and applications."*
- Box 2.2 Selected types of fullerenes.
  Attribution: AI-generated using the prompt *"Generate a simple table listing types of fullerenes such as C60, C70, and carbon nanotubes with their structures and properties."*
- Box 2.3 Selected applications of fullerenes in modern science.
  Attribution: AI-generated using the prompt *"Generate a simple table listing applications of fullerenes in nanochemistry, electronics, medicine, and energy."*
- Box 2.4 Future prospects of fullerene-based technologies.
  Attribution: AI-generated using the prompt *"Generate a simple table listing future prospects of fullerene-based technologies in energy, medicine, and electronics."*

Open Educational Resources (OER) Search Strings Suggested

- "carbon allotropes structures diagram OER chemistry"
- "carbon allotropes diamond graphite graphene fullerene OER image"
- "C60 fullerene buckyball structure diagram OER chemistry"
- "comparison fullerene diamond graphite OER image"
- "types of fullerenes C60 C70 nanotubes OER chemistry table"
- "fullerenes nanochemistry applications diagram OER"
- "fullerenes solar cells application OER image"
- "applications of fullerenes nanochemistry medicine energy OER table"
- "functionalised fullerenes diagram OER chemistry"
- "fullerenes challenges toxicity stability OER image"
- "future prospects fullerene technologies OER chemistry table"

General References

- Kroto, H. W., Heath, J. R., O'Brien, S. C., Curl, R. F., & Smalley, R. E. (1985). *C60: Buckminsterfullerene*. Nature, 318(6042), 162–163.
- Standard organic and materials chemistry textbooks were consulted for definitions and explanations of allotropy, diamond, graphite, graphene, and fullerene properties.

Course Code: CHM 102
Course Title: General Chemistry II
Course Unit: 2 Units

Series 1: Foundations and Development of Organic Chemistry
Series 2: Carbon Allotropes and Fullerenes in Modern Chemistry
Series 3: Electronic Theory, Structure Determination, and Stereochemistry
Series 4: Organic Functional Groups, Nomenclature, and Reaction Mechanisms
Series 5: Comparative and Transition Metal Chemistry

Series 3: Electronic Theory, Structure Determination, and Stereochemistry
Series Outline

Part 1: Fundamentals of electronic theory

- Concept of electronic theory in chemistry
- Role of electrons in bonding and molecular behaviour
- Applications of electronic theory in predicting reactivity

Part 2: Methods of structure determination

- Spectroscopic techniques (UV, IR, NMR, Mass Spectrometry)
- X-ray crystallography and its importance
- Comparative strengths and limitations of structure determination methods

Part 3: Principles of stereochemistry

- Definition of stereochemistry and its significance
- Types of isomerism (structural vs. stereoisomerism)
- Chirality and optical activity

Part 4: Applications of stereochemistry in modern chemistry

- Role in pharmaceuticals and drug design
- Importance in materials science and biochemistry
- Case studies of stereochemistry in everyday life

Introduction
Chemistry is often described as the study of matter and its transformations, but at its heart lies the behaviour of electrons. Understanding how electrons govern bonding, reactivity, and molecular structure is essential for explaining why substances behave the way they do. Equally important is the ability to determine molecular structures accurately and to appreciate how the

three-dimensional arrangement of atoms influences chemical properties. This Series brings these themes together, highlighting their relevance to both theoretical and applied chemistry.
The aim of this Series is to equip you with the knowledge of electronic theory, introduce you to the main techniques of structure determination, and develop your understanding of stereochemistry and its applications in modern science.
We shall commence this Series by exploring the fundamentals of electronic theory, focusing on how electrons influence bonding and reactivity. Next, we will examine methods of structure determination, including spectroscopic techniques and X-ray crystallography. Following that, we will consider the principles of stereochemistry, looking at isomerism, chirality, and optical activity. Finally, we will wrap up by discussing the applications of stereochemistry in pharmaceuticals, materials science, and everyday life, thereby connecting theory to practice.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **3.1** define electronic theory and explain the role of electrons in bonding and molecular behaviour,
- **3.2** demonstrate how electronic theory can be applied to predict chemical reactivity,
- **3.3** describe the main methods of structure determination, including spectroscopic techniques and X-ray crystallography,
- **3.4** analyse the strengths and limitations of different structure determination methods,
- **3.5** define stereochemistry and distinguish between structural isomerism and stereoisomerism,
- **3.6** explain the concepts of chirality and optical activity with relevant examples, and
- **3.7** evaluate the applications of stereochemistry in pharmaceuticals, materials science, and biochemistry.

3.1 Fundamentals Of Electronic Theory

3.1.1 Concept of electronic theory in chemistry

Electronic theory refers to the idea that the behaviour of atoms and molecules is largely determined by the arrangement and movement of electrons. This theory explains bonding, reactivity, and many physical properties of substances. By focusing on electrons, chemists can predict how atoms will interact, form compounds, and undergo chemical reactions.
Fill in the blank: The theory that explains bonding and reactivity based on the behaviour of electrons is called __________ theory.

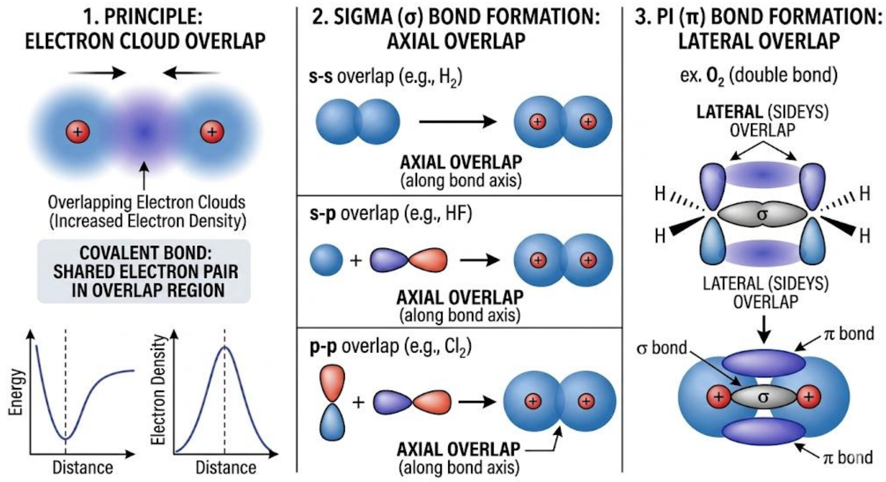


Figure 3.1 Representation of electronic theory in bonding.

3.1.2 Role of electrons in bonding and molecular behaviour

Electrons play a central role in chemical bonding. In **covalent bonding**, atoms share electrons to achieve stability. In **ionic bonding**, electrons are transferred from one atom to another, creating charged particles that attract each other. The distribution of electrons also influences molecular shape, polarity, and reactivity. For example, molecules with uneven electron distribution exhibit polarity, which affects how they interact with other substances.
Fill in the blank: When atoms share electrons to achieve stability, the bond formed is called a __________ bond.

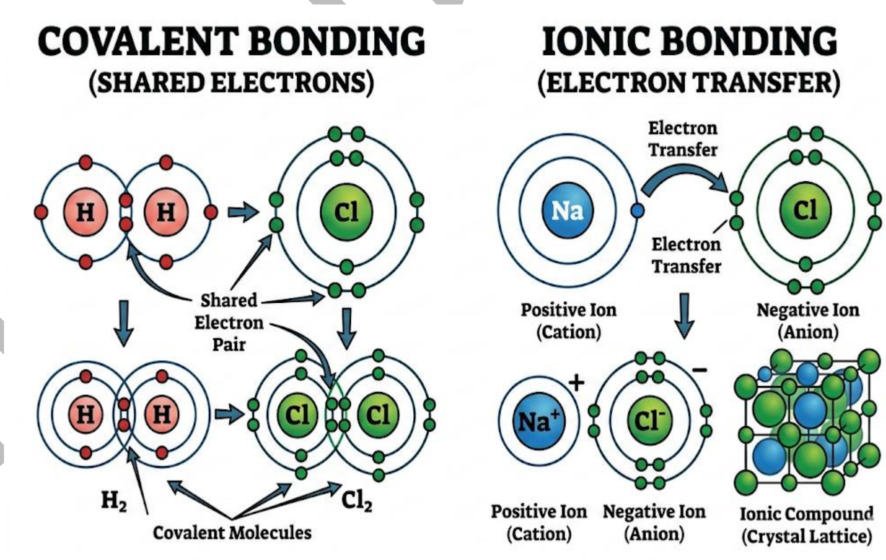


Plate 3.1 Covalent and ionic bonding illustrated.

3.1.3 Applications of electronic theory in predicting reactivity

Electronic theory helps chemists predict how substances will react. For instance, molecules with high electron density may act as **nucleophiles**, donating electrons to other species. Conversely, molecules with electron deficiency may act as **electrophiles**, accepting electrons. This framework is essential in organic chemistry, where reactions are often explained in terms of electron movement. Understanding these principles allows chemists to design reactions and anticipate products.

Fill in the blank: A species that donates electrons in a chemical reaction is called a __________.

Feature	Nucleophiles ("Nucleus-loving")	Electrophiles ("Electron-loving")
Electronic Nature	Electron-rich; has a high electron density.	Electron-poor; has a low electron density.
Charge	Negatively charged (Nu^-) or neutral with lone pairs.	Positively charged (E^+) or neutral with empty orbitals.
Lewis Definition	**Lewis Base**: Donates an electron pair.	**Lewis Acid**: Accepts an electron pair.
Common Examples	OH^-, CN^-, H_2O, NH_3, Cl^-	H^+, CH_3^+, NO_2^+, $AlCl_3$, BF_3
Role in Reaction	Attacks a positive center (nucleus).	Attacked by an electron-rich species.

Box 3.1 Key applications of electronic theory

Pilot Questions

1. What does electronic theory explain in chemistry?
2. How do covalent and ionic bonds differ in terms of electron behaviour?
3. What is the difference between a nucleophile and an electrophile in electronic theory?

3.2 Methods Of Structure Determination

3.2.1 Spectroscopic techniques

Spectroscopy refers to the study of how matter interacts with electromagnetic radiation. In chemistry, spectroscopic techniques are used to determine the structure of molecules. **Ultraviolet (UV) spectroscopy** measures absorption of UV light, often used to study conjugated systems.

Infrared (IR) spectroscopy identifies functional groups by measuring vibrations of chemical bonds. **Nuclear Magnetic Resonance (NMR) spectroscopy** provides detailed information about the arrangement of atoms in a molecule by observing how nuclei respond to magnetic fields. **Mass spectrometry (MS)** determines molecular mass and fragmentation patterns, helping to deduce molecular structure.
Fill in the blank: The spectroscopic technique that identifies functional groups by measuring bond vibrations is called __________ spectroscopy.

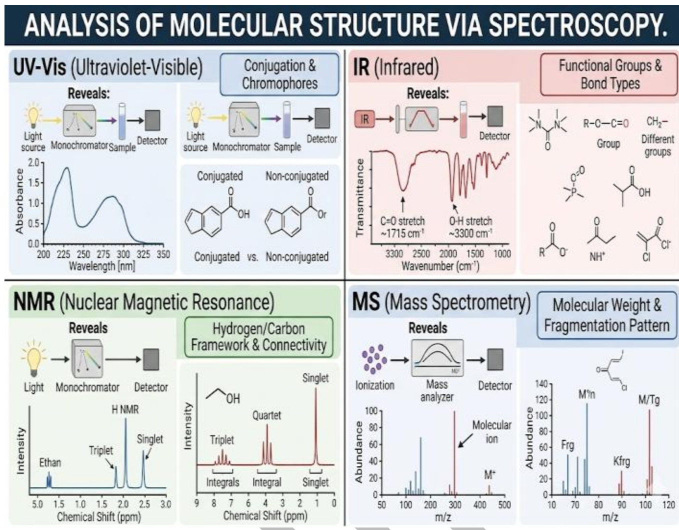


Figure 3.2 Overview of spectroscopic techniques in structure determination.

3.2.2 X-ray crystallography and its importance

X-ray crystallography is a powerful method used to determine the three-dimensional arrangement of atoms in crystalline solids. When X-rays are directed at a crystal, they are diffracted by the electron clouds of atoms, producing a diffraction pattern. By analysing this pattern, chemists can deduce the exact positions of atoms in the crystal lattice. This technique has been crucial in discovering the structures of complex molecules such as proteins and DNA.
Fill in the blank: The technique that uses diffraction of X-rays to determine atomic positions in crystals is called __________ crystallography.

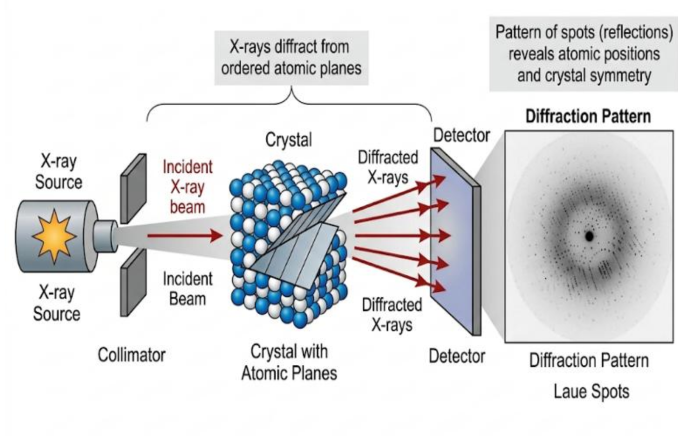


Plate 3.2 X-ray crystallography process.

3.2.3 Comparative strengths and limitations of structure determination methods

Each method of structure determination has its strengths and limitations. Spectroscopic techniques are fast and widely applicable, but they may provide indirect information that requires interpretation. X-ray crystallography gives precise atomic positions but requires high-quality crystals, which are not always easy to obtain. Mass spectrometry is excellent for determining molecular weight but less effective for complex three-dimensional structures. Chemists often use a combination of these methods to achieve accurate results.

