CHEMISTRY SYLLABUS

Pre-University

Higher 1/2/3

Syllabus 8873 / 9476 / 9813

Implementation starting with the 2025 Pre-University 1 cohort

Ministry of Education
SINGAPORE

CONTENTS

SECTION 1: INTRODUCTION

1. INTRODUCTION

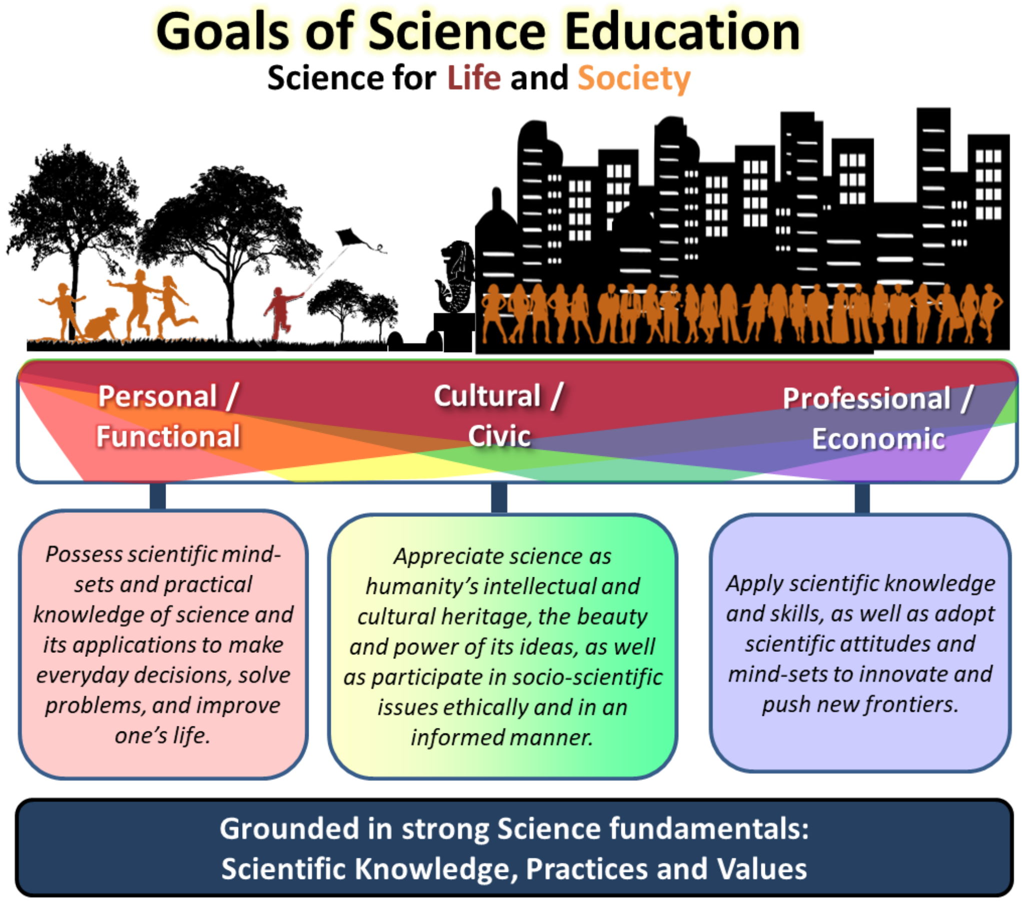
1.1 GOALS AND VISION OF SCIENCE EDUCATION

Our science students are diverse, with different needs, interests and aptitudes for science. Given the diversity of our science students and the needs of Singapore, the twin goals of science education are to:

a. Enthuse and nurture all students to be scientifically literate, so that they are able to make informed decisions and take responsible actions in their daily lives; and

b. Provide strong science fundamentals for students to innovate and pursue Science, Technology, Engineering, Math (STEM) for future learning and work.

The goals of science education, which serve the interwoven needs of the individual and society, can be unpacked into three dimensions: *personal/functional, cultural/civic* and *professional/economic*, as shown in **Figure 1.1**. *Science for Life and Society* is the tagline to capture the essence of these goals of science education, which can be achieved through developing strong fundamentals in scientific knowledge, practices and values.



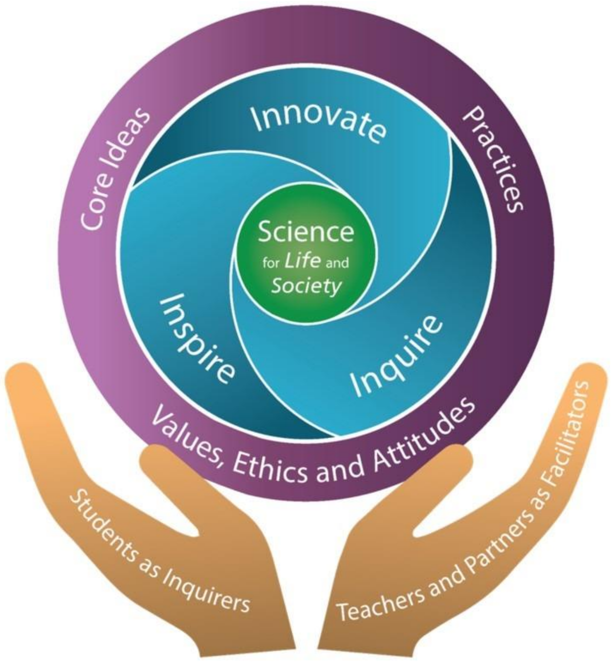
Possess scientific mind-sets and practical knowledge of science and its applications to make everyday decisions, solve problems, and improve one's life.

Appreciate science as humanity's intellectual and cultural heritage, the beauty and power of its ideas, as well as participate in socio-scientific issues ethically and in an informed manner.

Apply scientific knowledge and skills, as well as adopt scientific attitudes and mind-sets to innovate and push new frontiers.

Figure 1.1: Overview of Goals of Science Education in Singapore

The *Science Curriculum Framework*, as shown in **Figure 1.2**, encapsulates the thrust of science education in Singapore to provide students with strong fundamentals in science for life, learning, citizenry and work.



Goals
The twin goals of Science education, as represented by the tagline ***Science for Life and Society***, are central to the revised Science Curriculum Framework.

Vision (3 Ins)
Surrounding the innermost circle, the Vision of Science Education 2030 is articulated through the 3 **In**s – *Inspire, Inquire, Innovate.*

Three Domains
The outermost layer of the framework shows three domains, *Core Ideas*, *Practices*, and *Values, Ethics and Attitudes*.

Stakeholders
The pair of hands shows *students as inquirers*, supported by *teachers and partners as facilitators* of the students' learning experiences.

Figure 1.2: Science Curriculum Framework

The twin goals of science education, as represented by the tagline ***Science for Life and Society***, are central to the Science Curriculum Framework. Surrounding the innermost circle, the Vision of Science Education 2030 is articulated through the 3 **In**s – *Inspire*, *Inquire*, *Innovate*. The outermost layer of the framework shows three domains, *Core Ideas*, *Practices*, and *Values, Ethics and Attitudes*. The pair of hands shows *students as inquirers*, supported by *teachers and partners as facilitators* of the students' learning experiences.

The term *Core Ideas* refers to the fundamental ideas that are essential for the understanding of science. The term *Practices* signals the importance of "Ways of thinking and doing in science" and emphasises science as a human endeavour guided by *Values, Ethics and Attitudes* embedded within society. In addition, teaching and learning involves not just the students and teachers but other partners who can facilitate learning in various contexts to help students appreciate the application of science in their daily lives, society and the environment.

Our vision for science education, manifested through the three **In**-s, encapsulates the overall experience of our students in science education:

a. Inspired by science. Students enjoy learning science and are fascinated by how everyday phenomena have scientific connections and how science helps solve many of our global challenges. They regard science as relevant and meaningful, and appreciate how science and technology have transformed the world and improved our lives. Students are open to the possibility of pursuing science-related careers to serve the good of society.

b. Inquire like scientists. Students have strong fundamentals in science, and possess the spirit of scientific inquiry. They are able to engage confidently in the *Practices of Science* and are grounded in the knowledge, issues and questions that relate to the roles played by science in daily life, society and the environment. They can discern, weigh alternatives and evaluate claims and ideas critically, based on logical scientific evidence and arguments, while consciously suspending judgement where there is lack of evidence.

c. Innovate using science. Students apply science to generate creative solutions to solve real-world problems, ranging from those affecting everyday lives to complex problems affecting humanity. It is envisaged that there will be a strong pipeline of students who can contribute towards STEM research, innovation and enterprise.

The goals and vision of science education are aligned with the broader MOE framework of 21st Century Competencies (21CC). Inspired students, who inquire and innovate through the Practices of Science (POS), develop future-ready competencies such as critical, adaptive and inventive thinking. The 21CC framework shown in **Figure 1.3** guides the purposive development, through the total curriculum, of key competencies and mindsets for students to be successful in the future.

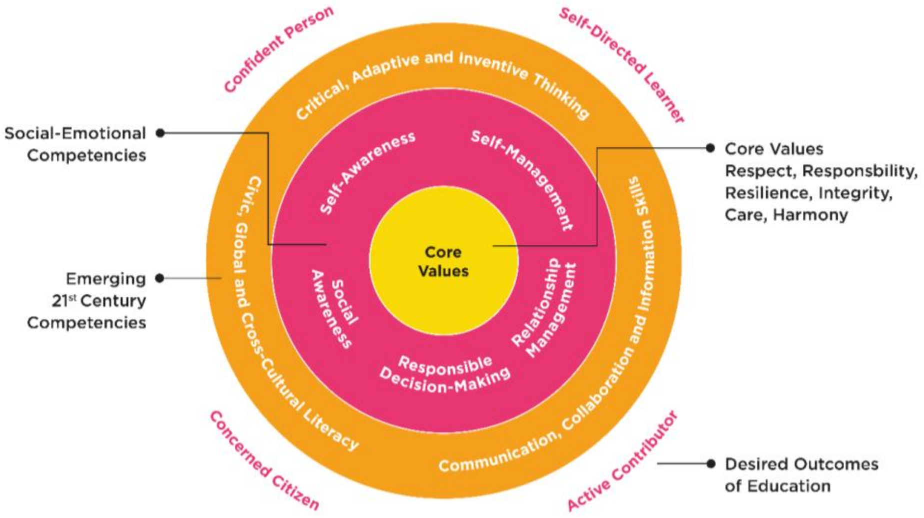


Figure 1.3: Framework for 21st Century Competencies and Student Outcomes

The teaching and learning of science naturally serve the larger goal of developing 21CC in students. The emerging 21CC domains that can be most naturally developed through the process of scientific inquiry, such as engaging in scientific investigation, reasoning, modelling and problem-solving, are **Critical, Adaptive and Inventive Thinking,** as well as **Communication**. The development of the other emerging 21CC domains (e.g. Collaboration, Information Skills, Civic and Global Literacy) depends on the context of the lesson. Intentional development of 21CC through science makes learning meaningful and facilitates the transfer of learning.