Fill in the blank: X-ray crystallography provides precise atomic positions but requires high-quality __________.

Technique	Primary Purpose	Major Strengths	Major Limitations
Spectroscopy (NMR, IR, UV-Vis)	Identifying functional groups and the hydrogen/carbon framework.	**Non-destructive**; excellent for identifying connectivity and specific bonds (e.g., $C=O$).	Often requires pure samples; NMR can be slow and requires specific isotopes (like ^{1}H or ^{13}C).
X-ray Crystallography	Determining the 3D arrangement of atoms in space.	Provides an **exact "map"** of atomic positions, bond lengths, and bond angles.	**Destructive** to the crystal; requires high-quality single crystals, which can be very difficult to grow.

Technique	Primary Purpose	Major Strengths	Major Limitations
Mass Spectrometry (MS)	Determining molecular weight and formula.	Extremely **sensitive** (needs very little sample); provides a "fingerprint" through fragmentation patterns.	**Destructive**; does not directly show how atoms are bonded together (connectivity).

Box 3.2 Strengths and limitations of structure determination methods

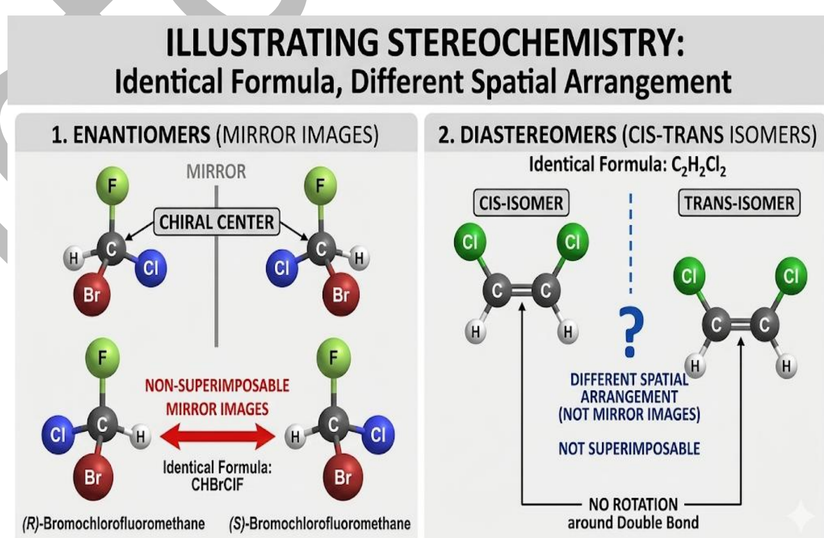
Pilot Questions

1. What information does IR spectroscopy provide about a molecule?
2. Why is X-ray crystallography considered important in chemistry?
3. Why do chemists often combine different structure determination methods?

3.3 Principles Of Stereochemistry

3.3.1 Definition of stereochemistry and its significance

Stereochemistry is the study of the three-dimensional arrangement of atoms in molecules and how this spatial orientation influences chemical behaviour. It is significant because molecules with the same molecular formula can differ in their spatial arrangement, leading to different physical and chemical properties. For example, stereochemistry explains why certain drugs are effective in one form but inactive or even harmful in another.
Fill in the blank: The branch of chemistry that studies the three-dimensional arrangement of atoms in molecules is called __________.



F

igure 3.3 Illustration of stereochemistry in molecules.

3.3.2 Types of isomerism

Isomerism refers to the phenomenon where compounds share the same molecular formula but differ in structure or arrangement. **Structural isomerism** occurs when atoms are connected differently, resulting in distinct structures. **Stereoisomerism** occurs when atoms are connected in the same way but differ in spatial orientation. Stereoisomerism includes **geometrical isomerism** (such as cis-trans isomers) and **optical isomerism** (mirror-image molecules).

Fill in the blank: When compounds have the same molecular formula but differ in spatial orientation, the phenomenon is called __________ isomerism.

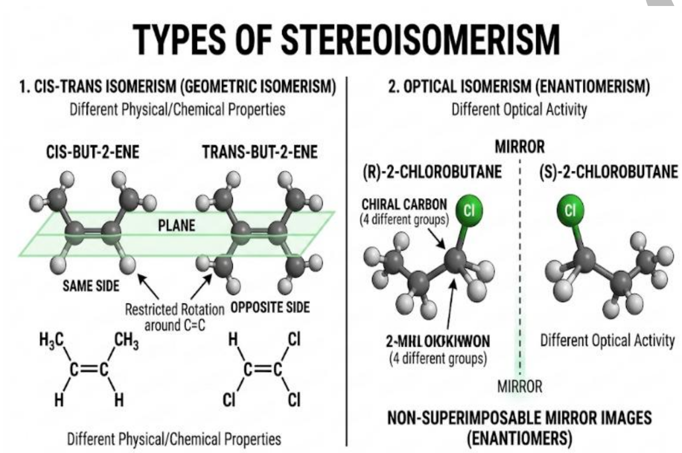


Plate 3.3 Types of stereoisomerism.

3.3.3 Chirality and optical activity

Chirality refers to the property of a molecule that cannot be superimposed on its mirror image, much like left and right hands. Molecules that exhibit chirality are called **chiral molecules**, and they often contain a carbon atom bonded to four different groups. **Optical activity** is the ability of chiral molecules to rotate plane-polarised light, with one form rotating it clockwise (dextrorotatory) and the other anticlockwise (levorotatory). This property is crucial in biochemistry and pharmaceuticals, where different enantiomers can have very different biological effects.

Fill in the blank: A molecule that cannot be superimposed on its mirror image is described as __________.

Term	Definition	Key Characteristic	Real-World Example
Chirality	The property of an object being non-superimposable on its mirror image.	Must have a **chiral center** (usually a carbon with 4 different groups).	Your hands; they are mirror images but cannot be perfectly layered.
Enantiomers	A pair of molecules that are non-superimposable mirror images of each other.	They have identical physical properties (boiling point, etc.) except for how they interact with light.	**(R)-Limonene** (smells like oranges) and **(S)-Limonene** (smells like lemons).
Optical Activity	The ability of a chiral substance to rotate the plane of **plane-polarized light**.	Measured using a **polarimeter**; denoted as \$(+)\$ or \$(-)\$.	Glucose (Dextrose) rotates light to the right \$(+)\$.

Box 3.3 Chirality and optical activity explained

Pilot Questions

1. What does stereochemistry study, and why is it important in chemistry?
2. How does structural isomerism differ from stereoisomerism?
3. What is chirality, and how does it relate to optical activity?

3.4 Applications Of Stereochemistry In Modern Chemistry

3.4.1 Role in pharmaceuticals and drug design

Stereochemistry plays a vital role in **pharmaceuticals**, which are chemical substances used to diagnose, treat, or prevent disease. Many drugs exist as stereoisomers, and often only one form (called the **active enantiomer**) produces the desired therapeutic effect, while the other may be inactive or even harmful. This makes stereochemical control essential in drug design and manufacturing. For example, the drug thalidomide demonstrated how one enantiomer could be therapeutic while the other caused severe side effects.

Fill in the blank: The form of a drug molecule that produces the desired therapeutic effect is called the __________ enantiomer.

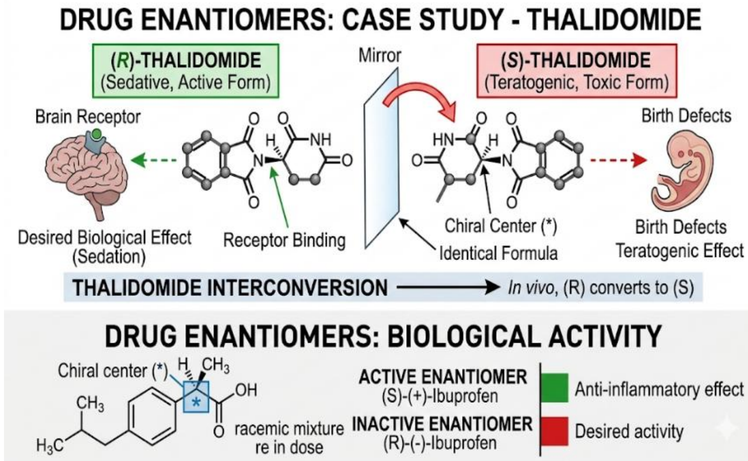


Figure 3.4 Role of stereochemistry in drug design.

3.4.2 Importance in materials science and biochemistry

In **materials science**, stereochemistry influences the properties of polymers and crystalline materials. The arrangement of atoms affects strength, flexibility, and conductivity. In **biochemistry**, stereochemistry is fundamental because biological molecules such as proteins, carbohydrates, and DNA are inherently chiral. Enzyme activity, receptor binding, and metabolic processes all depend on stereochemical interactions. This explains why living systems often distinguish between left-handed and right-handed molecules.

Fill in the blank: Biological molecules such as proteins and DNA are inherently __________, meaning they cannot be superimposed on their mirror images.

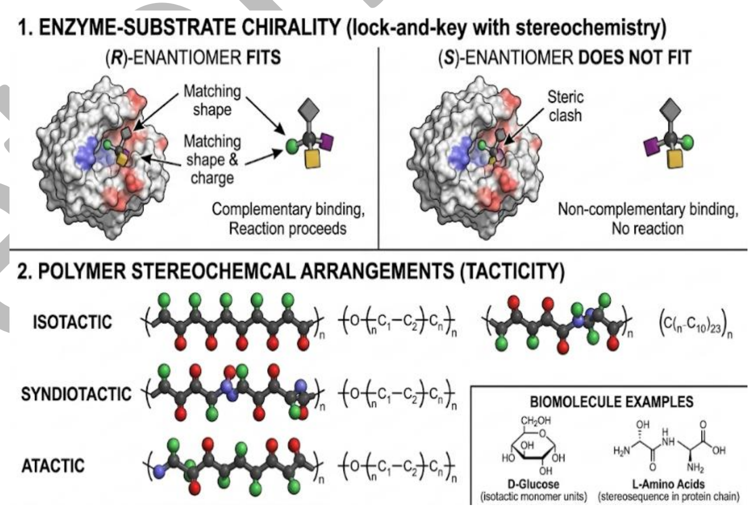


Plate 3.4 Stereochemistry in biochemistry and materials science.

3.4.3 Case studies of stereochemistry in everyday life

Stereochemistry is not limited to laboratories; it affects everyday life. The flavour and aroma of food often depend on stereoisomers, with one form producing a pleasant taste and another being

odourless or bitter. In fragrances, stereochemistry determines how molecules interact with receptors in the nose. Even in agriculture, stereochemistry influences the effectiveness of pesticides and herbicides. These examples show how stereochemistry connects chemistry to daily experiences.
Fill in the blank: The flavour and aroma of food often depend on the presence of specific __________ of molecules.

Field	Molecule	Enantiomer A (Right/Left)	Enantiomer B (Left/Right)	Impact
Food & Flavor	**Limonene**	**(+)-Limonene**: Oranges	**(-)-Limonene**: Lemons/Turpentine	Different odors due to how they fit into nasal receptors.
Fragrance	**Carvone**	**(+)-Carvone**: Caraway seeds	**(-)-Carvone**: Spearmint	Drastically different scent profiles from the same formula.
Agriculture	**Carpropamid** (Fungicide)	**(1S, 3R) isomer**: Highly active against rice blast.	**Other isomers**: Significantly less effective or inactive.	Precision in spatial arrangement reduces chemical waste.
Food (Sweetener)	**Aspartame**	**L,L-Aspartame**: Sweet (NutraSweet)	**D,D-Aspartame**: Bitter	The tongue's sweet receptors are stereospecific.

Box 3.4 Everyday examples of stereochemistry

Pilot Questions

1. Why is stereochemistry important in drug design and pharmaceuticals?
2. How does stereochemistry influence biological molecules such as proteins and DNA?
3. What are some everyday examples of stereochemistry in food, fragrances, or agriculture?

Series Summary

This Series has highlighted the importance of electronic theory, structure determination, and stereochemistry in modern chemistry. We began with the fundamentals of electronic theory, focusing on how electrons influence bonding and reactivity. Then we examined methods of structure determination, including spectroscopic techniques and X-ray crystallography, while considering their respective strengths and limitations. Following that, we explored the principles of stereochemistry, covering isomerism, chirality, and optical activity. Finally, we concluded with applications of stereochemistry in pharmaceuticals, materials science, biochemistry, and everyday life.

By completing this Series, you should now be able to define and apply electronic theory (SLO 3.1 and SLO 3.2), describe and analyse structure determination methods (SLO 3.3 and SLO 3.4), explain stereochemistry and its key concepts (SLO 3.5 and SLO 3.6), and evaluate its applications in science and daily contexts (SLO 3.7). These outcomes provide you with a clear foundation for appreciating how molecular structure and spatial arrangement influence chemical behaviour and practical applications.

Glossary of Terms

- **Chirality**
  A property of a molecule that cannot be superimposed on its mirror image, similar to the difference between left and right hands.
- **Electrophile**
  A species that accepts electrons during a chemical reaction, often because it is electron-deficient.
- **Electronic theory**
  The concept that the behaviour of atoms and molecules is determined by the arrangement and movement of electrons, which explains bonding and reactivity.
- **Enantiomer**
  One of a pair of chiral molecules that are mirror images of each other but not superimposable.
- **Infrared (IR) spectroscopy**
  A technique that identifies functional groups in molecules by measuring vibrations of chemical bonds when exposed to infrared radiation.
- **Isomerism**
  The phenomenon where compounds share the same molecular formula but differ in structure or spatial arrangement.