1.2 BACKGROUND ON THE 2025 A-LEVEL SCIENCE CURRICULUM

The A-Level science curriculum review ensures the continued relevance of the curriculum in laying a strong foundation of knowledge, skills and attitudes in order to prepare our students well for university, work and life in the future. The review is guided by internal and external scans and also took into consideration broader MOE emphases on learning for life as well as the development of 21st Century Competencies (21CC) and digital literacy (DL) in our students.

The key curricular shifts are to:

a. Strengthen POS[1], through enhancing digital literacy. The learning of science should reflect the evolving nature of the scientific disciplines as they are practised. Data collection, analysis, modelling, and interpreting data and evidence are important areas of the POS that can be strengthened and made more authentic with the use of information and communications technology. Digital literacy (DL)[2], including data competencies (DC) and computational thinking (CT), could also be naturally built up through the curriculum as students encounter opportunities to make use of a variety of hardware and software to investigate and model the world.

b. Maintain strong disciplinary fundamentals while layering in compelling real-world applications and interdisciplinary connections. Timely refreshing of the curricular content retains the focus on learning key concepts and core ideas in science, while embedding Science, Technology, Society and Environment (STSE) and Science, Technology, Engineering and Mathematics (STEM) contexts and applications more deliberately. This can help bring out the relevance and impact of science for more students.[3] To encourage debate and discussion, contexts could involve socio-scientific issues that prompt the exploration of values, ethics, and attitudes in science. Contexts related to sustainability will also feature to a greater extent across the science syllabuses in view of Singapore's commitment to the 2030 Agenda for Sustainable Development.[4]

c. Broaden practical work learning experiences beyond the confines of the laboratory and include more open-ended tasks to promote greater student agency, experimentation and authenticity. As pre-university students are building their "science identity", challenging them to take up an open-ended group investigative task increases student agency and forms an important part of their overall learning experience in science. The task design should encourage curiosity, problem-posing

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[1] The *Practices of Science* (POS) emphasises that science as a discipline is more than the acquisition of a body of knowledge; it is also a way of knowing and doing.

[2] DC refers to the handling and analysis of data. CT can be taught in the context tackling complex problems in scientific domains, and comprises four elements: decomposition, pattern recognition, abstraction, and algorithmic thinking.

[4] Bennett, J., Lubben, F., & Hogarth, S. (2007). Bringing science to life: A synthesis of the research evidence on the effects of context-based and STS approaches to science teaching. *Sci. Ed.*, 91(3): 347–370.

[5] See report Towards a sustainable and resilient Singapore.

and inventive thinking, thus providing opportunities for students to embrace uncertainty and ambiguity, and to learn through iteration and from failures. Such activities could include science investigations and/or engineering design challenges where students plan and carry out their own group investigative tasks and deepen their understanding of POS.

One of the strategic thrusts in the Educational Technology Masterplan (EdTech) 2030[5] is to strengthen the development of students' DL and technological skills. In curricular shift 1 above, the use of digital sensors for data collection and the use of spreadsheet to analyse and visualise data sets is well aligned to the "find", "think" and "create" components of the National Digital Literacy Programme (NDLP), as launched by MOE in 2020 (see **Figure 1.4**). Enhanced DL skills through the A-level science curriculum empowers students' to become technologically-adept innovators who can "discover" needs and "develop" solutions to real-world problems.

Find

Critically gather and evaluate information from, and use digital resources (including social media) in a safe, secure, responsible and ethical manner.

....

- Digital Safety & Security
- Digital Information Management
- Digital Responsibility

Think

Interpret and analyse data, and solve problems systemically.

....

- Data Competencies
- Computational Thinking

Apply

Use software and devices effectively and productively; facilitate the use of knowledge and skills in new contexts; keep up with technological developments.

....

- Device & Software Operations
- Digital Knowledge Currency

Create

Produce content and artefacts and collaborate with others digitally.

....

- Coding & Programming
- Digital Communication, Collaboration & Participation

Figure 1.4: MOE Framework for Strengthening Digital Literacy

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[5] https://www.moe.gov.sg/education-in-sg/educational-technology-journey/edtech-masterplan

1.3 PURPOSE AND VALUE OF CHEMISTRY EDUCATION AT PRE-UNIVERSITY

Chemistry is the study of the structure, properties and transformation of matter at the atomic/molecular level. Hence, Chemistry is often seen as playing a central role in science. It is built on an understanding of the laws of physics that govern the nature of particles such as atoms, protons and electrons, and at the same time provides a basis for studying and understanding the molecules and reactions in biological systems.

A key feature in the study of chemistry is the development of students' ability to navigate between the macroscopic phenomena, submicroscopic interactions and symbolic representations to attain deep conceptual understanding of the behaviours of chemical systems. This will enable students to extend this way of viewing and thinking about the behaviours of chemical systems to physical and biological phenomena, which are present in many aspects of daily life, e.g. environmental pollution and food science.

Through studying A-Level Chemistry, students develop an understanding of the chemical concepts and how these concepts are inter-related to each other within Chemistry as well as to other scientific disciplines. Students also have opportunities to learn about real-world applications of the chemistry concepts covered in the course, the impact of chemistry on our society and environment through up-to-date contexts such as those relating to Environmental Sustainability and Materials, and the contribution of chemistry in addressing challenges in these contexts. The A-Level Chemistry course also aims to develop scientific literacy in our students through the acquisition and application of core chemistry knowledge and science practices and values in daily life, society and the environment.

Aims of A-Level Chemistry Syllabuses

The syllabuses have been designed to build on and extend the content coverage and skills development at O-Level. Students will be assumed to have knowledge and understanding of Chemistry at O-Level, either as a single subject or as part of a balanced science course. Students may not simultaneously offer chemistry at the H1 and H2 levels, though they must take H2 Chemistry in order to take H3 Chemistry. The aims of a course based on these syllabuses are shown in **Table 1.1**.

Table 1.1: Aims of A-Level Chemistry

Aims	H1 Chemistry	H2 Chemistry	H3 Chemistry
Twin Goals of Science Education	1. provide students with an experience that develops interest in chemistry and builds the knowledge, skills and attitudes necessary for them to become scientifically literate citizens who are well-prepared for the challenges of the 21st century	1. provide students with an experience that develops interest in chemistry and builds the knowledge, skills and attitudes necessary for further studies in related fields 2. enable students to become scientifically literate citizens who are well-prepared for the challenges of the 21st century	2. provide students with an experience that deepens their knowledge and skills in chemistry, and foster attitudes necessary for further studies in related fields
Practices of Science & Values, Ethics and Attitudes	2. develop in students the understanding, skills, ethics and attitudes relevant to the *Practices of Science*, including the following: 2.1 demonstrating ways of thinking and doing in Science 2.2 understanding the nature of scientific knowledge 2.3 relating science, technology, society and environment	3. develop in students the understanding, skills, ethics and attitudes relevant to the *Practices of Science*, including the following: 3.1 demonstrating ways of thinking and doing in Science 3.2 understanding the nature of scientific knowledge 3.3 relating science, technology, society and environment	2. develop in students the appreciation of the practice, value and rigour of chemistry as a discipline

Disciplinary Ways of Thinking and Doing	3. develop the way of thinking to explain phenomena, approach and solve problems in chemical systems which involves students in: 3.1 understanding the structure, properties and transformation of matter at the atomic/molecular level and how they are related to each other 3.2 connecting between the submicroscopic, macroscopic and symbolic levels of representations in explaining and making predictions about chemical systems, structures and properties.	4. develop the way of thinking to explain phenomena, approach and solve problems in chemical systems which involves students in: 4.1 understanding the structure, properties and transformation of matter at the atomic/molecular level and how they are related to each other 4.2 connecting between the submicroscopic, macroscopic and symbolic levels of representations in explaining and making predictions about chemical systems, structures and properties.	3. develop in students the skills to analyse chemical issues, and to apply relevant concepts and techniques to solve problems.

1.4 A-LEVEL CHEMISTRY CURRICULUM FRAMEWORK

The A-Level Chemistry curriculum framework (see **Figure 1.5**) encapsulates *the Disciplinary Ideas* that are enduring and central in Chemistry and makes references to elements of the broader Science Curriculum Framework, such as the *Practices of Science* (POS), *Core Ideas*, as well as *Values, Ethics and Attitudes* (VEA) that are brought to life through *Learning Experience*s (LEs).