- **Mass spectrometry (MS)**
  An analytical technique that determines the molecular mass and fragmentation pattern of a compound, helping to deduce its structure.
- **Nuclear Magnetic Resonance (NMR) spectroscopy**
  A technique that provides detailed information about the arrangement of atoms in a molecule by observing how nuclei respond to magnetic fields.
- **Nucleophile**
  A species that donates electrons during a chemical reaction, often because it has high electron density.
- **Optical activity**
  The ability of chiral molecules to rotate plane-polarised light, either clockwise (dextrorotatory) or anticlockwise (levorotatory).
- **Spectroscopy**
  The study of how matter interacts with electromagnetic radiation, used in chemistry to determine molecular structure.
- **Stereochemistry**
  The study of the three-dimensional arrangement of atoms in molecules and how this spatial orientation influences chemical behaviour.
- **Structural isomerism**
  A type of isomerism where atoms are connected differently, resulting in distinct structures despite having the same molecular formula.
- **Ultraviolet (UV) spectroscopy**
  A technique that measures absorption of ultraviolet light, often used to study conjugated systems in molecules.
- **X-ray crystallography**
  A method used to determine the three-dimensional arrangement of atoms in crystalline solids by analysing diffraction patterns produced when X-rays strike a crystal.

Concept Check Questions [Series 3: Electronic Theory, Structure Determination, and Stereochemistry]

Objective Questions

1. Which type of spectroscopy identifies functional groups by measuring bond vibrations? (Linked to SLO 3.3)

A. UV spectroscopy
B. IR spectroscopy
C. NMR spectroscopy
D. Mass spectrometry

2. A molecule that cannot be superimposed on its mirror image is described as __________.

A. Achiral
B. Chiral
C. Symmetrical

D. Linear

3. Which method provides precise atomic positions but requires high-quality crystals? (Linked to SLO 3.4)

A. UV spectroscopy
B. IR spectroscopy
C. X-ray crystallography
D. Mass spectrometry

4. In electronic theory, a species that donates electrons in a reaction is called a __________. (Linked to SLO 3.2)

A. Electrophile
B. Nucleophile
C. Catalyst
D. Radical

Short-Answer Questions

1. Define electronic theory and explain its role in chemistry. (Linked to SLO 3.1)
2. Describe one difference between structural isomerism and stereoisomerism. (Linked to SLO 3.5)
3. State one limitation of X-ray crystallography. (Linked to SLO 3.4)
4. Give one example of how stereochemistry influences pharmaceuticals. (Linked to SLO 3.7)
5. Explain what optical activity means in relation to chiral molecules. (Linked to SLO 3.6)

Long-Answer Questions

1. Analyse the applications of electronic theory in predicting chemical reactivity, giving examples of nucleophiles and electrophiles. (Linked to SLO 3.2)
2. Evaluate the importance of stereochemistry in modern chemistry, with reference to pharmaceuticals, biochemistry, and everyday life. (Linked to SLO 3.7)

Answers to Concept Check Questions [Series 3: Electronic Theory, Structure Determination, and Stereochemistry]

Objective Questions

1. B. IR spectroscopy
2. Chiral
3. C. X-ray crystallography
4. Nucleophile

Short-Answer Questions

1. Electronic theory explains bonding and reactivity based on the behaviour of electrons, showing how they govern molecular interactions.
2. Structural isomerism involves different atom connections, while stereoisomerism involves the same connections but different spatial arrangements.
3. X-ray crystallography requires high-quality crystals, which are not always easy to obtain.
4. In pharmaceuticals, only one enantiomer of a drug may be active, while the other can be inactive or harmful.
5. Optical activity is the ability of chiral molecules to rotate plane-polarised light, either clockwise or anticlockwise.

Long-Answer Questions

1. **Basic response:** Electronic theory predicts reactivity by identifying nucleophiles (electron donors) and electrophiles (electron acceptors). For example, hydroxide ions act as nucleophiles, while carbocations act as electrophiles.
   Value-added response: Beyond this, electronic theory underpins mechanisms in organic chemistry, such as substitution and addition reactions, and helps chemists design synthetic pathways by anticipating electron flow.
2. **Basic response:** Stereochemistry is important because it influences drug activity, enzyme interactions, and properties of materials. For example, one enantiomer of a drug may be therapeutic while the other is harmful.
   Value-added response: Outstanding learners may note that stereochemistry also affects food flavours, fragrances, and agricultural chemicals. It is central to understanding biological systems, where chirality determines protein folding and DNA structure, and it drives innovation in materials science through stereoregular polymers.

Answers to Pilot Questions

Part 3.1 Fundamentals of electronic theory

1. Electronic theory explains bonding and reactivity in chemistry.
2. Covalent bonds involve sharing of electrons, while ionic bonds involve transfer of electrons.
3. A nucleophile donates electrons, while an electrophile accepts electrons.

Part 3.2 Methods of structure determination

1. IR spectroscopy provides information about functional groups in a molecule.
2. X-ray crystallography is important because it reveals precise atomic positions in crystals.
3. Chemists combine methods to obtain more accurate and complete structural information.

Part 3.3 Principles of stereochemistry

1. Stereochemistry studies the three-dimensional arrangement of atoms and its importance in chemical behaviour.
2. Structural isomerism differs from stereoisomerism because it involves different atom connections, while stereoisomerism involves different spatial arrangements.

3. Chirality refers to molecules that cannot be superimposed on their mirror images, and optical activity is their ability to rotate plane-polarised light.

Part 3.4 Applications of stereochemistry in modern chemistry

1. Stereochemistry is important in drug design because only one enantiomer may be active while the other can be harmful.
2. Stereochemistry influences biological molecules such as proteins and DNA, which are inherently chiral.
3. Everyday examples include flavours in food, fragrances, and the effectiveness of agricultural chemicals.

References and Attributions [Series 3: Electronic Theory, Structure Determination, and Stereochemistry]

Figures

- Figure 3.1 Representation of electronic theory in bonding.
  Attribution: AI-generated using the prompt *"Generate a labelled diagram showing electron clouds overlapping to form covalent bonds."*
- Figure 3.2 Overview of spectroscopic techniques in structure determination.
  Attribution: AI-generated using the prompt *"Generate a labelled diagram showing UV, IR, NMR, and MS spectroscopy with examples of what each reveals about molecular structure."*
- Figure 3.3 Illustration of stereochemistry in molecules.
  Attribution: AI-generated using the prompt *"Generate a labelled diagram showing two molecules with identical formulas but different spatial arrangements to illustrate stereochemistry."*
- Figure 3.4 Role of stereochemistry in drug design.
  Attribution: AI-generated using the prompt *"Generate a labelled diagram showing two enantiomers of a drug molecule, highlighting active and inactive forms."*

Plates

- Plate 3.1 Covalent and ionic bonding illustrated.
  Attribution: AI-generated using the prompt *"Create an illustration showing covalent bonding with shared electrons and ionic bonding with electron transfer."*
- Plate 3.2 X-ray crystallography process.
  Attribution: AI-generated using the prompt *"Create an illustration showing X-rays striking a crystal and producing a diffraction pattern used to determine atomic positions."*
- Plate 3.3 Types of stereoisomerism.
  Attribution: AI-generated using the prompt *"Create an illustration showing cis-trans isomers and optical isomers side by side to demonstrate stereoisomerism."*
- Plate 3.4 Stereochemistry in biochemistry and materials science.
  Attribution: AI-generated using the prompt *"Create an illustration showing chiral biomolecules interacting with enzymes and polymers with stereochemical arrangements."*

Boxes and Tables

- Box 3.1 Key applications of electronic theory.
  Attribution: AI-generated using the prompt *"Generate a simple table listing nucleophiles and electrophiles with examples of their roles in chemical reactions."*
- Box 3.2 Strengths and limitations of structure determination methods.
  Attribution: AI-generated using the prompt *"Generate a simple table comparing spectroscopy, X-ray crystallography, and mass spectrometry with their strengths and limitations."*
- Box 3.3 Chirality and optical activity explained.
  Attribution: AI-generated using the prompt *"Generate a simple table explaining chirality, enantiomers, and optical activity with examples."*
- Box 3.4 Everyday examples of stereochemistry.
  Attribution: AI-generated using the prompt *"Generate a simple table listing everyday examples of stereochemistry in food flavour, fragrances, and agriculture."*

Open Educational Resources (OER) Search Strings Suggested

- "electronic theory bonding diagram OER chemistry"
- "covalent ionic bonding diagram OER chemistry"
- "spectroscopy techniques UV IR NMR MS OER chemistry diagram"
- "X-ray crystallography diffraction pattern OER chemistry image"
- "structure determination methods strengths limitations OER chemistry table"
- "stereochemistry molecular arrangement diagram OER chemistry"
- "cis trans optical isomerism diagram OER chemistry"
- "chirality optical activity enantiomers OER chemistry table"
- "drug enantiomers stereochemistry diagram OER chemistry"
- "stereochemistry biomolecules enzymes polymers OER image"
- "stereochemistry everyday life food fragrance agriculture OER chemistry table"

General References

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- Eliel, E. L., Wilen, S. H., & Mander, L. N. (1994). *Stereochemistry of Organic Compounds*. Wiley.

Course Code: CHM 102
Course Title: General Chemistry II
Course Unit: 2 Units

Series 1: Foundations and Development of Organic Chemistry
Series 2: Carbon Allotropes and Fullerenes in Modern Chemistry
Series 3: Electronic Theory, Structure Determination, and Stereochemistry
Series 4: Organic Functional Groups, Nomenclature, and Reaction Mechanisms
Series 5: Comparative and Transition Metal Chemistry

Series 4: Organic Functional Groups, Nomenclature, and Reaction Mechanisms

Series Outline

4.1 Organic Functional Groups

- **4.1.1 Classification of Functional Groups**

- Definition of **functional group**: a specific group of atoms within a molecule responsible for characteristic chemical reactions.
- Examples: hydroxyl, carbonyl, carboxyl, amino.

- **4.1.2 Physical and Chemical Properties of Functional Groups**

- Influence on solubility, boiling point, and reactivity.

- **4.1.3 Functional Group Interconversions**

- Simple transformations such as alcohol to aldehyde, alkene to alkane.

4.2 Nomenclature of Organic Compounds

- **4.2.1 IUPAC Rules of Nomenclature**

- Systematic naming conventions for alkanes, alkenes, alkynes, and aromatics.

- **4.2.2 Naming Compounds with Functional Groups**

- Priority rules for multiple functional groups.

- **4.2.3 Common Names versus Systematic Names**

- Historical and practical usage.

4.3 Reaction Mechanisms in Organic Chemistry

- **4.3.1 Concept of Reaction Mechanism**
- Definition of **mechanism**: step-by-step description of how a chemical reaction occurs.
- **4.3.2 Types of Organic Reactions**
- Substitution, addition, elimination, rearrangement.
- **4.3.3 Energy Profiles and Transition States**
- Activation energy, intermediates, and catalysts.
- **4.3.4 Illustrative Mechanisms**
- SN1, SN2, E1, E2 reactions.

4.4 Applications of Functional Groups and Mechanisms

- **4.4.1 Functional Groups in Everyday Life**
- Pharmaceuticals, polymers, food chemistry.
- **4.4.2 Mechanistic Understanding in Industrial Processes**
- Petrochemicals, synthesis of dyes, and agrochemicals.

Introduction

Organic chemistry is often described as the chemistry of life, since it deals with compounds built around carbon, the element that forms the backbone of biomolecules, fuels, and countless industrial materials. In this Series, we turn our attention to the essential building blocks of organic chemistry: functional groups, the rules of nomenclature, and the mechanisms that explain how organic reactions occur. These topics are central to understanding how molecules behave and interact, and they provide the foundation for advanced study in chemistry, biochemistry, and related fields.

The aim of this Series is to equip you with the ability to identify and classify organic functional groups, apply systematic rules of nomenclature to name organic compounds accurately, and analyse reaction mechanisms to explain how and why organic transformations take place.

We shall commence this Series by examining organic functional groups, their classification, and their properties. Next, we will move on to the nomenclature of organic compounds, focusing on IUPAC rules and the naming of compounds with multiple functional groups. Following that, we will explore reaction mechanisms, considering the different types of organic reactions and their energy profiles. Finally, we will conclude by discussing the applications of functional groups and mechanisms in everyday life and industrial processes, thereby rounding off the Series with practical relevance.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **4.1** define organic functional groups and classify them according to their structural features,
- **4.2** explain the physical and chemical properties associated with common functional groups,
- **4.3** apply systematic IUPAC rules to name organic compounds accurately,
- **4.4** differentiate between common names and systematic names of organic compounds,
- **4.5** describe the concept of reaction mechanism and outline the steps involved in selected organic reactions,
- **4.6** analyse the energy profiles of organic reactions, identifying intermediates and transition states,
- **4.7** demonstrate the mechanisms of substitution and elimination reactions such as SN1, SN2, E1, and E2, and
- **4.8** evaluate the practical applications of functional groups and reaction mechanisms in everyday life and industrial processes.

4.1 Organic Functional Groups

4.1.1 Classification of functional groups

A **functional group** is a specific group of atoms within a molecule that is responsible for the characteristic chemical reactions of that molecule. Functional groups provide a way to classify organic compounds according to their reactivity and properties. Common examples include the **hydroxyl group** (–OH), which is found in alcohols, the **carbonyl group** (C=O), present in aldehydes and ketones, and the **carboxyl group** (–COOH), characteristic of carboxylic acids. Functional groups can be broadly classified into families such as hydrocarbons, oxygen-containing groups, nitrogen-containing groups, and halogen-containing groups. Each family exhibits distinct chemical behaviour, which makes classification a useful tool for predicting reactions.

Fill in the blank: The ______ group is responsible for the acidic properties of carboxylic acids.

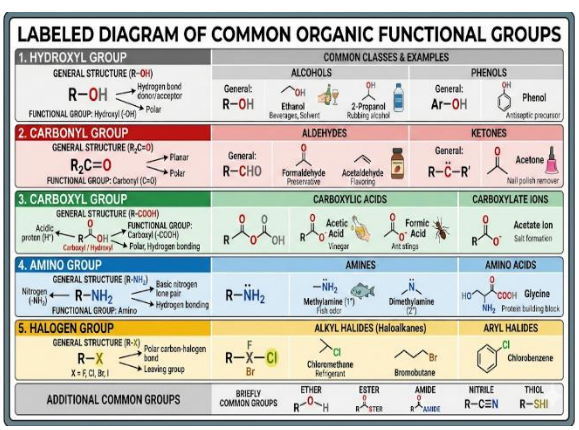


Figure 4.1 Common organic functional groups.

4.1.2 Physical and chemical properties of functional groups

The presence of a functional group influences both the **physical properties** and **chemical properties** of a compound. Physical properties such as boiling point, melting point, and solubility are often determined by the type of bonding and polarity introduced by the functional group. For example, alcohols with hydroxyl groups can form hydrogen bonds, which raise their boiling points compared to hydrocarbons of similar molecular weight.

Chemical properties, on the other hand, are defined by the reactivity of the functional group. For instance, aldehydes and ketones undergo nucleophilic addition reactions due to the polarised carbonyl bond.

Fill in the blank: Compounds containing the ______ group can form hydrogen bonds, which increase their boiling points.

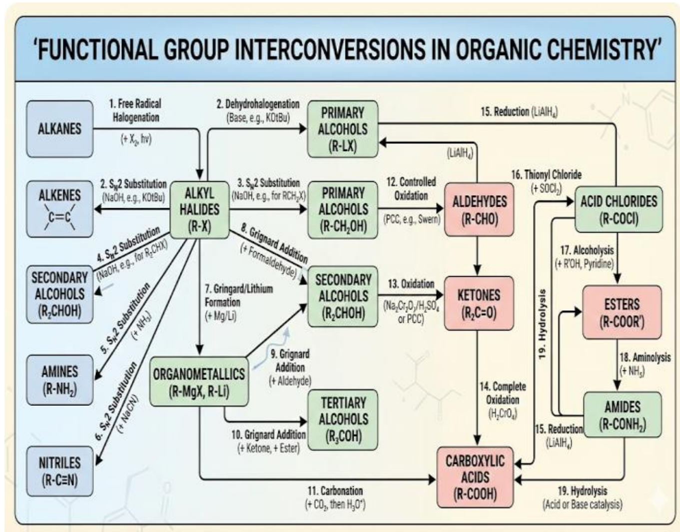
Functional Group	**Structure (General)**	**Primary Intermolecular Forces**	**Boiling Point**	**Solubility in Water**
Hydrocarbons	$R-H$	London Dispersion Forces	**Lowest**	**Insoluble** (Non-polar)
Aldehydes	$R-CHO$	Dipole-Dipole	**Medium**	**Moderate** (Can accept H-bonds)
Alcohols	$R-OH$	Hydrogen Bonding	**High**	**High** (Donor & Acceptor)
Carboxylic Acids	$R-COOH$	Strong Hydrogen Bonding	**Highest**	**Highest** (Forms stable dimers)

Table 4.1 Influence of functional groups on physical properties.

4.1.3 Functional group interconversions

One of the most important aspects of organic chemistry is the ability to transform one functional group into another. These **functional group interconversions** are the basis of synthetic chemistry. For example, alcohols can be oxidised to aldehydes or ketones, and alkenes can be hydrogenated to alkanes. Such transformations allow chemists to design pathways for synthesising complex molecules from simpler starting materials.

Fill in the blank: The oxidation of a primary alcohol produces an ______ as the first product.



Box 4.1 Examples of functional group interconversions.

Pilot questions 4.1

1. Which functional group is characteristic of alcohols?
2. What type of bond is present in the carbonyl group?
3. Why do alcohols generally have higher boiling points than alkanes of similar molecular weight?
4. What is the first product formed when a primary alcohol is oxidised?
5. Name one example of a functional group interconversion.

4.2 Nomenclature of Organic Compounds

4.2.1 IUPAC rules of nomenclature

The **International Union of Pure and Applied Chemistry (IUPAC)** provides a systematic set of rules for naming organic compounds. These rules ensure that each compound has a unique and universally recognised name. The process involves identifying the longest continuous carbon chain, determining the principal functional group, and assigning locants (numbers) to indicate the positions of substituents.

For example, in naming alkanes, the suffix "–ane" is used, while alkenes and alkynes use "–ene" and "–yne" respectively. Aromatic compounds are named based on the benzene ring, with substituents indicated by prefixes and locants.

Fill in the blank: The suffix used for naming alkanes according to IUPAC rules is ______.

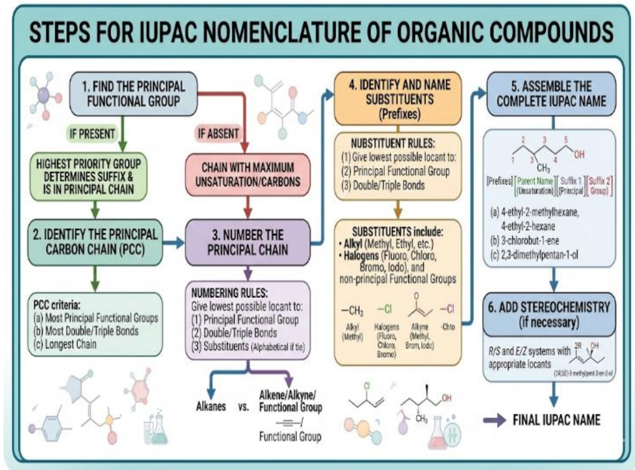


Figure 4.2 Steps in IUPAC nomenclature.

4.2.2 Naming compounds with functional groups

When a compound contains one or more **functional groups**, the rules of nomenclature require assigning priority to the group that determines the suffix of the name. For instance, carboxylic acids take precedence over alcohols, so a molecule containing both will be named as a carboxylic acid. Substituents of lower priority are named as prefixes.

The numbering of the carbon chain must ensure that the principal functional group receives the lowest possible locant. This avoids ambiguity and ensures consistency across different compounds.

Fill in the blank: In a compound containing both a hydroxyl group and a carboxyl group, the _______ group takes naming priority.

Priority	Functional Group	Structure	Prefix	Suffix
1	**Carboxylic Acid**	$R-COOH$	Carboxy-	-oic acid
2	**Ester**	$R-COOR$	Alkoxycarbonyl-	-oate
3	**Amide**	$R-CONH_2$	Amido-	-amide
4	**Nitrile**	$R-C \equiv N$	Cyano-	-nitrile
5	**Aldehyde**	$R-CHO$	Oxo- / Formyl-	-al

Priority	Functional Group	Structure	Prefix	Suffix
6	**Ketone**	$R-C(=O)R$	Oxo-	-one
7	**Alcohol**	$R-OH$	Hydroxy-	-ol
8	**Amine**	$R-NH_2$	Amino-	-amine
9	**Alkene**	$R_2C=CR_2$	Alkenyl-	-ene
10	**Alkyne**	$R-C \equiv C-R$	Alkynyl-	-yne
11	**Alkane**	$R-CH_2-R$	Alkyl-	-ane

Table 4.2 Priority order of functional groups in IUPAC nomenclature.

4.2.3 Common names versus systematic names

Many organic compounds have **common names**, which are traditional names often derived from historical sources or practical usage. For example, acetic acid is the common name for ethanoic acid, and formaldehyde is the common name for methanal. While common names are widely used in everyday contexts, systematic names are preferred in scientific communication because they are precise and universally accepted.

Learners should be able to recognise both naming systems, but when writing scientific reports or examinations, systematic names must be used.

Fill in the blank: The systematic name for acetic acid is ______.

Common Name	IUPAC Systematic Name	Chemical Formula	Typical Use/Source
Formic acid	Methanoic acid	$HCOOH$	Ant stings, bee venom
Acetic acid	Ethanoic acid	CH_3COOH	Vinegar
Acetone	Propan-2-one	CH_3COCH_3	Nail polish remover
Formaldehyde	Methanal	$HCHO$	Preservative

Common Name	IUPAC Systematic Name	Chemical Formula	Typical Use/Source
Acetaldehyde	Ethanal	CH_3CHO	Ripening fruit flavor
Acetylene	Ethyne	C_2H_2	Welding torches
Ethylene	Ethene	C_2H_4	Plant hormone (ripening)
Isopropyl alcohol	Propan-2-ol	$(CH_3)_2CHOH$	Rubbing alcohol
Chloroform	Trichloromethane	$CHCl_3$	Former anesthetic
Toluene	Methylbenzene	$C_6H_5CH_3$	Industrial solvent

Box 4.2 Examples of common names and their systematic equivalents.

Pilot questions 4.2

1. What is the suffix used for naming alkenes according to IUPAC rules?
2. Which functional group takes priority when naming a compound containing both an alcohol and a ketone?
3. Why is it important to assign locants in nomenclature?
4. Give the systematic name for formaldehyde.
5. What is the main difference between common names and systematic names?

4.3 Reaction Mechanisms in Organic Chemistry

4.3.1 Concept of reaction mechanism

A **reaction mechanism** is a step-by-step description of how a chemical reaction occurs at the molecular level. It explains the sequence of bond-breaking and bond-forming events, the intermediates formed, and the transition states passed through. Understanding mechanisms allows chemists to predict the outcome of reactions and design new synthetic pathways.
Fill in the blank: A _______ mechanism describes the detailed steps by which a chemical reaction proceeds.

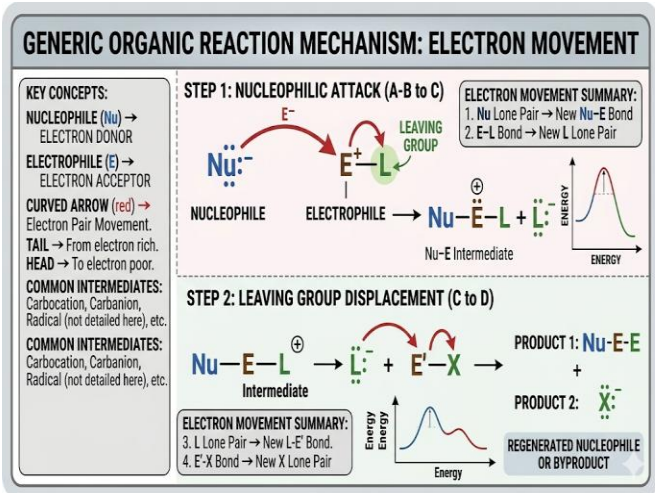


Figure 4.3 General representation of a reaction mechanism.

4.3.2 Types of organic reactions

Organic reactions can be classified into several types based on the changes that occur. The main categories include:

- **Substitution reactions**, where one atom or group is replaced by another.
- **Addition reactions**, where atoms or groups are added to a molecule, often across a double bond.
- **Elimination reactions**, where atoms or groups are removed, usually forming a double bond.
- **Rearrangement reactions**, where the structure of a molecule is reorganised without changing its overall composition.

Fill in the blank: When a halogen atom replaces a hydrogen atom in an alkane, the reaction is classified as a ______ reaction.

Reaction Type	Description	General Change	Example Reaction
Substitution	One atom or group is replaced by another.	$A-B + C \rightarrow A-C + B$	Chlorination of Methane ($CH_4 + Cl_2 \rightarrow CH_3Cl + HCl$)
Addition	Two reactants combine to form a single product; usually involves breaking a double/triple bond.	$A=B + C \rightarrow C-A-B$	Hydrogenation of Ethylene ($C_2H_4 + H_2 \rightarrow C_2H_6$)

Reaction Type	Description	General Change	Example Reaction
Elimination	A single reactant splits into two products; usually results in the formation of a double/triple bond.	$C-A-B \rightarrow A=B + C$	Dehydration of Ethanol ($C_2H_5OH \rightarrow C_2H_4 + H_2O$)
Rearrangement	A single reactant undergoes a reorganization of bonds/atoms to form an isomer.	$A \rightarrow B$ (Isomerization)	Butane to Isobutane conversion

Table 4.3 Types of organic reactions with examples.

4.3.3 Energy profiles and transition states

Every chemical reaction involves an **activation energy**, which is the minimum energy required for the reaction to occur. The reaction pathway can be represented by an **energy profile diagram**, showing the energy changes as reactants are converted to products.

A **transition state** is a high-energy, unstable arrangement of atoms that exists momentarily during the reaction. Intermediates, on the other hand, are species that form between steps and have a finite lifetime. Recognising these features helps explain why some reactions are faster or slower than others.

Fill in the blank: The unstable arrangement of atoms at the highest point of the energy profile is called the _______ state.

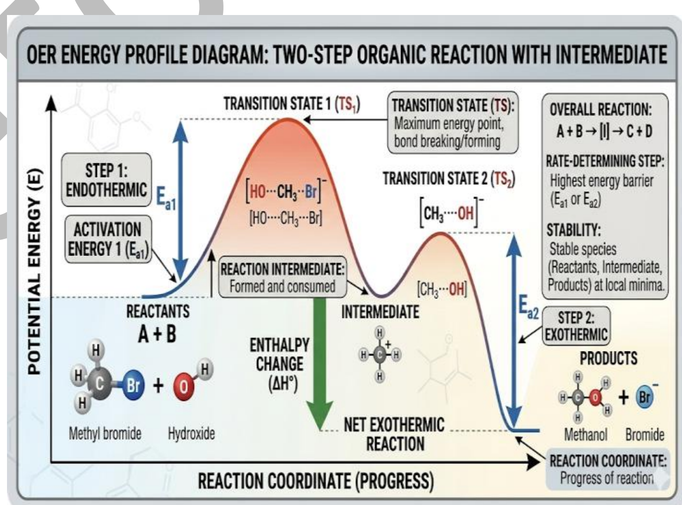


Figure 4.4 Energy profile of a chemical reaction.