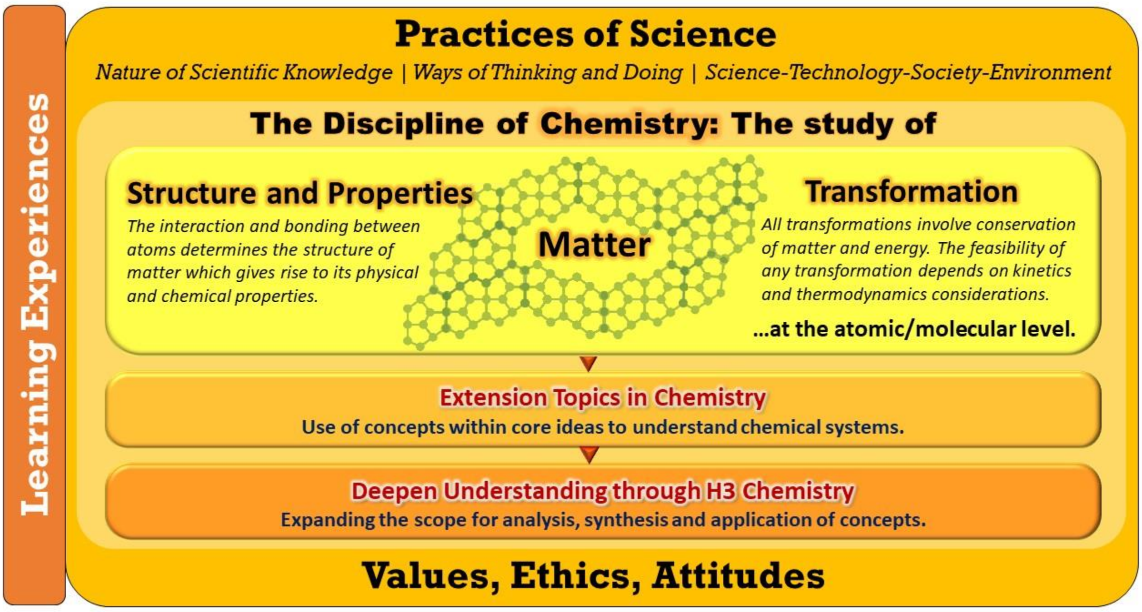

Figure 1.5: A-level Chemistry Curriculum Framework

The content in both H1 and H2 Chemistry syllabuses are organised into two levels:

- *Core Ideas*. There are three core ideas, namely Matter, Structure and Properties, and Transformation, which are fundamental in the study of Chemistry. Concepts in these core ideas are inter-related and form the basis for which further learning and understanding of chemical phenomena and reactions is built upon. (see **Section 1.4.2**)

- *Extension Topics.* Concepts in the core ideas extend into the learning of different chemical systems such as the chemistry of organic compounds, including polymers. For H2 Chemistry, the extension topics also include the chemistry of aqueous solutions, electrochemistry, and the chemistry of transition elements. As an example, an understanding of concepts of Chemical Bonding and The Periodic Table is extended to the study of the Chemistry of Transition Elements where students learn to appreciate the similarity and differences when comparing with main group metals.

Organising the content through the two levels highlights the importance of conceptual understanding in core ideas and how they extend to different chemical systems.

- The Additional Content in H3 complements the H2 curriculum with a stronger focus on applications. The content expands the scope for students to engage in deeper and more extensive integration of concepts with what has been learnt in H2 Chemistry.

They also allow a deeper appreciation of the unity and beauty of the discipline of chemistry.

- Relevance of Chemistry in the real world: Real-world contexts are weaved into the narratives and learning experiences for the different topics to draw connections between concepts and everyday life, develop scientific literacy and enable learners to see the impact of chemistry on our society and environment. **Two interrelated themes are emphasised in A-Level Chemistry, they are Environmental Sustainability and Materials.** With these themes in the curriculum, students have opportunities to relate what they learnt in A-Level Chemistry to global issues such as impact of climate change and appreciate the push for scientific innovation to address global needs and environmental challenges.

The *Practices of Science* highlight the ways of thinking and doing that are inherent in the scientific approach, with the aim of equipping students with the understanding, skills, and attitudes shared by the scientific disciplines, including an appropriate approach to ethical issues.

The *Values, Ethics, Attitudes* undergird the study of science and the use of related knowledge and skills to make a positive contribution to humanity.

1.4.1 VALUES, ETHICS, ATTITUDES

Although science uses objective methods to arrive at evidence-based conclusions, it is in fact a human enterprise conducted in particular social contexts, which thus involves consideration of values and ethics. The intent of fostering an awareness and appreciation of these values in the curriculum is to sensitise our students to the ethical implications of the application of science in society.

Humanity will face challenges in the upcoming centuries that require the development of scientific and technological solutions, alongside other approaches, but these solutions have complex outcomes and there is a need to consider their impact in terms of their benefits and drawbacks to humanity and the ethical issues involved. This is complicated by a myriad of beliefs and value systems. Thus, science education needs to equip students with attitudes (see **Table 1.2**) and the ability to articulate their ethical stance as they participate in discussions about socio-scientific issues[6] that involve ethical dilemmas, with no single right answers.

Table 1.2: Values, Ethics, Attitudes

Values, Ethics, and Attitudes	Description
Curiosity	Desiring to explore the environment and question what is found.
Creativity	Seeking innovative and relevant ways to solve problems.
Integrity	Handling and communicating data and information with complete honesty.
Objectivity	Seeking data and information to validate observations and explanations without bias.
Open-mindedness	Accepting all knowledge as tentative and suspending judgment. Tolerance for ambiguity. Willingness to change views if the evidence is convincing.
Resilience	Not giving up on the pursuit for answers / solutions. Willingness to take risks and embrace failure as part of the learning process.
Responsibility	Showing care and concern for living things and awareness of our responsibility for the quality of the environment.
Healthy Scepticism	Questioning the observations, methods, processes and data, as well as trying to review one's own ideas.

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[6] Examples of socio-scientific issues are genetic engineering (e.g. cloning and gene therapy), reproductive technology, climate change and the adoption of nuclear energy.

1.4.2 CORE IDEAS

Our science curriculum is organised around *Core Ideas*, which are distilled ideas central to the discipline of science.

Core Ideas help students appreciate the connectedness and the conceptual links within and across the different sub-disciplines of science (i.e. biology, chemistry and physics). The **Unifying Ideas** across science (biology, chemistry and physics) are described in **Table 1.3**, and the **Disciplinary Ideas** within chemistry are listed in **Table 1.4**. *Core Ideas* represent the enduring understanding that emerges from learning each science subject. These ideas cut across traditional content boundaries, providing a broader way of thinking about phenomena in the natural world.

Table 1.3: Unifying Ideas across science subjects

Unifying Idea	Description
Pattern	A pattern is an observed sequence or repetition in nature. A way to make sense of the world around us is to organise its diversity through classification based on similarities and differences, and recognising deviations. Understanding patterns helps us to also predict events and processes that occur in the natural world
Diversity	Diversity refers to the variety of living and non-living things around us. Such diversity in the natural and man-made worlds helps to maintain a balance in the ecosystem and provide us with useful resources to develop solutions to real world problems. We have to use the resources in nature responsibly and sustainably.
System	A system comprises parts which interact with one another within a boundary. Interactions within and between systems can be explored at different scales. Studying systems allow us to understand how different parts with different functions, may work together for a common purpose.
Structure	Structure refers to the arrangement of and relations between parts of a system. Making sense of the structure of systems and their parts leads to a deeper understanding of their functions and properties, which allow us to make and test predictions of their behaviours.
Energy	Energy is required for things to work. The total amount of energy within a chosen system is always the same (i.e. conserved). While energy cannot be created or destroyed, it can be transferred from one energy store to another during an event or process. In these processes some energy may become less useful.

Unifying Idea	Description
Matter	Matter is anything that has mass and occupies space. All matter in the Universe, living and non-living, are made up of very small particles called atoms. The behaviour and arrangement of the atoms explain the properties of different materials. We can better appreciate nature by understanding the structure and properties of matter.
Balance	Balance is achieved when opposing forces or influences act on a system to allow the system to be in equilibrium or in a steady state. Maintaining balance is important in living things and in ecosystems. We are able to design stable systems through understanding the mechanisms by which balance is achieved.
Change	Change is caused by interactions within and across systems, which may involve forces or the flow of matter and energy. Different types of interactions allow us to understand the behaviour of systems and make predictions on how changes in one factor affects the other factors in a system.

Table 1.4: Disciplinary Ideas within Chemistry

Disciplinary Ideas
1. Matter is made up of a variety of chemical elements, each with characteristic properties, and the smallest particle that characterises a chemical element is an atom. 2. The structure of matter and its chemical and physical properties are determined by the arrangement of particles and electrostatic interactions between the particles. 3. Energy changes across and within systems usually occur during physical and chemical changes, when there is rearrangement of particles. 4. Energy plays a key role in influencing the rate and extent of physical and chemical changes. 5. Matter and energy are conserved in all physical and chemical changes.

1.4.3 PRACTICES OF SCIENCE (POS)

Science as a discipline is more than the acquisition of a body of knowledge (e.g. scientific facts, concepts, laws, and theories); it is a way of knowing and doing. It includes an understanding of the nature of scientific knowledge and how this knowledge is generated, established and communicated.

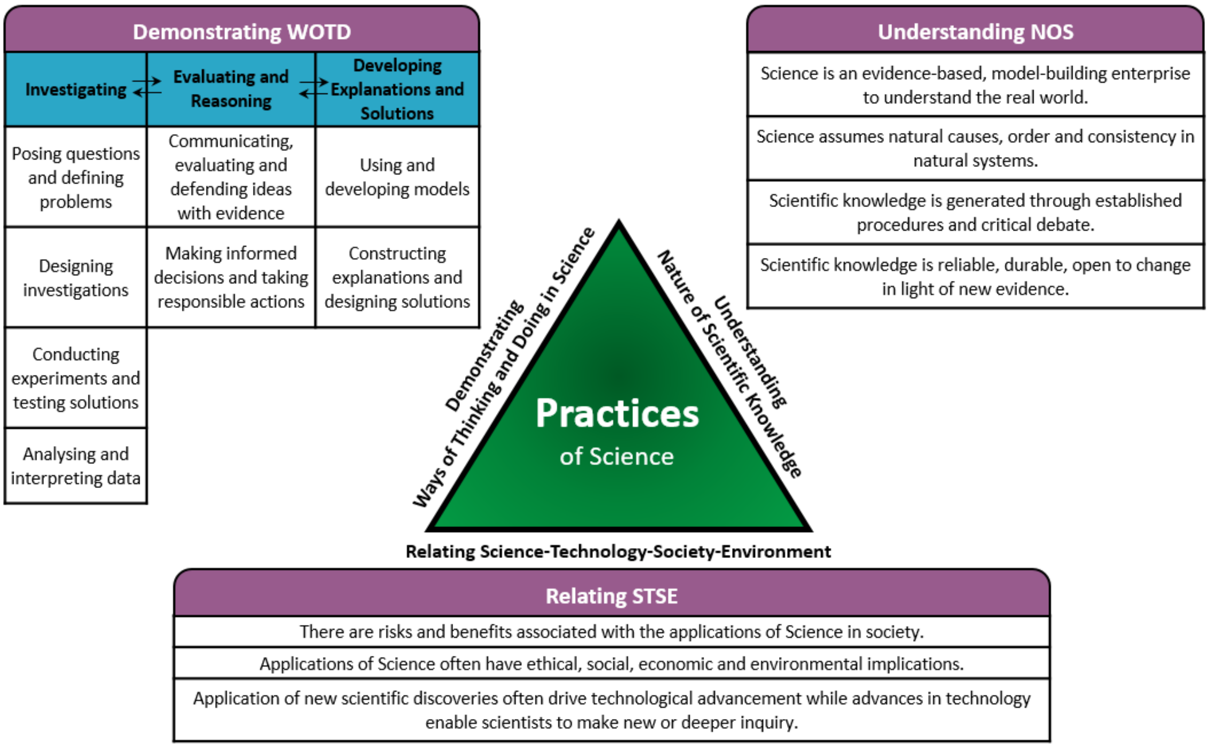
Teaching students the nature of science (NOS) helps them develop an accurate understanding of what science is and how it is practised and applied in society. Students should be encouraged to consider relevant ethical issues, how scientific knowledge is developed, and the strengths and limitations of science.