4.3.4 Illustrative mechanisms

Two important substitution mechanisms are **SN1** and **SN2**. In an SN1 reaction, the rate depends only on the concentration of the substrate, and the reaction proceeds through a carbocation intermediate. In contrast, an SN2 reaction involves a single step where the nucleophile attacks the substrate as the leaving group departs.

Elimination reactions can also proceed via two pathways: **E1** and **E2**. The E1 mechanism involves a carbocation intermediate, while the E2 mechanism occurs in a single concerted step.

Fill in the blank: In an SN2 reaction, the nucleophile attacks the substrate from the ______ side relative to the leaving group.

Feature	SN1	SN2	E1	E2
Kinetics (Rate Law)	First-order: $k[RX]$	Second-order: $k[RX][Nu^-]$	First-order: $k[RX]$	Second-order: $k[RX][Base^-]$
Intermediate	Carbocation	None (Concerted)	Carbocation	None (Concerted)
Substrate Preference	$3^\circ > 2^\circ \gg 1^\circ$	$CH_3 > 1^\circ > 2^\circ \gg 3^\circ$	$3^\circ > 2^\circ \gg 1^\circ$	$3^\circ > 2^\circ > 1^\circ$
Stereochemistry	Racemization	Inversion (Walden)	Mixed (Zaitsev preference)	Anti-periplanar requirement
Nucleophile/Base	Weak (e.g., H_2O, ROH)	Strong (e.g., OH^-, CN^-)	Weak (e.g., H_2O, ROH)	Strong (e.g., OR^-, NH_2^-)
Solvent	Polar Protic	Polar Aprotic	Polar Protic	Variable

Box 4.3 Comparison of SN1, SN2, E1, and E2 mechanisms.

Pilot questions 4.3

1. What is meant by the term reaction mechanism?
2. Which type of reaction involves the replacement of one atom or group by another?
3. What is the name given to the unstable arrangement of atoms at the highest point of the energy profile?

4. How does the SN1 mechanism differ from the SN2 mechanism?
5. Which elimination mechanism involves a carbocation intermediate?

4.4 Applications of Functional Groups and Mechanisms

4.4.1 Functional groups in everyday life

Organic **functional groups** are not abstract concepts confined to textbooks; they are present in many substances we encounter daily. For example, the hydroxyl group in alcohols is found in beverages and antiseptics, while the carboxyl group in fatty acids is essential for nutrition and metabolism. Amino groups are present in proteins, which are vital for growth and repair. Functional groups also determine the properties of polymers, dyes, and flavouring agents. Their presence explains why certain compounds dissolve in water, why some have distinctive odours, and why others are biologically active.

Fill in the blank: The ______ group is responsible for the acidic properties of fatty acids.

Plate 4.1 Everyday products containing organic functional groups.

4.4.2 Mechanistic understanding in industrial processes

The study of **reaction mechanisms** is crucial in industrial chemistry, where efficiency and selectivity are highly valued. For instance, understanding the SN1 and SN2 mechanisms helps chemists design better synthetic routes for pharmaceuticals. Similarly, elimination reactions are used in the production of alkenes, which serve as precursors for plastics and synthetic fibres. Catalysts are often employed to lower activation energy and increase reaction rates. By analysing mechanisms, industries can optimise conditions such as temperature, pressure, and solvent choice to achieve maximum yield with minimal waste.

Fill in the blank: In industrial chemistry, catalysts are used to lower the ______ energy of reactions.

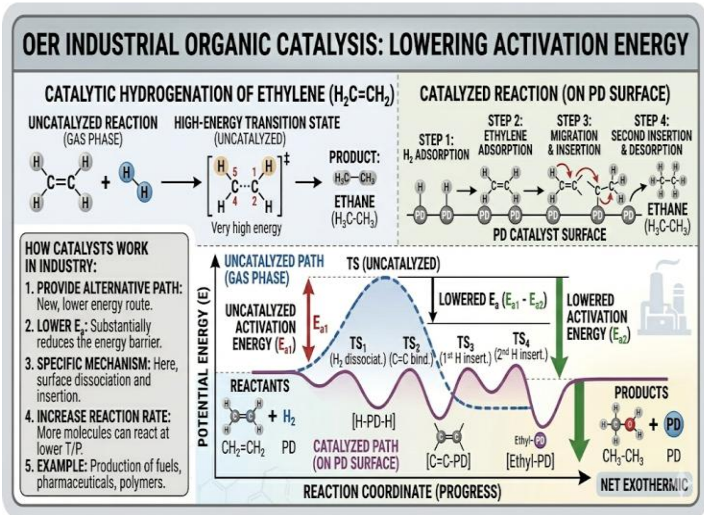


Figure 4.5 Role of catalysts in industrial organic reactions.

Pilot questions 4.4

1. Which functional group is present in vinegar?
2. Why are amino groups important in proteins?
3. What role do catalysts play in industrial organic reactions?
4. Which reaction mechanism is commonly used in the synthesis of pharmaceuticals?
5. Give one example of how functional groups influence the properties of everyday products.

Series Summary

This Series has highlighted the importance of organic functional groups, systematic nomenclature, and reaction mechanisms as the foundation of organic chemistry. We began by classifying functional groups and examining their physical and chemical properties, then progressed to the rules of nomenclature, focusing on IUPAC conventions and the distinction between common and systematic names. Following that, we explored reaction mechanisms, considering substitution, addition, elimination, and rearrangement reactions, supported by energy profiles and illustrative examples. Finally, we concluded with practical applications, showing how these concepts are relevant in everyday life and industrial processes.

By completing this Series, you should now be able to define and classify functional groups, explain their properties, apply systematic nomenclature rules, differentiate between naming systems, describe and analyse reaction mechanisms, interpret energy profiles, demonstrate substitution and elimination pathways, and evaluate their applications in real-world contexts. These abilities directly reflect the Series Learning Outcomes and provide you with a strong foundation for further study and practice in organic chemistry.

Glossary of Terms

- **Activation energy**: The minimum amount of energy required for a chemical reaction to occur.
- **Addition reaction**: A type of organic reaction in which atoms or groups are added to a molecule, often across a double bond.
- **Aldehyde**: An organic compound containing a carbonyl group bonded to at least one hydrogen atom.
- **Amino group**: A functional group consisting of a nitrogen atom bonded to hydrogen atoms, commonly found in proteins.
- **Carbocation**: A positively charged carbon species formed as an intermediate in some reaction mechanisms.
- **Carboxyl group**: A functional group consisting of a carbon atom double-bonded to an oxygen atom and bonded to a hydroxyl group, characteristic of carboxylic acids.
- **Common name**: A traditional or historical name for a compound, often used in everyday contexts but not systematic.
- **Elimination reaction**: A type of organic reaction in which atoms or groups are removed from a molecule, usually forming a double bond.
- **Energy profile diagram**: A graphical representation of the energy changes during a chemical reaction, showing activation energy, transition states, and intermediates.
- **Functional group**: A specific group of atoms within a molecule responsible for characteristic chemical reactions.
- **Hydroxyl group**: A functional group consisting of an oxygen atom bonded to a hydrogen atom, found in alcohols.
- **IUPAC nomenclature**: The systematic method of naming chemical compounds established by the International Union of Pure and Applied Chemistry.
- **Intermediate**: A species formed temporarily during a chemical reaction, existing between reactants and products.
- **Ketone**: An organic compound containing a carbonyl group bonded to two carbon atoms.
- **Locant**: A number used in nomenclature to indicate the position of a substituent or functional group on the carbon chain.
- **Nucleophile**: A species that donates an electron pair to form a chemical bond in a reaction.
- **Oxidation**: A chemical process involving the loss of electrons or an increase in oxidation state, often converting alcohols to aldehydes or ketones.
- **Reaction mechanism**: A step-by-step description of how a chemical reaction occurs, including bond changes, intermediates, and transition states.
- **Rearrangement reaction**: A type of organic reaction in which the structure of a molecule is reorganised without changing its overall composition.
- **Substitution reaction**: A type of organic reaction in which one atom or group is replaced by another.
- **Systematic name**: The precise name of a compound based on IUPAC rules, ensuring universal recognition.
- **Transition state**: A high-energy, unstable arrangement of atoms that exists momentarily during a chemical reaction.

Concept Check Questions 4: Organic Functional Groups, Nomenclature, and Reaction Mechanisms

Objective Questions

1. Which functional group is characteristic of alcohols? (Linked to SLO 4.1)
   a) Carbonyl group
   b) Hydroxyl group
   c) Carboxyl group
   d) Amino group
2. What suffix is used for naming alkanes according to IUPAC rules? (Linked to SLO 4.3)
   a) –ene
   b) –yne
   c) –ane
   d) –ol
3. In an SN1 reaction, the rate depends on the concentration of which species? (Linked to SLO 4.5)
   a) Nucleophile
   b) Substrate
   c) Catalyst
   d) Solvent
4. Which elimination mechanism involves a carbocation intermediate? (Linked to SLO 4.7)
   a) E1
   b) E2
   c) SN1
   d) SN2
5. What is the unstable arrangement of atoms at the highest point of the energy profile called? (Linked to SLO 4.6)
   a) Intermediate
   b) Transition state
   c) Catalyst
   d) Reactant

Short-Answer Questions

1. Define a functional group and give one example. (Linked to SLO 4.1)
2. Explain why alcohols generally have higher boiling points than alkanes of similar molecular weight. (Linked to SLO 4.2)
3. Differentiate between common names and systematic names of organic compounds. (Linked to SLO 4.4)
4. Describe the main difference between SN1 and SN2 mechanisms. (Linked to SLO 4.5)
5. State one industrial application of reaction mechanisms. (Linked to SLO 4.8)

Long-Answer Questions

1. Analyse the role of functional groups in determining the physical and chemical properties of organic compounds, using at least three examples. (Linked to SLO 4.2)

2. Demonstrate how to apply IUPAC rules to name a compound containing both a hydroxyl group and a carboxyl group, explaining the priority rules. (Linked to SLO 4.3)
3. Evaluate the importance of understanding reaction mechanisms in pharmaceutical synthesis, with reference to substitution and elimination reactions. (Linked to SLO 4.8)

Answers to Concept Check Questions [Series 4: Organic Functional Groups, Nomenclature, and Reaction Mechanisms]

Objective Questions

1. b) Hydroxyl group
2. c) –ane
3. b) Substrate
4. a) E1
5. b) Transition state

Short-Answer Questions

1. A functional group is a specific group of atoms within a molecule responsible for characteristic chemical reactions. Example: hydroxyl group (–OH).
2. Alcohols form hydrogen bonds due to the hydroxyl group, which increases their boiling points compared to alkanes.
3. Common names are traditional and often historical, while systematic names follow IUPAC rules and are precise and universally recognised.
4. SN1 involves a carbocation intermediate and depends only on substrate concentration, while SN2 occurs in one step and depends on both substrate and nucleophile concentration.
5. Reaction mechanisms are applied in designing efficient synthetic routes for pharmaceuticals, plastics, and agrochemicals.

Long-Answer Questions

1. **Basic response:** Functional groups influence properties such as solubility, boiling point, and reactivity. For example, hydroxyl groups allow hydrogen bonding, carbonyl groups undergo nucleophilic addition, and carboxyl groups impart acidity.
   Value-added response: Beyond these, functional groups also determine biological activity, industrial applications, and environmental behaviour. For instance, amino groups in proteins enable enzyme activity, while halogen groups affect the stability of polymers.
2. **Basic response:** In a compound with both hydroxyl and carboxyl groups, the carboxyl group takes priority, so the compound is named as a carboxylic acid. The hydroxyl group is treated as a substituent.
   Value-added response: For example, $HOCH_2COOH$ is named systematically as 2-hydroxyethanoic acid. This demonstrates the application of priority rules and locants in nomenclature.
3. **Basic response:** Understanding mechanisms such as SN1, SN2, E1, and E2 helps chemists design pharmaceutical syntheses with predictable outcomes.

Value-added response: In drug development, mechanistic knowledge allows optimisation of reaction conditions, minimisation of side products, and improvement of stereoselectivity, which is critical for producing safe and effective medicines.

Answers to Pilot Questions [Series 4: Organic Functional Groups, Nomenclature, and Reaction Mechanisms]

Part 4.1 Organic Functional Groups

1. Hydroxyl group.
2. Carbon–oxygen double bond.
3. Because alcohols form hydrogen bonds due to the hydroxyl group.
4. Aldehyde.
5. Alcohol to aldehyde, alkene to alkane, ketone to alcohol.

Part 4.2 Nomenclature of Organic Compounds

1. –ene.
2. Ketone.
3. To indicate the exact position of substituents or functional groups.
4. Methanal.
5. Common names are traditional and less precise, while systematic names follow IUPAC rules and are universally recognised.

Part 4.3 Reaction Mechanisms in Organic Chemistry

1. A step-by-step description of how a chemical reaction occurs.
2. Substitution reaction.
3. Transition state.
4. SN1 involves a carbocation intermediate and depends only on substrate concentration, while SN2 occurs in one step and depends on both substrate and nucleophile concentration.
5. E1 mechanism.

Part 4.4 Applications of Functional Groups and Mechanisms

1. Carboxyl group (acetic acid in vinegar).
2. They are essential for protein structure and biological activity.
3. Catalysts lower activation energy and increase reaction rates.
4. Substitution mechanisms such as SN1 and SN2.
5. Functional groups influence solubility, odour, and reactivity in everyday products.