Understanding the nature of scientific knowledge, demonstrating science inquiry skills and relating science and society are the three components that form our *Practices of Science* which are explicitly articulated in the syllabus to allow teachers to embed them as learning objectives in their lessons. The students' understanding of the nature and limitations of science and scientific inquiry are developed effectively when the practices are taught in the context of relevant science content.

Time should be set aside to allow students to reflect on how the POS contribute to the accumulation of scientific knowledge. This means, for example, that when students pose questions, plan and conduct investigations, develop models or engage in arguments, they should have opportunities to think about what they have done and why.

The use of technology and tools are essential to doing and learning science. Just as the slide rule has given way to pocket calculators, the use of computer software for data analysis and visualisation has become common practice today. Thus, the POS described here include the use of digital technology in teaching and learning science where appropriate.

See **Figure 1.6** for the components of POS, which will be discussed in **Table 1.5**.



Demonstrating WOTD

Investigating ⇄	Evaluating and Reasoning ⇄	Developing Explanations and Solutions
Posing questions and defining problems	Communicating, evaluating and defending ideas with evidence	Using and developing models
Designing investigations	Making informed decisions and taking responsible actions	Constructing explanations and designing solutions
Conducting experiments and testing solutions		
Analysing and interpreting data		

Understanding NOS

- Science is an evidence-based, model-building enterprise to understand the real world.
- Science assumes natural causes, order and consistency in natural systems.
- Scientific knowledge is generated through established procedures and critical debate.
- Scientific knowledge is reliable, durable, open to change in light of new evidence.

Relating STSE

- There are risks and benefits associated with the applications of Science in society.
- Applications of Science often have ethical, social, economic and environmental implications.
- Application of new scientific discoveries often drive technological advancement while advances in technology enable scientists to make new or deeper inquiry.

Figure 1.6: Practices of Science

Table 1.5: Components of POS

Demonstrating WOTD

WOTD in Science illustrates a set of established practices associated with scientific inquiry to gather evidence and test ideas on how the natural world works. The three broad, iterative domains of scientific activity are:

Investigating

Posing questions and defining problems. Scientific questions initiate the drive to find out more about the natural and man-made world(s), such as what is and how it works. The applications of Science are motivated by finding solutions to problems. This also involves asking questions and scoping the problem so that it may be solved through the application of science and technology.

Designing investigations. Scientific investigations are often carried out as part of scientific inquiry into a phenomenon or testing of a theory or model that explains the world. In the applications of science, investigations are also conducted to identify the most appropriate solution or determine ways to improve on a technological system. Various criteria are considered in planning investigations, including the general approach, the apparatus and type of data needed.

Conducting experiments and testing solutions. This involves the application of techniques, methods, understanding on a range of apparatus and equipment (including sensors and dataloggers) and/or apply methods.

Analysing and interpreting data. Scientists are actively involved in organising and interpreting data to reveal any patterns and relationships that may serve as evidence for communicating to others. Students learning science should be introduced to the use of technology as an aid in practical work or as a tool for the interpretation of experimental and theoretical results. The use of digital tools can allow a great volume of data to be systematically and efficiently analysed, to decide on and/or predict the efficacy of a model.

Evaluating and Reasoning

Communicating, evaluating and defending ideas with evidence. Practices in Science and technology involve clear and persuasive communication of ideas in various forms (e.g. orally, written, visual) and media (e.g. journals, newspaper, news). In the process, reasoning, argumentation and critique of ideas are practiced, based on evidence, such that explanations and design solutions become acceptable within the scientific and technological communities.

Making informed decisions and taking responsible actions. This involves identifying and analysing a situation competently and reflect upon the implication of decisions made based on various considerations (e.g. economic, social, environmental and ethical).

Developing Evaluations and Solutions

Using and developing models. Models are approximations of phenomena or systems that are based on evidence and hold potential for describing, explaining and predicting phenomena to aid scientific inquiry and/or analyse technological systems.

Constructing explanations and designing solutions. Science strives to explain the causes of phenomena while scientific applications endeavour to solve problems. The process of constructive explanations and designing solutions are iterative and systematic.

Understanding NOS

Science is an epistemic endeavour to build a better understanding of reality. What kinds of knowledge can scientists build?

Science is an evidence-based, model-building enterprise to understand the real world. Science is a unique way of knowing which uses empirical standards, logical arguments, and sceptical reviews. It consists of both a body of knowledge of natural systems and the processes used to refine, elaborate, revise, and extend this knowledge.

Science assumes natural causes, order and consistency in natural systems. Scientists often use hypotheses to develop and test theories and explanations for physical phenomena. Science assumes that objects and events in natural systems occur in consistent patterns that are understandable through measurement and observation. Scientific knowledge is based on the assumption that natural laws operate today as they did in the past and they will continue to do so in the future[7]. Theories are validated by the scientific community before they are accepted.

Scientific knowledge is generated through established procedures and critical debate. Collaboration by students in their science learning echoes the social NOS for practising scientists. By presenting their work and ideas to others as part of the scientific community, they develop multiple ways to observe and measure, suggest predictions and propose inferences.

Scientific knowledge is reliable, durable, open to change in light of new evidence. Scientific explanations are tentative and open to revision if sufficient evidence or arguments can be provided. Scientific knowledge advances as old ideas are replaced by better explanations.

Relating STSE

Science is not done completely independent of the other spheres of human activity. The relationships and connections to these areas are important as students learn science in context.

There are risks and benefits associated with the applications of science in society. Science and its applications have the potential to bring about both benefits and harm to society.

Applications of science often have ethical, social, economic, and environmental implications. It is useful to be able to predict some of these implications while appreciating the possibility of unintended consequences.

Applications of new scientific discoveries often drive technological advancements while advances in technology enable scientists to make new or deeper inquiry. Science and technology can exist in a virtuous cycle, with new science inspiring new technology, and advances in engineering allowing the successful execution of challenging experiments (e.g. achieving greater precision in measurements, carrying out complex investigations or analysis).

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[7] Laws are regularities or descriptions of natural phenomena. A scientific theory is a substantiated explanation of an aspect of the natural world, based on a body of facts that has been repeatedly verified through observation and experiment.

SECTION 2A:

CONTENT FOR H1 CHEMISTRY

2.1 SYLLABUS NARRATIVE: THE H1 CHEMISTRY CURRICULUM
2.2 CORE IDEA 1: MATTER
2.3 CORE IDEA 2: STRUCTURE AND PROPERTIES
2.4 CORE IDEA 3: TRANSFORMATION
2.5 EXTENSION TOPIC

2A. CONTENT: H1 CHEMISTRY

Core Ideas, Extension Topic and Themes

The topics in H1 Chemistry are organised as two levels underpinned by the Practices of Science:

- Core Ideas: The three Core Ideas of Chemistry are *Matter*, *Structure and Properties*, and *Transformation*. The concepts in these Core Ideas are interrelated and form the basis for which further learning and understanding of chemical phenomena and reactions is built upon.

- Extension Topic: Concepts in the Core Ideas extend into the study of Polymers and organic chemistry.

Core Ideas	**Topics**
Core Idea 1: Matter	1. Atomic Structure
Core Idea 2: Structure and Properties	2. Chemical Bonding
	3. Theories of Acids and Bases
	4. The Periodic Table
Core Idea 3: Transformation	5. The Mole Concept and Stoichiometry
	6. Chemical Energetics: Thermochemistry
	7. Reaction Kinetics
	8. Chemical Equilibria
Extension Topic:	9. Polymers and Organic Chemistry

- Relevance of Chemistry in the real world through the themes of Environmental Sustainability and Materials: Real-world contexts are weaved into the narratives and learning experiences incorporating the two themes for the different topics can help to draw connections between concepts and everyday life, develop scientific literacy and enable learners to see the impact of chemistry on our society and environment. These contexts are broadly classified under the themes of Environmental Sustainability and Materials. These two interrelated themes are timely in view of climate change and the push for scientific innovation to address global needs and environmental challenges.

Narratives

Narratives describe the Core Ideas and the attendant concepts in a coherent manner. They highlight

- the connections within and across the three Core Ideas in chemistry,
- links between the Core Ideas and Extension Topics,
- links to unifying ideas that cut across science subjects, and
- connections to themes of Environmental Sustainability and Materials.

2.1 SYLLABUS NARRATIVE: THE H1 CHEMISTRY CURRICULUM

The H1 Chemistry curriculum provides students with the opportunity to appreciate the connections between the concepts in the Core Ideas of *Matter*, *Structure and Properties*, and *Transformation*, and to apply these to the study of Polymers and Organic chemistry in the *Extension Topic*. This is illustrated in the H1 Chemistry Content Map.

Chemistry is about the study of matter, its interactions and transformations. At a macroscopic level, we observe matter and its interactions everywhere in our daily life. The submicroscopic level looks at the structure of matter that gives rise to these interactions. At O-Level, students have been introduced to the fundamental idea that matter is made up of particles and the simple atomic model (electrons in discrete shells around a positively charged nucleus). This allows students to apply the key ideas of conservation of matter and energy in the quantitative treatment of reactions such as stoichiometry and thermochemistry.

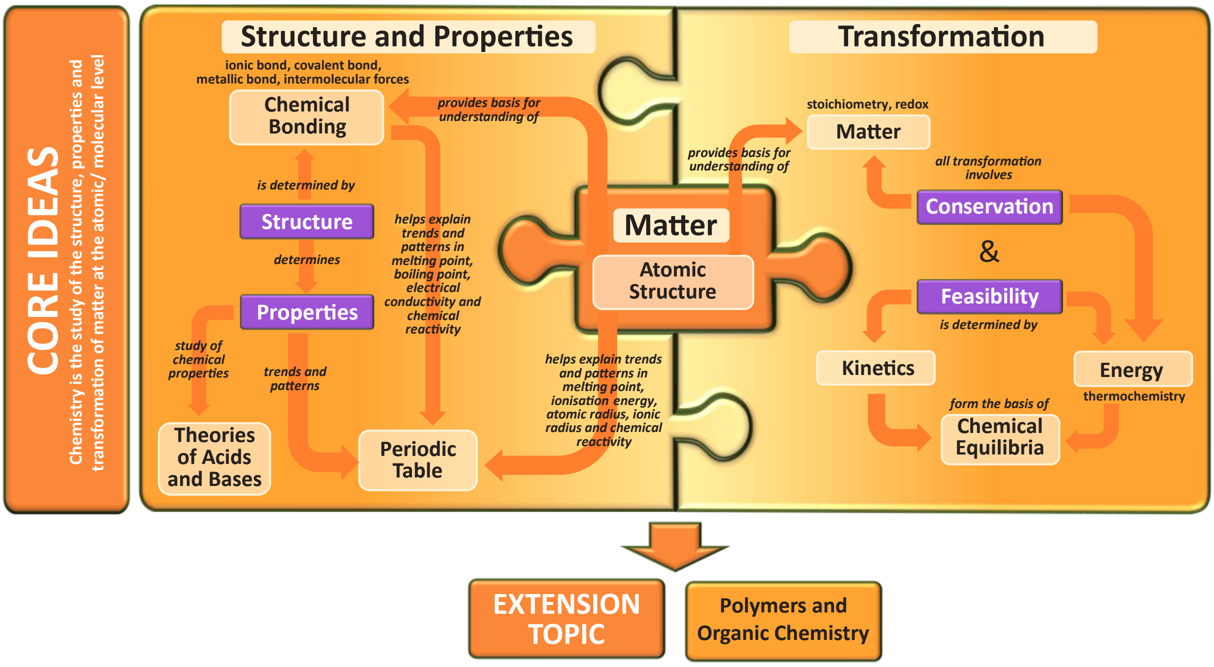
In H1 Chemistry, an in-depth study of the electronic structure of atoms provides the basis for the study of chemical bonding. The Valence Shell Electron Pair Repulsion (VSEPR) model is used to rationalise the three-dimensional structure of molecules, which determines the type of interactions possible and also helps to explain the physical and chemical properties. Knowledge of structure and bonding is also important to study and predict trends in properties of matter and its reactions.

Transformation of matter involves the study of the feasibility and the extent of chemical reactions. Considerations of energetics and kinetics account for the feasibility while an understanding in equilibrium explains the extent of chemical reactions. The energetics dimension builds upon prior knowledge of thermochemistry, by contextualising the concept of enthalpy change in specific processes, e.g. combustion, bond breaking and lattice formation. To highlight the empirical aspects of Chemistry, methods for the determination of enthalpy changes will also be discussed. The chemical kinetics facet of a reaction can be understood quantitatively by relating the rate of reaction to the concentration of reactants. The qualitative aspect which deals with the factors affecting rate of reactions will be covered based on the collision theory.

The concepts in chemical energetics and kinetics will form the basis for the study of Chemical Equilibrium. Theoretically all reactions are reversible, and the notion of dynamic equilibrium will be introduced. The concept of equilibrium constant (K) gives a measure of the extent of a reversible reaction. Factors which determine the position of equilibrium will also be examined. Chemical equilibria involving aqueous acids and bases will be dealt with in greater depth, in view of the relevance and prevalence of these concepts which cuts across chemical systems.

The extension topic on Polymers and Organic Chemistry features applications of core concepts to a real-world context where specific examples, such as plastics and proteins, provide the opportunity for students to apply their knowledge on structure and bonding to understand the properties and uses of these materials.

H1 Chemistry Content Map



2.2 Core Idea 1: Matter

1. [H1] ATOMIC STRUCTURE

5th century BC	**Democritus**	Held that all matter is composed of the smallest indivisible bodies, called atoms (from Greek ἄτομον, atomon, i.e. ‘uncuttable’, ‘indivisible’)
4th century BC	**Aristotle**	Proposed a fifth element, aether, from which stars and planets were made, in addition to the four elements, earth, water, air and fire, described earlier by Empedocles
Middle Ages	**Alchemy**	Sought Aristotle’s fifth element to effect the transformation of other base metals into precious gold; helped develop many apparatus and experimental techniques still in use today
1661	**Robert Boyle**	Referred to as ‘The Father of Chemistry’; defined elements as substances which could not be broken down into nor formed from simpler substances
1774	**Antoine Lavoisier**	Discovered the law of conservation of mass; defined an element as a basic substance that could not be further broken down by the methods of chemistry
1704	**Isaac Newton**	Proposed a mechanical universe with small solid masses in motion
1805	**John Dalton**	Proposed that each element consists of atoms of a single, unique type, and that chemical compounds are formed by combinations of these atoms

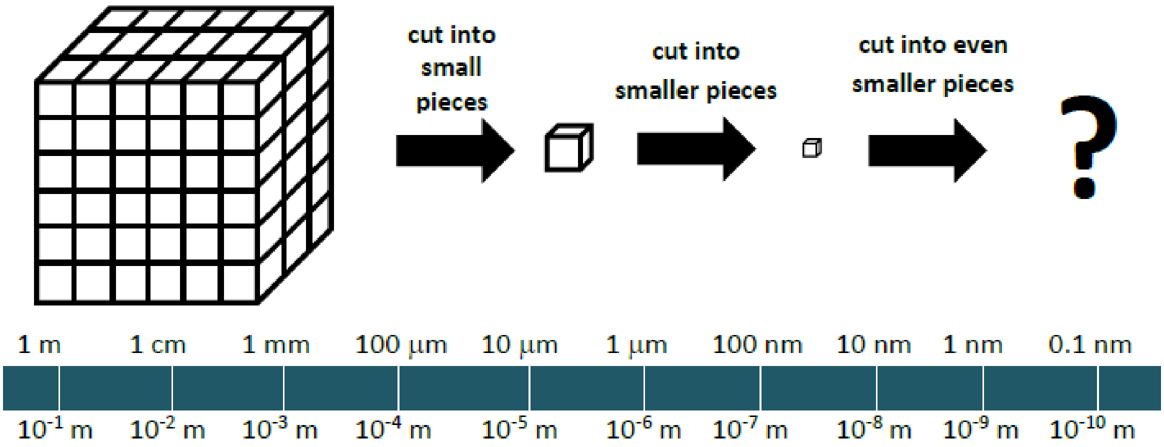
The development of atomic theory has come a long way since John Dalton’s work, and our understanding of the nature of matter and the structure of atoms has deepened with the work of scientists such as J. J. Thompson, Ernest Rutherford, Niels Bohr, Louis de Broglie, Erwin Schrödinger and Werner Heisenberg, just to name a few.

Today, the atom is still a basic unit of matter and the current quantum mechanical model of an atom features a dense central nucleus comprising protons and neutrons, surrounded by a cloud of electrons, and we also know that although the electron is a true fundamental particle, the proton and neutron are themselves made up of more elementary particles known as quarks.

In this section, the structure of an atom will be explored for a more in-depth understanding. This forms the basis for subsequent understanding of chemical bonds that give rise to the variety of chemical structures that exhibit a range of physical and chemical properties. In all processes involving the forming and breaking of chemical bonds, matter is conserved – atoms are neither created nor destroyed.

Connections to theme of Materials

In Atomic Structure, we step into the “invisible” sub-microscopic world of materials (substances or matter) around us. There is a limit to which matter can be cut into smaller pieces before it loses its properties and chemical identity. The ancient Greeks used the word atoma (meaning indivisible units) to describe this smallest unit of matter. “Indivisibility” became a central concept of modern atomic theory where the smallest unit of matter that retains its chemical identity is called an atom. All materials around us, be it natural or artificial, are made up of atoms. Atoms are very small, with a diameter about 0.1 nanometer (nm). Atoms are too small to be seen directly through a microscope. Electron microscopes could be used to generate images of micro/nanostructures. The size of a material can influence its properties; properties of a material at nanoscale (generally defined as having a length ≤ 100 nm) can be very different from its corresponding bulk material at a larger scale dimension.



In this topic, we investigate the electronic structure of atoms, which influences the interactions between matter, as well as interactions between matter and electromagnetic radiation.

A simple appreciation of electromagnetic radiation and the interactions of electromagnetic radiation with matter would be useful in helping us explain phenomena in everyday life.

1. [H1] Atomic Structure

Guiding Questions

What makes up an atom?

How has the understanding of atomic structure developed and evolved?

What is the evidence showing that the electrons in an atom exist in discrete energy levels?

What do you understand by electronic configuration? How are the electrons arranged in the atoms of a given element?

How are the arrangement of an element's electrons and its position in the Periodic Table related?