References and Attributions [Series 4: Organic Functional Groups, Nomenclature, and Reaction Mechanisms]

General References

- International Union of Pure and Applied Chemistry (IUPAC). (2014). *Nomenclature of Organic Chemistry: IUPAC Recommendations and Preferred Names 2013*. Cambridge: Royal Society of Chemistry.
- McMurry, J. (2021). *Organic Chemistry* (10th ed.). Boston: Cengage Learning.
- Solomons, T. W. G., Fryhle, C. B., & Snyder, S. A. (2020). *Organic Chemistry* (12th ed.). Hoboken: Wiley.
- OpenStax. (2016). *Chemistry*. Houston: Rice University. Available under Creative Commons licence at https://openstax.org/books/chemistry

Illustrations and OER Sources

- **Figure 4.1 Common organic functional groups**

- Suggested AI prompt: "Generate a labelled diagram of common organic functional groups including hydroxyl, carbonyl, carboxyl, amino, and halogen groups."
- Search string: "OER diagram common organic functional groups chemistry"
- Attribution: OpenStax Chemistry (2016), Chapter 24, Creative Commons licence.

- **Table 4.1 Influence of functional groups on physical properties**

- Suggested AI prompt: "Create a table comparing boiling points and solubility of hydrocarbons, alcohols, aldehydes, and carboxylic acids."
- Search string: "OER table physical properties functional groups chemistry"
- Attribution: Adapted from OpenStax Chemistry (2016), Chapter 24.

- **Box 4.1 Examples of functional group interconversions**

- Suggested AI prompt: "Generate a text box listing common functional group interconversions with arrows showing transformations."
- Search string: "OER organic chemistry functional group interconversions examples"
- Attribution: Adapted from McMurry (2021).

- **Figure 4.2 Steps in IUPAC nomenclature**

- Suggested AI prompt: "Generate a flowchart illustrating the steps of IUPAC nomenclature for organic compounds."
- Search string: "OER diagram IUPAC nomenclature organic chemistry"
- Attribution: IUPAC (2014).

- **Table 4.2 Priority order of functional groups in IUPAC nomenclature**

- Suggested AI prompt: "Create a table showing the priority order of functional groups in IUPAC nomenclature."

- Search string: “OER functional group priority table IUPAC nomenclature”
- Attribution: IUPAC (2014).

- **Box 4.2 Examples of common names and their systematic equivalents**

- Suggested AI prompt: “Generate a text box listing common names of organic compounds alongside their systematic IUPAC names.”
- Search string: “OER organic chemistry common vs systematic names examples”
- Attribution: Solomons et al. (2020).

- **Figure 4.3 General representation of a reaction mechanism**

- Suggested AI prompt: “Generate a diagram illustrating a generic organic reaction mechanism with curved arrows showing electron movement.”
- Search string: “OER diagram organic reaction mechanism electron movement”
- Attribution: OpenStax Chemistry (2016).

Table 4.3 Types of organic reactions with examples

- Suggested AI prompt: “Create a table showing types of organic reactions with examples, such as substitution, addition, elimination, and rearrangement.”
- Search string: “OER organic chemistry reaction types examples table”
- Attribution: McMurry (2021).

- **Figure 4.4 Energy profile of a chemical reaction**

- Suggested AI prompt: “Generate an energy profile diagram for a chemical reaction showing activation energy, transition state, and intermediates.”
- Search string: “OER energy profile diagram organic chemistry”
- Attribution: OpenStax Chemistry (2016).

- **Box 4.3 Comparison of SN1, SN2, E1, and E2 mechanisms**

- Suggested AI prompt: “Generate a text box comparing SN1, SN2, E1, and E2 mechanisms with key features such as intermediates, rate laws, and stereochemistry.”
- Search string: “OER SN1 SN2 E1 E2 reaction mechanisms comparison”
- Attribution: Solomons et al. (2020).
-

Plate 4.1 Everyday products containing organic functional groups

-
- Suggested AI prompt: “Generate an image showing household products like vinegar, sanitiser, and nylon fabric, labelled with their functional groups.”
- Search string: “OER everyday products organic functional groups chemistry”
- Attribution: Adapted from OpenStax Chemistry (2016).

- **Figure 4.5 Role of catalysts in industrial organic reactions**

- Suggested AI prompt: “Generate a diagram illustrating an industrial organic reaction with catalysts lowering activation energy.”
- Search string: “OER industrial organic chemistry catalysts reaction mechanisms”
- Attribution: McMurry (2021).

Course Code: CHM 102
Course Title: General Chemistry II
Course Unit: 2 Units

Series 1: Foundations and Development of Organic Chemistry
Series 2: Carbon Allotropes and Fullerenes in Modern Chemistry
Series 3: Electronic Theory, Structure Determination, and Stereochemistry
Series 4: Organic Functional Groups, Nomenclature, and Reaction Mechanisms
Series 5: Comparative and Transition Metal Chemistry

Series 5: Comparative and Transition Metal Chemistry

Series Outline

5.1 Comparative Chemistry of Main Group Elements

- 5.1.1 Periodic trends and properties
- 5.1.2 Comparative reactivity of alkali, alkaline earth, and halogen groups
- 5.1.3 Industrial and everyday applications of main group elements

5.2 Introduction to Transition Metals

- 5.2.1 General characteristics of transition metals
- 5.2.2 Electronic configurations and oxidation states
- 5.2.3 Magnetic properties and colouration in compounds

5.3 Coordination Chemistry

- 5.3.1 Definition of coordination compounds and ligands
- 5.3.2 Nomenclature of coordination complexes
- 5.3.3 Bonding theories: Valence Bond Theory (VBT) and Crystal Field Theory (CFT)

5.4 Applications of Transition Metal Chemistry

- 5.4.1 Catalysis in industrial processes
- 5.4.2 Biological roles of transition metals
- 5.4.3 Transition metals in materials science and technology

Introduction

Chemistry is not only about carbon-based compounds but also about the diverse behaviour of elements across the periodic table. In this Series, we turn our attention to comparative chemistry and the fascinating world of transition metals. These elements are central to many industrial processes, biological systems, and advanced materials, making their study highly relevant to both academic and practical applications.
The aim of this Series is to provide you with a clear understanding of the comparative properties of main group elements, the unique characteristics of transition metals, the principles of coordination chemistry, and the wide-ranging applications of these elements in science and technology.
We shall commence this Series by exploring the comparative chemistry of main group elements, focusing on periodic trends, reactivity, and applications. Next, we will move on to the introduction of transition metals, examining their electronic configurations, oxidation states, and distinctive properties such as magnetism and colour. Following that, we will study coordination chemistry, including the definition of complexes, nomenclature, and bonding theories such as Valence Bond Theory and Crystal Field Theory. Finally, we will conclude by considering the applications of transition metals in catalysis, biological systems, and materials science, thereby rounding off the Series with practical insights into their importance.

Series Learning Outcomes

Upon completing this Series, you should be able to:

5.1 define the periodic trends and comparative properties of main group elements,
5.2 explain the reactivity patterns of alkali, alkaline earth, and halogen groups,
5.3 describe the general characteristics of transition metals, including variable oxidation states and electronic configurations,
5.4 analyse the magnetic properties and colouration of transition metal compounds,
5.5 define coordination compounds and identify different types of ligands,
5.6 demonstrate the correct nomenclature of coordination complexes,
5.7 apply bonding theories such as Valence Bond Theory and Crystal Field Theory to explain the structures and properties of coordination compounds, and
5.8 evaluate the applications of transition metals in catalysis, biological systems, and materials science.

5.1 Comparative Chemistry of Main Group Elements

5.1.1 Periodic trends and properties

The **main group elements** are those found in Groups 1, 2, and 13–18 of the periodic table. They display clear **periodic trends**, which are recurring patterns in properties such as atomic radius,

ionisation energy, and electronegativity. For example, atomic radius increases down a group due to the addition of electron shells, while ionisation energy generally decreases because outer electrons are further from the nucleus.
These trends help explain why elements in the same group often have similar chemical behaviour. For instance, alkali metals are highly reactive because they readily lose their single valence electron, while halogens are reactive because they readily gain one electron to complete their outer shell.
Fill in the blank: The tendency of atoms to attract electrons in a chemical bond is called ______.

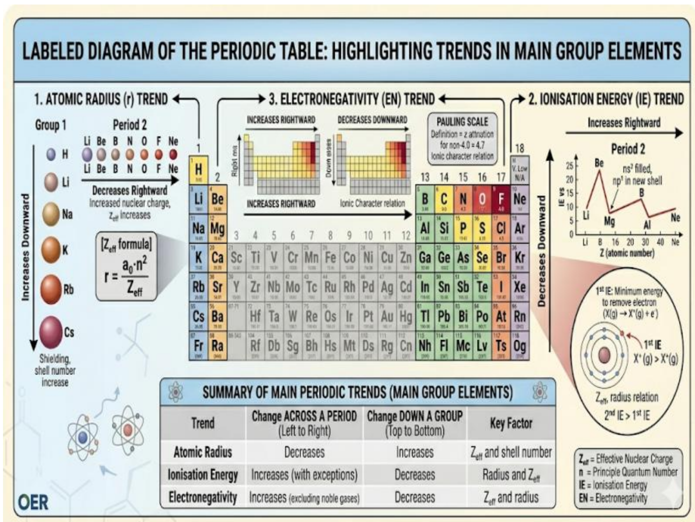


Figure 5.1 Periodic trends in main group elements.

5.1.2 Comparative reactivity of alkali, alkaline earth, and halogen groups

The **alkali metals** (Group 1) are highly reactive, especially with water, producing hydrogen gas and alkaline solutions. Their reactivity increases down the group as the outer electron becomes easier to remove. The **alkaline earth metals** (Group 2) are less reactive but still form basic oxides and hydroxides.
The **halogens** (Group 17) are reactive non-metals that readily form salts with metals. Their reactivity decreases down the group because the larger atomic size makes it harder to attract additional electrons. Comparing these groups highlights how periodic trends influence chemical behaviour.
Fill in the blank: When sodium reacts with water, the gas produced is ______.

Feature	Alkali Metals (Group 1)	Alkaline Earth Metals (Group 2)	Halogens (Group 17)
Electronic Configuration	ns^1 (1 valence e^-)	ns^2 (2 valence e^-)	ns^2np^5 (7 valence e^-)

Feature	Alkali Metals (Group 1)	Alkaline Earth Metals (Group 2)	Halogens (Group 17)
Primary Chemical Behavior	**Highly Electropositive**	**Electropositive**	**Highly Electronegative**
Reactivity Strategy	Loses $1\ e^-$ (forms $+1$ ion)	Loses $2\ e^-$ (forms $+2$ ion)	Gains $1\ e^-$ (forms -1 ion)
Overall Reactivity	**Extreme** (must be stored under oil)	**Very High** (less than Group 1)	**Extreme** (vigor increases *up* the group)
Reactivity Trend (Down Group)	**Increases** (e^- easier to lose)	**Increases** (e^- easier to lose)	**Decreases** (e^- harder to attract)
Interaction with Oxygen	Vigorous (forms oxides, peroxides, superoxides)	Rapid (forms stable oxides)	Forms various unstable, acidic oxides
Interaction with Halogens	Forms stable alkali halides (e.g., $NaCl$)	Forms stable alkaline earth halides (e.g., $MgCl_2$)	N/A (self-reactivity is a diatomic state)

Table 5.1 Comparative reactivity of alkali metals, alkaline earth metals, and halogens.

5.1.3 Industrial and everyday applications of main group elements

Main group elements are widely used in industry and daily life. Sodium and potassium compounds are essential in fertilisers, while calcium compounds are used in cement and glass manufacture. Halogens such as chlorine are used in water purification and disinfectants, while fluorine compounds are found in toothpaste and refrigerants.

These applications demonstrate how the properties of main group elements are harnessed for practical purposes. Understanding their chemistry allows us to appreciate their importance in both natural processes and technological advancements.

Fill in the blank: The halogen commonly used in water purification is ______.

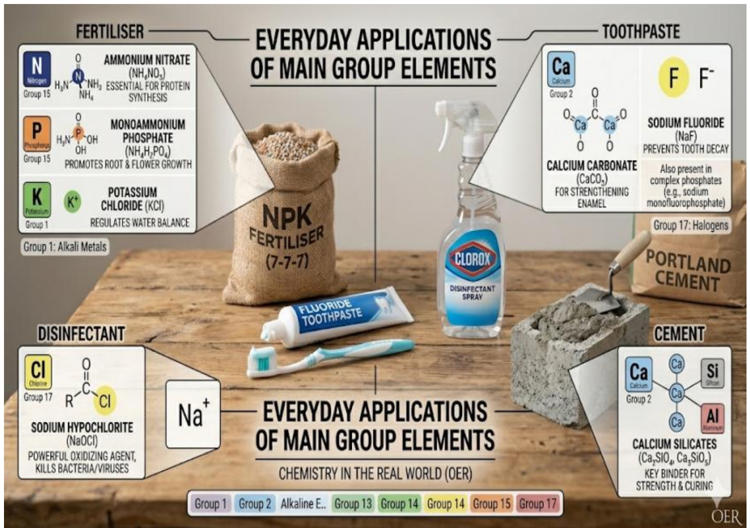


Plate 5.1 Everyday applications of main group elements.

Pilot questions 5.1

1. What is meant by the term periodic trend?
2. Which property decreases down Group 1, making alkali metals more reactive?
3. What gas is produced when sodium reacts with water?
4. Why does the reactivity of halogens decrease down the group?
5. Give one industrial application of calcium compounds.

5.2 Introduction to Transition Metals

5.2.1 General characteristics of transition metals

Transition metals are elements found in Groups 3–12 of the periodic table. They are characterised by having partially filled d-orbitals, which give rise to unique chemical and physical properties. These include variable oxidation states, the ability to form coloured compounds, and the presence of magnetic behaviour. Transition metals are also good conductors of heat and electricity, and many are malleable and ductile.
Because of these properties, transition metals play a vital role in catalysis, alloy formation, and biological systems. Their versatility makes them distinct from main group elements.
Fill in the blank: Transition metals are characterised by having partially filled ______ orbitals.