Learning Outcomes

Students should be able to:

(a) identify and describe protons, neutrons and electrons in terms of their relative charges and relative masses

(b) deduce the behaviour of beams of protons, neutrons and electrons in an electric field

(c) describe the distribution of mass and charges within an atom

(d) deduce the numbers of protons, neutrons and electrons present in both atoms and ions given proton and nucleon numbers (and charge)

(e) (i) describe the contribution of protons and neutrons to atomic nuclei in terms of proton number and nucleon number
  (ii) distinguish between isotopes on the basis of different numbers of neutrons present

(f) describe the number and relative energies of the s, p and d orbitals for the principal quantum numbers 1, 2 and 3 and also the 4s and 4p orbitals

(g) describe the shapes of s and p orbitals
[knowledge of wave functions is **not** required]

(h) state the electronic configuration of atoms and ions given the proton number (and charge)

(i) explain the factors influencing the ionisation energies of elements (see the *Data Booklet*) (see also Section 4)

(j) deduce the electronic configurations of elements from successive ionisation energy data

Learning Outcomes Students should be able to:	
(k)	interpret successive ionisation energy data of an element in terms of the position of that element within the Periodic Table

2.3 CORE IDEA 2: STRUCTURE AND PROPERTIES

[H1] CHEMICAL BONDING
[H1] THEORIES OF ACIDS AND BASES
[H1] THE PERIODIC TABLE

The concepts covered will provide students with the opportunity to appreciate how the structure of atoms determines the type of bonding and interaction that can take place, and use these concepts to observe and predict the patterns and trends in the chemical and physical properties of matter and its reactions.

The concept of the atomic structure provides the basis for the study of chemical bonding, which builds upon knowledge of how chemical bonds (e.g. ionic bonds, covalent bonds) are formed. By extending this knowledge into an understanding of the electrostatic nature of chemical bonds, this helps in viewing the classification of chemical bonds on a continuum rather than as discrete descriptions. This augments the understanding of intermolecular forces of attraction. The study of the three-dimensional structures of elements and/or their compounds and the types of interactions present explains their chemical and physical properties.

The chemical properties of acids and bases will be covered in greater depth with the introduction of Brønsted definition of acids and bases. The study of the property of gases will focus on the importance of intermolecular forces leading to liquefaction.

The study of trends and patterns in the chemical and physical properties of elements in the Periodic Table is built upon prior knowledge of Period and Group trends acquired at the secondary science level. At the A-Level, trends in the physical and chemical properties of the elements and their compounds will be covered in greater depth.

Connections to themes of Environmental Sustainability and Materials

The interactions between matter resulted in a diversity of materials of different structures and properties. Observing patterns in reactivity and how the structure of a substance affects its properties can be useful for designing and synthesising new materials.

In the past, people have designed materials to last for as long as they could. However, when materials are designed not to naturally degrade easily, they pose issues during disposal. So what factors must be considered when we design materials that can last for the duration of use, and yet can be degraded or recycled when they are no longer needed? Design principles for new materials no longer rest upon durability, but include careful considerations on sustainability, in particular biodegradability and recycling.

Maintaining **balance**, where the system is in equilibrium or a steady state, is important in living things as well as ecosystems. **Diversity** is an important part of maintaining balance in the ecosystem. The variety of living and non-living things around us interact with one another. Interactions within and between **systems** meant that the fates of systems are intertwined.

Our everyday activities, for example from power generation, transport, agricultural practices, industries, contribute to anthropogenic CO_2 released to the environment.

The rapid increase in atmospheric CO_2 disturbed the equilibrium of the carbon cycle, which inadvertently affected the acid-base equilibrium of our oceans – the largest aqueous system that covers more than 70% of earth's surface. Our oceans play a major role in regulating atmospheric carbon dioxide. The oceans, with pH about 8.2, absorb atmospheric CO_2 gas, which is acidic in nature. It has a natural buffering capacity, where the carbonate/hydrogencarbonate equilibria is sustained by calcium carbonate minerals in the deep ocean floor and marine organisms with shells or exoskeletons rich in calcium carbonate. The rapid increase in atmospheric concentration of CO_2 over the last 200 years (as well as warmer temperatures) has shifted the equilibrium. The pH of surface ocean waters has decreased by 0.1 pH units, which is about 30% increase in acidity[8]. Ocean acidification impacts the marine ecosystem adversely. This in turn affects humans and other animals who rely on the ocean for food. **So, what actions can we take to restore the equilibrium in our oceans?**

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[8] https://edu.rsc.org/feature/ocean-acidification/2020203.article

2. [H1] Chemical Bonding

Guiding Questions

What holds particles together?

What are the different models that describe the forces that hold particles together?

How do these models explain the properties of matter?

How do we determine the shapes of molecules?

Learning Outcomes

Students should be able to:

(a) show understanding that all chemical bonds are electrostatic in nature and describe:
  (i) ionic bond as the electrostatic attraction between oppositely charged ions
  (ii) covalent bond as the electrostatic attraction between a shared pair of electrons and positively charged nuclei
  (iii) metallic bond as the electrostatic attraction between a lattice of positive ions and delocalised electrons

(b) describe, including the use of 'dot-and-cross' diagrams,
  (i) ionic bonding as in sodium chloride and magnesium oxide

  (ii) covalent bonding as in hydrogen; oxygen; nitrogen; chlorine; hydrogen chloride; carbon dioxide; methane; ethene

  (iii) co-ordinate (dative covalent) bonding, as in formation of the ammonium ion and in the Al_2Cl_6 molecule

(c) describe covalent bonding in terms of orbital overlap (limited to s and p orbitals only), giving σ and π bonds (see also Section 9)

(d) explain the shapes of, and bond angles in, molecules such as BF_3 (trigonal planar); CO_2 (linear); CH_4 (tetrahedral); NH_3 (trigonal pyramidal); H_2O (bent); SF_6 (octahedral) by using the Valence Shell Electron Pair Repulsion theory

(e) predict the shapes of, and bond angles in, molecules analogous to those specified in (d)

(f) explain and deduce bond polarity using the concept of electronegativity [quantitative treatment of electronegativity is **not** required]

(g) deduce the polarity of a molecule using bond polarity and its molecular shape (analogous to those specified in (d))

Learning Outcomes
Students should be able to:

(h) describe the following forces of attraction (electrostatic in nature):
  (i) intermolecular forces, based on permanent and induced dipoles, as in liquid and gaseous $CHCl_3$, Br_2 and the noble gases
  (ii) hydrogen bonding, using ammonia and water as examples of molecules containing –NH and –OH groups

(i) outline the importance of intermolecular forces to the liquefaction of gases when subjected to high pressure and/or low temperature

(j) outline the importance of hydrogen bonding to the physical properties of substances, including ice and water

(k) explain the terms *bond energy* and *bond length* for covalent bonds

(l) compare the reactivities of covalent bonds in terms of bond energy, bond length and bond polarity

(m) describe, in simple terms, the lattice structure of a crystalline solid which is:
  (i) ionic, as in sodium chloride and magnesium oxide
  (ii) simple molecular, as in iodine
  (iii) giant molecular, as in graphite and diamond
  (iv) hydrogen-bonded, as in ice
  (v) metallic, as in copper
  [the concept of the 'unit cell' is **not** required]

(n) describe, interpret and/or predict the effect of different types of structure and bonding on the physical properties of substances

(o) suggest the type of structure and bonding present in a substance from given information

3. [H1] Theories of Acids and Bases

Guiding Questions

What are acids and bases?

What models can be used to classify substances as acids or bases?

What is a strong or weak acid/base? How can the strengths of acids and bases be represented and determined? What is the relationship between the concentration of acid, pH and strength of an acid?

What are buffers? How do buffers work?

Learning Outcomes

Students should be able to:

(a) show understanding of, and apply the Arrhenius theory of acids and bases

(b) show understanding of, and apply the Brønsted–Lowry theory of acids and bases, including the concept of conjugate acids and conjugate bases

(c) explain qualitatively the differences in behaviour between strong and weak acids and bases in terms of the extent of dissociation

(d) explain the terms pH; K_a; K_b; K_w [the relationship $K_w = K_aK_b$ is **not** required]

(e) calculate [H^+(aq)] and pH values for strong acids and strong bases

(f) explain the choice of suitable indicators for acid-base titrations, given appropriate data, in terms of the strengths of the acids and bases

(g) (i) explain how buffer solutions control pH
  (ii) describe and explain the uses of buffer solutions, including the role of CO_3^{2-}/HCO_3^- in maintaining pH in oceans, and how the rapid increase in atmospheric carbon dioxide gas contributed to ocean acidification

4. [H1] The Periodic Table

Guiding Questions

What are the trends and variations in physical and chemical properties in elements and compounds?

How can the trends and variations in atomic, physical and chemical properties be explained?

How can we predict the properties of elements and their compounds?

Learning Outcomes

Students should be able to:

Trends and variations in atomic and physical properties

For elements in the third period (sodium to chlorine) and in Group 17 (chlorine to iodine), students should be able to:

(a) recognise variation in the electronic configurations across a Period and down a Group

(b) describe and explain qualitatively the general trends and variations in atomic radius, ionic radius, first ionisation energy and electronegativity:
  - (i) across a Period in terms of shielding and nuclear charge
  - (ii) down a Group in terms of increasing number of electron shells, shielding and nuclear charge

(c) interpret the variation in melting point and in electrical conductivity across a Period in terms of structure and bonding in the elements (metallic, giant molecular, or simple molecular)

(d) describe and explain the trend in volatility of the Group 17 elements in terms of instantaneous dipole-induced dipole attraction

Trends and variations in chemical properties

For elements in the third period (sodium to chlorine), students should be able to:

(e) (i) state and explain the variation in the highest oxidation number of the elements in oxides (for Na_2O; MgO; Al_2O_3; SiO_2; P_4O_{10}; SO_3) and chlorides (for NaCl; $MgCl_2$; $AlCl_3$; $SiCl_4$; PCl_5)
  - (ii) state and explain the variation in bonding in oxides and chlorides in terms of electronegativity (with the exception of $AlCl_3$)
  - (iii) describe the reactions of the oxides with water (for Na_2O; MgO; Al_2O_3; SiO_2; P_4O_{10}; SO_3)

Learning Outcomes
Students should be able to:

- (iv) describe and explain the acid/base behaviour of oxides (for Na_2O; MgO; Al_2O_3; SiO_2; P_4O_{10}; SO_3) and hydroxides (for $NaOH$; $Mg(OH)_2$; $Al(OH)_3$), including, where relevant, amphoteric behaviour in reaction with sodium hydroxide (only) and acids
- (v) describe and explain the reactions of the chlorides with water (for $NaCl$; $MgCl_2$; $AlCl_3$; $SiCl_4$; PCl_5)
- (vi) suggest the types of structure and bonding present in the oxides and chlorides from observations of their chemical and physical properties

For elements in Group 1 (lithium to caesium) and Group 17 (chlorine to iodine), students should be able to:

(f) describe and explain the relative reactivity of elements of:
  (i) Group 1 as reducing agents in terms of ease of loss of electrons
  (ii) Group 17 as oxidising agents in terms of ease of gain of electrons

(g) describe and explain the trend in thermal stability of Group 17 hydrides in terms of bond energies

In addition, students should be able to:

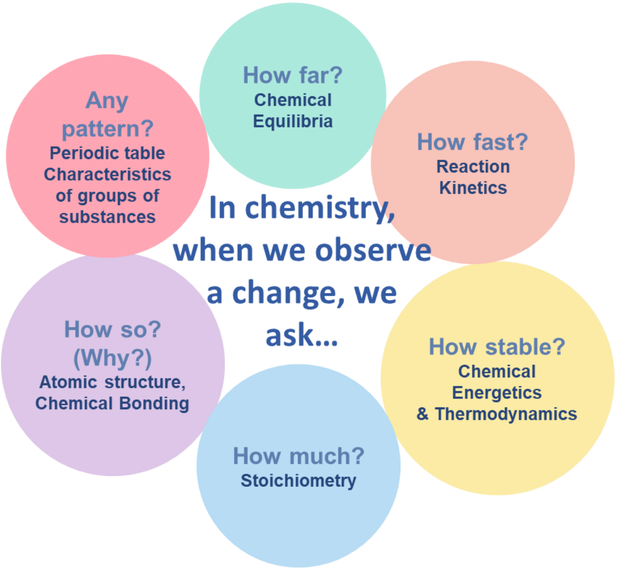
(h) predict the characteristic properties of an element in a given Group by using knowledge of chemical periodicity

(i) deduce the nature, possible position in the Periodic Table, and identity of unknown elements from given information of physical and chemical properties

2.4 CORE IDEA 3: TRANSFORMATION

[H1] THE MOLE CONCEPT AND STOICHIOMETRY
[H1] CHEMICAL ENERGETICS: THERMOCHEMISTRY
[H1] REACTION KINETICS
[H1] CHEMICAL EQUILIBRIA

Why does water expand when it cools and turns into ice? How do instant heat packs and instant cold packs work? If a sentence written using an erasable pen is erased, would it be possible to reverse the process to see the sentence again? How do enzymes in laundry detergents remove dirt from clothes? Why can't such biological detergents be used in hot wash cycles in washing machines?



Transformation of matter involves a change in the chemical and/or physical properties of the substance. Chemical transformations involve the reorganisation or transfer of valence electrons among the reactants to form new substances. Physical transformations however, do not result in changes in the elemental composition of the substance, e.g. a change in physical state from a solid to liquid. In all transformations, matter and energy *must* be conserved. The conservation of matter is the basis of **stoichiometric** relationships in a balanced equation where atoms and charges are conserved. Not all transformations can be directly observed, though. While some changes can be observed at the macroscopic level (e.g. changes in colour, state, temperature, smell), others occur at the submicroscopic level without affecting the bulk properties of matter (e.g. processes in **dynamic equilibrium**). Also, not all transformation occurs within the timescale of observation; the rate of change (**kinetics**) needs to be considered. For example, the conversion of diamond to a more stable form, graphite, is so slow that it can never be observed within the life span of a human. Finally, the extent of the transformation will not be complete if the chemical or physical process is reversible. Changes in temperature, concentration or pressure, otherwise known as disturbances to the system, can affect the position of the **equilibrium** of the transformation.

Why do transformations take place at all?

There are many examples in daily life in which changes occur and do not occur. The **structure and properties** of substances influence how they interact with each other and change, but do not guarantee that the change can take place. A deeper understanding involves **energy** as the key consideration for any transformation to take place.

Connections to themes of Environmental Sustainability and Materials

Humans have explored and exploited changes in **materials** around us for our own benefit ever since we mastered the art of starting and maintaining fire. **Thermal energy** is useful to accelerate and activate transformations that involved changes to the structure and properties of materials. However, no matter how hard ancient chemists (alchemists) worked on transmutation of base elements into precious metals (e.g. trying to convert lead into gold) by subjecting materials to intense heat and mechanical forces, none succeeded in their attempts. As alchemists continued their observations and experimentations on materials, they paved the way for modern chemistry and medicine, sometimes through serendipitous discoveries. Gradually, scientists gathered evidence that corroborated theories and laws involving the transformation of matter. For example,

- **Law of conservation of matter:** During any physical or chemical change, the total mass of the products remains equal to the total mass of the reactants.
- **Law of conservation of energy:** The total energy of an isolated system remains constant.

The law of definite proportion[9] and law of multiple proportions[10] paved the way for stoichiometry and mole concept.

We need to think about how we can **minimise the impact of our actions on the environment**. Some questions or issues we might wish to think about in the following topics:
- Should optimising percentage yield be the goal of chemical synthesis?
- How might the concept of Reduce, Reuse and Recycle (3Rs) be applied in Chemistry?
- What do we really mean when we say we have a global energy and natural resource crisis?
- What is the best method to increase the rate of a chemical reaction while being environmentally friendly?

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[9] A chemical compound contains the same elements chemically combined together in the same proportion by mass.

[10] When two elements chemically combine with each other to form two or more compounds, the ratios of the masses of one element that combines with the fixed mass of the other are simple whole numbers.

5. [H1] The Mole Concept and Stoichiometry

Guiding Questions

What is a mole? Why is it important in chemistry?

What is the significance of a balanced equation?

How can the amount of reactants and products in a chemical reaction be determined?

Learning Outcomes

Students should be able to:

[the term relative formula mass or M_r will be used for ionic compounds]

(a) define the terms *relative atomic*, *isotopic*, *molecular* and *formula mass*

(b) define the term *mole* in terms of the Avogadro constant

(c) calculate the relative atomic mass of an element given the relative abundances of its isotopes

(d) define the terms *empirical* and *molecular formula*

(e) calculate empirical and molecular formulae using combustion data or composition by mass

(f) write and/or construct balanced equations

(g) describe and explain redox processes in terms of electron transfer and/or of changes in oxidation number (oxidation state) as exemplified by Fe^{3+}/Fe^{2+} and MnO_4^-/Mn^{2+}

(h) construct redox equations using the relevant half-equations

(i) perform calculations, including use of the mole concept, involving:
  (i) reacting masses (from formulae and equations)
  (ii) volumes of gases (e.g. in the burning of hydrocarbons)
  (iii) volumes and concentrations of solutions

  [when performing calculations, students' answers should reflect the number of significant figures given or asked for in the question]

(j) deduce stoichiometric relationships from calculations such as those in (i)

6. [H1] Chemical Energetics: Thermochemistry

Guiding Questions

What are the energy changes in a chemical or physical process?

Why do some chemical or physical processes take place spontaneously?

How can we measure or find the energy change in a chemical or physical process?

Learning Outcomes

Students should be able to:

(a) explain that most chemical reactions are accompanied by energy changes, principally in the form of heat usually associated with the breaking and forming of chemical bonds; the reaction can be exothermic (ΔH negative) or endothermic (ΔH positive)

(b) construct and interpret an energy profile diagram, in terms of the enthalpy change of the reaction and of the activation energy (see also Section 7)

(c) explain and use the terms:
   (i) *enthalpy change of reaction* and *standard conditions*, with particular reference to: formation; combustion; neutralisation
   (ii) *bond energy* (ΔH positive, i.e. bond breaking) (see also Section 2)
   (iii) *lattice energy* (ΔH negative, i.e. gaseous ions to solid lattice)

(d) calculate enthalpy changes from appropriate experimental results, including the use of the relationship: heat change = $mc\Delta T$

(e) explain, in qualitative terms, the effect of ionic charge and of ionic radius on the numerical magnitude of a lattice energy

(f) apply Hess' Law to carry out calculations involving given simple energy cycles and relevant energy terms (restricted to enthalpy changes of formation, combustion and neutralisation), with particular reference to:
   (i) determining enthalpy changes that cannot be found by direct experiment, e.g. an enthalpy change of formation from enthalpy changes of combustion
   (ii) average bond energies
   [construction of energy cycles is **not** required]

7. [H1] Reaction Kinetics

Guiding Questions

What do we mean by rate of reaction? How can we measure it?

What are the factors affecting rate? Why?

How can we determine and express the relationship between rate and concentration mathematically? How are the other factors affecting rate featured in this equation?

What are the general types of catalysts? How are they similar and how do their modes of action differ?

Learning Outcomes

Students should be able to:

(a) explain and use the terms: *rate of reaction; rate equation; order of reaction; rate constant; half-life of a reaction; activation energy; catalysis*

(b) construct and use rate equations of the form rate = $k[A]^m[B]^n$ (limited to simple cases of single-step reactions for which m and n are 0, 1 or 2), including:
  (i) deducing the order of a reaction by the initial rates method
  (ii) justifying, for zero- and first-order reactions, the order of reaction from concentration-time graphs
  (iii) calculating an initial rate using concentration data
  [integrated forms of rate equations are **not** required]

(c) show understanding that the half-life of a first-order reaction is independent of concentration

(d) explain qualitatively, in terms of frequency of collisions, the effect of concentration changes on the rate of a reaction

(e) show understanding, including reference to the Boltzmann distribution, of what is meant by the term *activation energy*

(f) explain qualitatively, in terms both of the Boltzmann distribution and of collision frequency, the effect of temperature change on a rate constant (and hence, on the rate) of a reaction

(g) (i) explain that, in the presence of a catalyst, a reaction follows a different pathway, i.e. one of lower activation energy, giving a larger rate constant
  (ii) interpret this catalytic effect in terms of the Boltzmann distribution

Learning Outcomes

Students should be able to:

(h) outline the mode of action of heterogeneous catalysis, as exemplified by the catalytic removal of oxides of nitrogen in the exhaust gases from car engines

(i) describe enzymes as protein molecules that act as biological catalysts with high specificity (in the reactions that they catalyse and in their choice of substrates as exemplified by the lock-and-key model), temperature sensitivity and pH sensitivity
[Knowledge of the levels of structure of proteins is **not** required. Details of the denaturation process will be discussed in 9(m).]