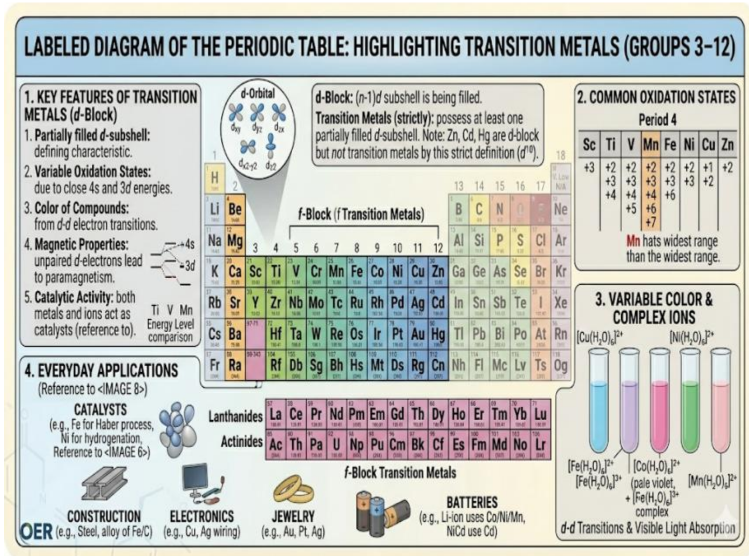


Figure 5.2 Position of transition metals in the periodic table.

5.2.2 Electronic configurations and oxidation states

The **electronic configuration** of transition metals involves filling the d-orbitals after the s-orbitals of the preceding period. This arrangement allows them to exhibit **variable oxidation states**, meaning they can lose different numbers of electrons depending on the reaction. For example, iron can exist as Fe^{2+} or Fe^{3+}, while copper can exist as Cu^{+} or Cu^{2+}.
This variability is important in redox reactions and in the formation of coordination compounds. It also explains why transition metals are widely used in industrial and biological processes.
Fill in the blank: Iron commonly exhibits two oxidation states, ______ and ______.

Metal	Symbol	Common Oxidation States	Examples of Compounds
Chromium	Cr	$+2, \mathbf{+3}, \mathbf{+6}$	Cr_2O_3 (Green), $K_2Cr_2O_7$ (Orange)
Manganese	Mn	$\mathbf{+2}, +3, \mathbf{+4}, +6, \mathbf{+7}$	MnO_2 (Black), $KMnO_4$ (Purple)
Iron	Fe	$\mathbf{+2}, \mathbf{+3}$	FeO (Black), Fe_2O_3 (Rust/Red)
Copper	Cu	$+1, \mathbf{+2}$	Cu_2O (Red), $CuSO_4$ (Blue)

Table 5.2 Common oxidation states of selected transition metals.

5.2.3 Magnetic properties and colouration in compounds

Transition metals often exhibit **magnetic properties** due to unpaired electrons in their d-orbitals. For example, iron, cobalt, and nickel are ferromagnetic, meaning they can be permanently magnetised. Other transition metals may show paramagnetism or diamagnetism depending on their electron arrangements.

Another distinctive feature is the **colouration of compounds**. Transition metal ions absorb specific wavelengths of light due to d–d electron transitions, and the remaining light gives the compound its colour. For instance, copper(II) compounds are typically blue, while chromium compounds can be green or orange.

Fill in the blank: The blue colour of copper(II) compounds is due to ______ transitions in the d-orbitals.

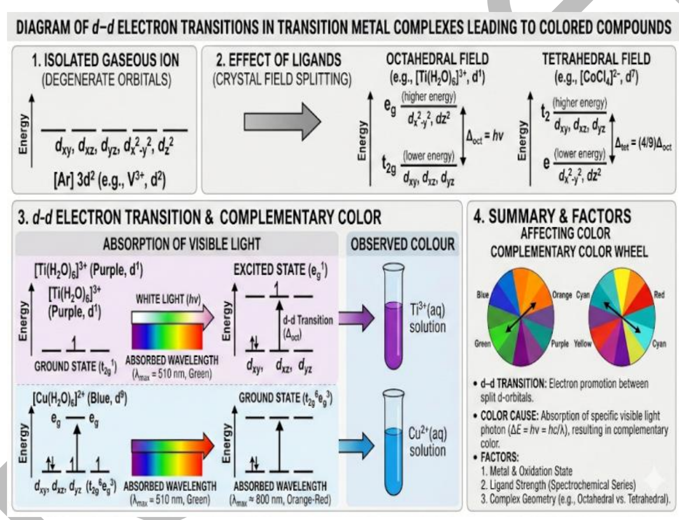


Figure 5.3 Colouration in transition metal compounds due to d–d transitions.

Pilot questions 5.2

1. What is the defining characteristic of transition metals in terms of their orbitals?
2. Give two common oxidation states of iron.
3. Why do transition metals exhibit variable oxidation states?
4. Name one transition metal that is ferromagnetic.
5. What causes the colouration of transition metal compounds?

5.3 Coordination Chemistry

5.3.1 Definition of coordination compounds and ligands

A **coordination compound** is a chemical substance in which a central metal atom or ion is bonded to surrounding molecules or ions, known as **ligands**. Ligands are species that donate a pair of electrons to the metal centre, forming coordinate covalent bonds. They can be neutral (such as water or ammonia) or negatively charged (such as chloride or cyanide).

Coordination compounds are important because they explain the behaviour of transition metals in biological systems, industrial catalysts, and coloured materials.

Fill in the blank: The molecules or ions that donate electron pairs to a central metal atom in a coordination compound are called ______.

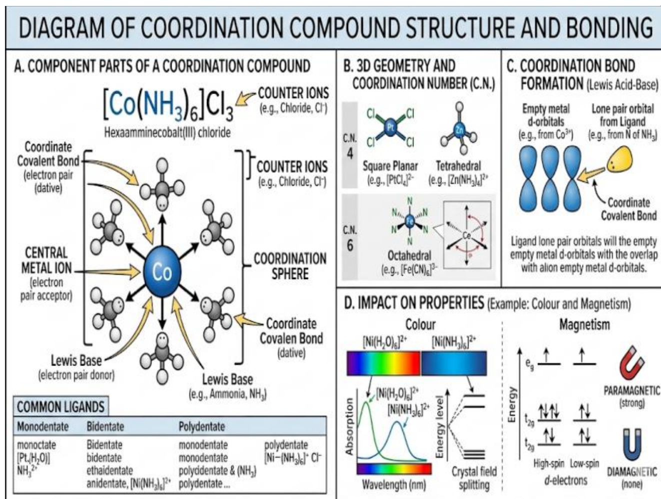


Figure 5.4 Structure of a coordination compound.

5.3.2 Nomenclature of coordination complexes

The **nomenclature of coordination complexes** follows specific rules set by IUPAC. The name begins with the ligands, listed in alphabetical order, followed by the central metal. If the complex is an anion, the metal name ends with the suffix –ate. Oxidation states of the metal are indicated in Roman numerals.

For example, $[Cu(NH_3)_4]^{2+}$ is named tetraamminecopper(II) ion, while $[Fe(CN)_6]^{3-}$ is named hexacyanoferrate(III) ion.

Fill in the blank: In naming coordination complexes, the oxidation state of the central metal is shown using ______ numerals.

Formula	IUPAC Systematic Name	Key Note
$[Co(NH_3)_6]Cl_3$	**Hexaamminecobalt(III) chloride**	"Ammine" refers to NH_3 ligands.

Formula	IUPAC Systematic Name	Key Note
$[Pt(NH_3)_2Cl_2]$	**Diamminedichloroplatinum(II)**	Neutral complex; ligands are alphabetical (a before c).
$K_4[Fe(CN)_6]$	**Potassium hexacyanoferrate(II)**	Metal ends in "-ate" because it's in an anionic complex.
$[Cu(H_2O)_6]^{2+}$	**Hexaaquacopper(II) ion**	"Aqua" refers to water ligands.
$[Ni(CO)_4]$	**Tetracarbonylnickel(0)**	Nickel has an oxidation state of zero here.
$[Cr(en)_3]Cl_3$	**Tris(ethylenediamine)chromium(III) chloride**	Uses "tris" because the ligand name already contains a prefix (di).

Table 5.3 Examples of coordination complex nomenclature.

5.3.3 Bonding theories: Valence Bond Theory (VBT) and Crystal Field Theory (CFT)

Valence Bond Theory (VBT) explains bonding in coordination compounds by considering hybridisation of the metal's orbitals. For example, in $[Ni(CN)_4]^{2-}$, the nickel ion undergoes dsp^2 hybridisation to form square planar geometry.

Crystal Field Theory (CFT) focuses on the splitting of d-orbitals when ligands approach the central metal ion. The arrangement of ligands causes some d-orbitals to have higher energy than others, leading to characteristic colours and magnetic properties. For example, in an octahedral complex, the d-orbitals split into two sets: t_{2g} (lower energy) and e_g (higher energy).

Fill in the blank: In an octahedral complex, the d-orbitals split into two sets known as ______ and ______.

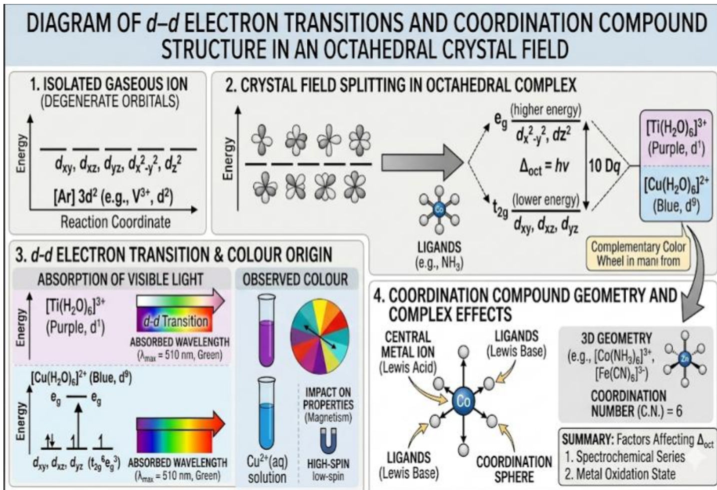


Figure 5.5 Crystal field splitting in an octahedral complex.

Pilot questions 5.3

1. What is a coordination compound?
2. What are ligands, and how do they bond to metals?
3. How is the oxidation state of the central metal indicated in the nomenclature of coordination complexes?
4. What type of hybridisation occurs in $[Ni(CN)_4]^{2-}$ according to Valence Bond Theory?
5. In an octahedral complex, into which two sets do the d-orbitals split according to Crystal Field Theory?

5.4 Applications of Transition Metal Chemistry

5.4.1 Catalysis in industrial processes

Catalysis refers to the acceleration of chemical reactions by substances called catalysts, which are not consumed in the process. Transition metals are widely used as catalysts because of their ability to adopt variable oxidation states and form complexes with reactants. For example, iron is used in the Haber process for ammonia production, while platinum and palladium are employed in catalytic converters to reduce harmful emissions from vehicles.

These applications highlight the economic and environmental importance of transition metals in industry.

Fill in the blank: The transition metal commonly used in the Haber process for ammonia production is ______.

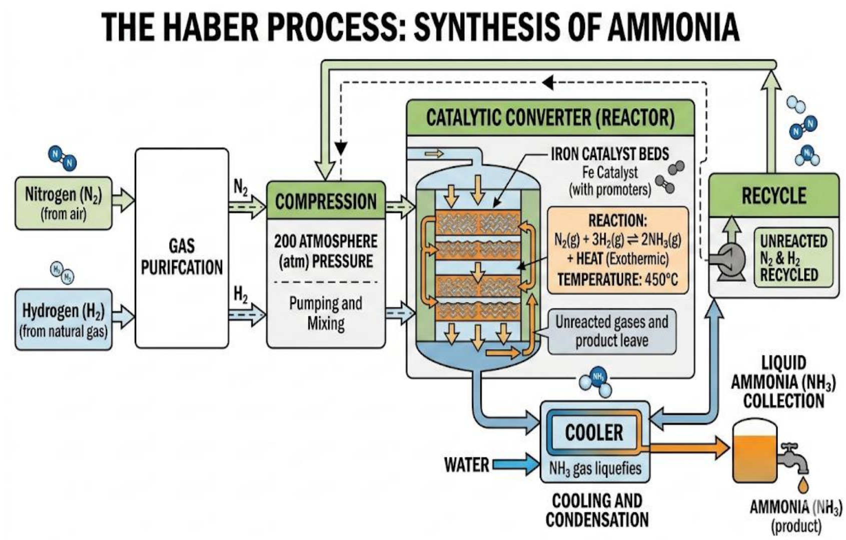


Figure 5.6 Catalytic role of iron in the Haber process.

5.4.2 Biological roles of transition metals

Transition metals also play crucial roles in biological systems. For instance, iron in haemoglobin enables oxygen transport in blood, while magnesium is central to chlorophyll, allowing plants to carry out photosynthesis. Copper and zinc are essential cofactors in many enzymes, supporting vital metabolic processes.

These examples demonstrate how transition metals are indispensable for life, linking chemistry directly to biology.

Fill in the blank: The transition metal present in haemoglobin that allows oxygen transport is ______.

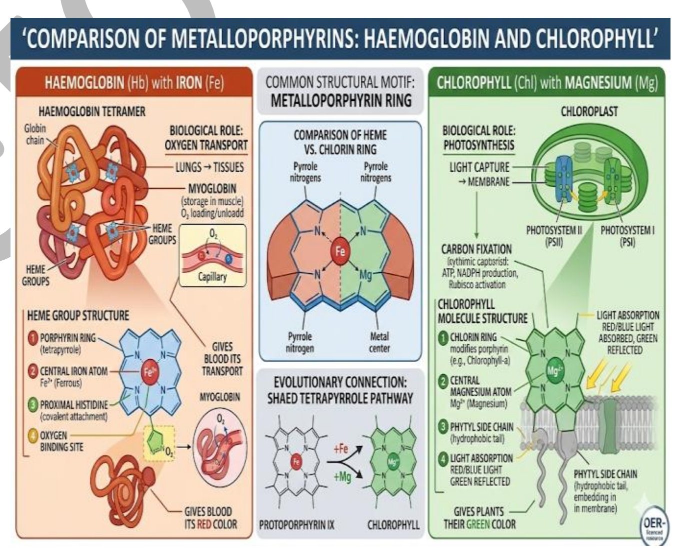


Plate 5.2 Biological roles of transition metals in haemoglobin and chlorophyll.

5.4.3 Transition metals in materials science and technology

Transition metals are essential in materials science due to their strength, durability, and electronic properties. Alloys such as steel (iron and carbon) and stainless steel (iron, chromium, and nickel) are widely used in construction and manufacturing. Transition metals also contribute to advanced technologies: titanium is used in aerospace materials, while copper is vital in electrical wiring.

In addition, transition metals are central to emerging technologies such as superconductors and nanomaterials, which promise new applications in energy and electronics.

Fill in the blank: Stainless steel is an alloy of iron, carbon, and ______.

Industry	Key Metals	Biological & Technical Roles
Alloys & Construction	Iron, Chromium, Nickel, Copper	**Stainless Steel:** Cr and Ni prevent rusting in medical tools. **Brass:** Cu and Zn provide low friction for gears and valves.
Electronics & Energy	Copper, Silver, Cobalt, Gold	**Conductivity:** Cu and Ag are the gold standards for high-efficiency wiring. **Energy Storage:** Co is critical for high-density Li-ion battery cathodes.
Aerospace & Defense	Titanium, Scandium, Nickel	**Superalloys:** Ni-based alloys withstand the extreme heat of jet turbines. **Strength-to-Weight:** Ti and Sc create lightweight, ultra-strong airframes.

Industry	Key Metals	Biological & Technical Roles
Nanotechnology	Gold, Platinum, Silver	**Medicine:** Au nanoparticles enable targeted drug delivery. **Electronics:** Ag nanowires are used in flexible, transparent touchscreens.
Catalysis	Platinum, Palladium, Rhodium	**Environmental:** Used in catalytic converters to reduce toxic exhaust emissions. **Synthesis:** Essential for industrial chemical production.

Box 5.4 Applications of transition metals in materials science and technology.

Pilot questions 5.4

1. Which transition metal is used as a catalyst in the Haber process?
2. What role does iron play in haemoglobin?
3. Which transition metal is central to chlorophyll in plants?
4. Name one transition metal used in aerospace materials.
5. Which transition metals are present in stainless steel?

Series Summary

This Series has introduced you to the comparative chemistry of main group elements and the distinctive features of transition metals. We began by examining periodic trends and reactivity patterns in the main group, then moved on to the general characteristics of transition metals, including their electronic configurations, oxidation states, magnetic behaviour, and colouration. Following that, we explored coordination chemistry, focusing on the definition of coordination compounds, the role of ligands, systematic nomenclature, and bonding theories such as Valence Bond Theory and Crystal Field Theory. Finally, we considered the wide-ranging applications of transition metals in catalysis, biological systems, and materials science.

By engaging with these topics, you should now be able to define periodic trends and explain reactivity patterns (SLO 5.1 and SLO 5.2), describe the properties of transition metals (SLO 5.3 and SLO 5.4), identify and name coordination compounds (SLO 5.5 and SLO 5.6), apply bonding theories to explain their behaviour (SLO 5.7), and evaluate their applications in industry, biology, and technology (SLO 5.8). This Series has therefore equipped you with both conceptual understanding and practical insights into the chemistry of main group and transition elements.

Glossary of Terms

- **Catalysis**: The process of speeding up a chemical reaction using a substance called a catalyst, which is not consumed in the reaction.
- **Coordination compound**: A chemical substance in which a central metal atom or ion is bonded to surrounding molecules or ions called ligands.
- **Crystal Field Theory (CFT)**: A bonding theory that explains the splitting of d-orbitals in transition metal complexes when ligands approach the central metal ion.
- **Ferromagnetism**: A property of certain metals, such as iron, cobalt, and nickel, that allows them to be permanently magnetised.
- **Ligand**: A molecule or ion that donates a pair of electrons to a central metal atom or ion in a coordination compound.
- **Oxidation state**: The number that represents how many electrons an atom has lost, gained, or shared in a chemical compound.
- **Periodic trend**: A recurring pattern in the properties of elements across the periodic table, such as atomic radius or electronegativity.
- **Transition metal**: An element found in Groups 3–12 of the periodic table, characterised by partially filled d-orbitals and properties such as variable oxidation states and coloured compounds.
- **Valence Bond Theory (VBT)**: A bonding theory that explains how orbitals of a central metal atom hybridise to form bonds with ligands in coordination compounds.

Concept Check Questions 5: Comparative and Transition Metal Chemistry

Objective Questions

1. Which group of elements is characterised by partially filled d-orbitals? (Linked to SLO 5.3)
   a) Alkali metals
   b) Alkaline earth metals
   c) Transition metals
   d) Halogens
2. Which property generally increases down Group 1, making alkali metals more reactive? (Linked to SLO 5.2)
   a) Ionisation energy
   b) Atomic radius
   c) Electronegativity
   d) Melting point
3. In naming coordination complexes, the oxidation state of the central metal is indicated using: (Linked to SLO 5.6)
   a) Arabic numerals
   b) Roman numerals
   c) Greek letters
   d) Superscripts
4. Which transition metal is used as a catalyst in the Haber process? (Linked to SLO 5.8)
   a) Copper
   b) Iron

c) Nickel
d) Platinum
5. In an octahedral complex, the d-orbitals split into two sets known as: (Linked to SLO 5.7)
a) s and p
b) t_2g and e_g
c) σ and π
d) α and β

Short-Answer Questions

1. Define a periodic trend and give one example. (Linked to SLO 5.1)
2. Explain why halogen reactivity decreases down Group 17. (Linked to SLO 5.2)
3. State two general characteristics of transition metals. (Linked to SLO 5.3)
4. Differentiate between Valence Bond Theory and Crystal Field Theory in coordination chemistry. (Linked to SLO 5.7)
5. Give one biological role of a transition metal. (Linked to SLO 5.8)

Long-Answer Questions

1. Analyse the comparative reactivity of alkali metals, alkaline earth metals, and halogens, linking their behaviour to periodic trends. (Linked to SLO 5.2)
2. Demonstrate how to name a coordination complex containing both neutral and anionic ligands, explaining the rules of nomenclature. (Linked to SLO 5.6)
3. Evaluate the importance of transition metals in industrial and biological systems, with examples from catalysis and enzyme function. (Linked to SLO 5.8)

Answers to Concept Check Questions [Series 5: Comparative and Transition Metal Chemistry]

Objective Questions

1. c) Transition metals
2. b) Atomic radius
3. b) Roman numerals
4. b) Iron
5. b) t_2g and e_g

Short-Answer Questions

1. A periodic trend is a recurring pattern in element properties across the periodic table. Example: atomic radius increases down a group.
2. Halogen reactivity decreases down Group 17 because larger atoms have reduced ability to attract additional electrons.
3. Transition metals commonly show variable oxidation states and form coloured compounds.
4. Valence Bond Theory explains bonding through orbital hybridisation, while Crystal Field Theory explains bonding by d-orbital splitting due to ligand interactions.

5. Iron in haemoglobin enables oxygen transport in blood.

Long-Answer Questions

1. **Basic response:** Alkali metals become more reactive down the group due to decreasing ionisation energy, alkaline earth metals are less reactive but form basic oxides, and halogens become less reactive down the group due to reduced electronegativity.
   Value-added response: These reactivity patterns are explained by periodic trends in atomic radius, ionisation energy, and electron affinity, which influence how easily atoms lose or gain electrons.
2. **Basic response:** In naming coordination complexes, ligands are listed alphabetically, followed by the metal with its oxidation state in Roman numerals.
   Value-added response: For example, $[Co(NH_3)_4Cl_2]^+$ is named tetraammine dichlorocobalt(III) ion. This demonstrates the systematic application of IUPAC rules for both neutral and anionic ligands.
3. **Basic response:** Transition metals are important in catalysis, such as iron in the Haber process, and in biology, such as iron in haemoglobin.
   Value-added response: Beyond these, transition metals are central to advanced technologies, including platinum in catalytic converters, magnesium in chlorophyll for photosynthesis, and copper in electrical wiring, showing their wide-ranging impact on industry, health, and technology.

Answers to Pilot Questions [Series 5: Comparative and Transition Metal Chemistry]

Part 5.1 Comparative Chemistry of Main Group Elements

1. A recurring pattern in properties of elements across the periodic table.
2. Ionisation energy.
3. Hydrogen gas.
4. Because larger atoms have reduced ability to attract additional electrons.
5. Cement manufacture.

Part 5.2 Introduction to Transition Metals

1. Partially filled d-orbitals.
2. +2 and +3.
3. Because they can lose different numbers of electrons depending on the reaction.
4. Iron.
5. d–d electron transitions.

Part 5.3 Coordination Chemistry

1. A compound with a central metal atom or ion bonded to surrounding ligands.
2. Molecules or ions that donate electron pairs to a central metal atom or ion.
3. Roman numerals.

4. dsp^2 hybridisation.
5. t_{2g} and e_g.

Part 5.4 Applications of Transition Metal Chemistry

1. Iron.
2. It enables oxygen transport in blood.
3. Magnesium.
4. Titanium.
5. Chromium and nickel.

References and Attributions [Series 5: Comparative and Transition Metal Chemistry]

General References

- International Union of Pure and Applied Chemistry (IUPAC). (2014). *Nomenclature of Inorganic Chemistry: IUPAC Recommendations 2013*. Cambridge: Royal Society of Chemistry.
- Housecroft, C. E., & Sharpe, A. G. (2018). *Inorganic Chemistry* (5th ed.). Harlow: Pearson Education.
- Miessler, G. L., Fischer, P. J., & Tarr, D. A. (2014). *Inorganic Chemistry* (5th ed.). Boston: Pearson.
- OpenStax. (2016). *Chemistry*. Houston: Rice University. Available under Creative Commons licence at https://openstax.org/books/chemistry

Illustrations and OER Sources

- **Figure 5.1 Periodic trends in main group elements**

- Suggested AI prompt: “Generate a labelled diagram of the periodic table highlighting trends in atomic radius, ionisation energy, and electronegativity.”
- Attribution: Adapted from OpenStax Chemistry (2016), Chapter 8.

- **Table 5.1 Comparative reactivity of alkali metals, alkaline earth metals, and halogens**

- Suggested AI prompt: “Create a table comparing the reactivity of alkali metals, alkaline earth metals, and halogens with examples of reactions.”
- Attribution: Adapted from Housecroft & Sharpe (2018).

- **Plate 5.1 Everyday applications of main group elements**

- Suggested AI prompt: “Generate an image showing fertiliser, toothpaste, disinfectant, and cement, labelled with the main group elements they contain.”
- Attribution: OpenStax Chemistry (2016), Chapter 8.

- **Figure 5.2 Position of transition metals in the periodic table**

- Suggested AI prompt: “Generate a periodic table diagram highlighting transition metals in Groups 3–12.”
- Attribution: Adapted from Miessler et al. (2014).

- **Table 5.2 Common oxidation states of selected transition metals**

- Suggested AI prompt: “Create a table showing common oxidation states of transition metals such as iron, copper, manganese, and chromium.”
- Attribution: Adapted from Housecroft & Sharpe (2018).

- **Figure 5.3 Colouration in transition metal compounds due to d–d transitions**

- Suggested AI prompt: “Generate a diagram showing d–d electron transitions in transition metals leading to coloured compounds.”
- Attribution: Adapted from Miessler et al. (2014).

- **Figure 5.4 Structure of a coordination compound**

- Suggested AI prompt: “Generate a diagram of a coordination compound showing a central metal ion surrounded by ligands.”
- Attribution: OpenStax Chemistry (2016), Chapter 24.

- **Table 5.3 Examples of coordination complex nomenclature**

- Suggested AI prompt: “Create a table showing examples of coordination complexes and their systematic names according to IUPAC rules.”
- Attribution: IUPAC (2014).

- **Figure 5.5 Crystal field splitting in an octahedral complex**

- Suggested AI prompt: “Generate a diagram showing crystal field splitting of d-orbitals in an octahedral complex.”
- Attribution: Adapted from Housecroft & Sharpe (2018).

- **Figure 5.6 Catalytic role of iron in the Haber process**

- Suggested AI prompt: “Generate a diagram of the Haber process showing nitrogen and hydrogen reacting with iron catalyst to produce ammonia.”
- Attribution: OpenStax Chemistry (2016), Chapter 12.

- **Plate 5.2 Biological roles of transition metals in haemoglobin and chlorophyll**

- Suggested AI prompt: “Generate an image showing haemoglobin with iron and chlorophyll with magnesium, labelled to highlight their biological roles.”
- Attribution: Adapted from OpenStax Chemistry (2016), Chapter 24.

- **Box 5.4 Applications of transition metals in materials science and technology**

- Suggested AI prompt: “Generate a text box listing applications of transition metals in alloys, electronics, aerospace, and nanotechnology.”
- Attribution: Adapted from Miessler et al. (2014).