8. [H1] Chemical Equilibria

Guiding Questions

What are the characteristics of a system that has reached dynamic equilibrium? How can we describe such a system at equilibrium?
Why would systems tend towards a state of equilibrium?
What happens when a system at equilibrium is disturbed?
What are the factors to consider for optimal yield in a reversible reaction?

Learning Outcomes
Students should be able to:

(a) explain, in terms of rates of the forward and reverse reactions, what is meant by a *reversible reaction* and *dynamic equilibrium*

(b) state Le Chatelier's Principle and apply it to deduce qualitatively (from appropriate information) the effects of changes in concentration, pressure or temperature, on a system at equilibrium

(c) deduce whether changes in concentration, pressure or temperature or the presence of a catalyst affect the value of the equilibrium constant for a reaction

(d) deduce expressions for equilibrium constants in terms of concentrations, K_c

(e) calculate the values of equilibrium constants in terms of concentrations from appropriate data

(f) calculate the quantities present at equilibrium, given appropriate data (such calculations will not require the solving of quadratic equations)

(g) describe and explain the conditions used in the Haber process, as an example of the importance of an understanding of chemical equilibrium in the chemical industry

2.5 EXTENSION TOPIC: POLYMERS AND ORGANIC CHEMISTRY

[H1] POLYMERS AND ORGANIC CHEMISTRY

What is Organic Chemistry?

Organic chemistry is the study of the structure, properties, composition, reactions and preparation of carbon-containing compounds, which include not only hydrocarbons (compounds containing carbon and hydrogen only) but also compounds with any number of other elements, such as nitrogen, oxygen, halogens, phosphorus, silicon and sulfur, in addition to hydrogen.

Carbon, with a ground state electronic configuration of $1s^2\ 2s^2\ 2p^2$, has four valence electrons (Core Idea 1: Matter) and is able to form single, double and triple bonds with a variety of other atoms. Carbon is also unique among the elements in its unsurpassable ability to self-link into chains or rings of different sizes, giving rise to the millions of organic compounds known.

History of Organic Chemistry

The development of Organic Chemistry occurred over a long period of time, during which the knowledge acquired through observation is organised and rationalised using different theories and models (see diagram below).

Antiquity	**Romans and Egyptians**	Used organic chemicals in ancient times such as dyes, medicines and poisons from nature, although the chemical compositions were unknown. E.g. indigotin from the indigo and woad plants
1807	**Jöns Jakob Berzelius**	The first person to make the distinction between organic compounds (those containing carbon) and inorganic compounds. However, being a vitalist, he subscribed to the notion that 'all organic compounds can arise with the operation of vital force inherent to living cells'
1828	**Friedrich Wöhler**	Synthesised the organic compound, urea (H_2NCONH_2), fortuitously while heating the inorganic salt, ammonium cyanate (NH_4NCO)
1850s–1900s	**Pierre Eugène Marcellin Berthelot**	Showed that all classes of organic compounds could be synthesised
1858	**August Kekulé and Archibald Scott Couper**	Independently developed the valence theory of carbon for the understanding of structures in organic chemistry
1862	**Emil Erlenmeyer**	The first person to suggest that double and triple bonds could form between carbon atoms
1864	**Alexander Crum Brown**	The first person to draw ethene with the C=C unit to represent the double bond
1874	**Jacobus Henricus van't Hoff**	Accounted for the phenomenon of optical activity by assuming that the bonds around carbon atoms were arranged in a tetrahedral manner. Awarded the first Nobel Prize in Chemistry in 1901
1916	**Gilbert Newton Lewis**	Introduced the concept of a covalent bond formed by the sharing of a pair of electrons, and the formulation of the Lewis structure

Organic chemistry was first made a branch of modern chemistry by Jöns Jakob Berzelius in the early 1800s. He classified chemical compounds into two main groups: those originating from living or once-living matter, which he termed **organic**, and those originating from mineral or non-living matter, which he termed **inorganic**. Berzelius, similar to most chemists of that era, believed that organic compounds could only come from living organisms mediated by some vital force, known as **vitalism**.

In 1828, Friedrich Wöhler, ironically a student of Berzelius's, discovered that the organic compound urea could be made by heating ammonium cyanate, an inorganic salt. This observation demonstrated for the very first time that an organic compound could be synthesised from an inorganic source, which led eventually to the rejection of vitalism as a scientific theory.

Wöhler's observation represents a milestone in the history of science for two reasons. First, it challenged the idea of vitalism. Second, this also marked the discovery of **isomerism** – the phenomenon of two or more different chemical structures (ammonium cyanate and urea) based on the same chemical formula (N_2H_4CO).

Chemists began their quest for ways to rationalise isomerism, which in turn led to theories pertaining to the structure and bonding of chemical compounds. By the 1860s, chemists like Kekulé and Couper separately published papers on relating the chemical formula of a compound to the ways the atoms are linked, that a carbon atom forms four bonds and carbon atoms can bond to one another. By the 1900s chemists like Lewis and Pauling developed models to understand the nature of the chemical bond, particularly the **covalent bond** for organic chemistry. The number of known organic compounds also increased exponentially throughout this time.

By the 20th century, organic chemistry has found applications in materials chemistry, pharmacology, chemical engineering and petro-chemistry, amongst many others. Millions of new substances were discovered or synthesised during this period, and today over 98% of all known compounds are organic.

The section on polymers extends the basic concepts of organic chemistry and polymerisation at O-Level. Functional groups, which are specific groups of atoms attached to a carbon backbone, dictate the chemical and physical properties of organic molecules and draw the links between structure and bonding with the desired properties in everyday materials and the structural elucidation of unknown compounds.

Connections to theme of Environmental Sustainability

With the knowledge of Organic Chemistry, organic molecules that have specific structures and therefore, properties, can be designed and synthesised in the laboratory through careful control of the reagents and conditions used. An example of organic molecules whose properties have enabled their use in many applications as well as brought convenience and possibilities to our lives is plastics, a material that is part of a bigger class of organic compounds known as organic polymers.

Plastics are ubiquitous in our everyday life. In the food supply chain, the properties of plastics enable them to be used as food packaging which helps to extend shelf-life of food and which supports safe handling and distribution of food, thus contributing to minimising food wastage[11]. In the healthcare sector, plastics have contributed to improved hygiene such as in the form of sterile single-use materials like syringes and disposable face masks, amongst many other medical devices and uses[12]. Plastics are also components in electrical products such as mobile phones and laptops. Its lightweight property has also led to use of plastics in transportation, contributing to reduced carbon emissions.

However, plastic waste and their disposal, especially single-use plastics, has also led to growing environmental concerns such as pollution of oceans, posing a threat to marine lives and human health[13]. In addition, a major source of chemical feedstock to manufacture common plastics comes from crude oil, a finite resource[14].

Organic Chemistry can collectively play a role in the design and synthesis of useful materials such as the plastics that we are familiar with, as well as alternative plastics that are easier to degrade, recycle or produce less toxic waste, thereby contributing to sustainability. For instance, the study of organic reactions provides a foundation for understanding how polymers are formed and how they degrade in the natural environment. This can lead to the design and synthesis of plastics using suitable reagents and conditions to facilitate an environmentally friendly degradation method for plastics. This would also require a good understanding of organic reactions and the factors that influence reactivities of organic molecules and reactions. How the properties of plastics can be controlled at the molecular level[15] also enables an appreciation of the role of structure in influencing the properties of matter (Core Idea 2: Structure and Properties).

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9. [H1] Polymers and Organic Chemistry

Guiding Questions

What are the main classes of organic compounds?

What are some terms commonly used in the description of organic reactions and reactivities?

What is isomerism? What are the different types of isomerism?

What type of reactions do each class of compound undergo?

What are polymers?

How are polymers formed and what are their uses?

How are the uses/properties of polymers related to their structure and bonding?

Learning Outcomes

Students should be able to:

(a) interpret, and use the nomenclature, general formulae and structural formulae (including displayed formulae) of the following classes of compounds:
  (i) hydrocarbons (alkanes, alkenes and benzene)
  (ii) halogenoalkanes
  (iii) alcohols (including primary, secondary and tertiary)
  (iv) aldehydes and ketones
  (v) carboxylic acids
  (vi) esters
  (vii) amines
  (viii) amides
  (ix) amino acids

(b) interpret, and use the following terminology associated with organic reactions:
  (i) functional group
  (ii) addition, substitution, elimination
  (iii) condensation, hydrolysis
  (iv) oxidation and reduction
  [in equations for organic redox reactions, the symbols [O] and [H] are acceptable]

(c) describe constitutional (structural) isomerism

(d) describe *cis-trans* isomerism in alkenes, and explain its origin in terms of restricted rotation due to the presence of π bonds
  [use of *E, Z* nomenclature is **not** required]

(e) deduce the possible isomers for an organic molecule of known molecular formula

Learning Outcomes
Students should be able to:

(f) (i) describe the shapes of the ethane, ethene and benzene molecules
  (ii) explain the shapes of, and bond angles, in the ethane, ethene and benzene molecules in relation to σ and π carbon-carbon bonds
   [knowledge of hybridisation is not required]
  (iii) predict the shapes of, and bond angles in, molecules analogous to those specified in (f)(ii)

(g) describe the chemistry of the following classes of compounds:
  (i) alkanes (exemplified by ethane) as being generally unreactive except in terms of combustion and substitution by chlorine in the presence of ultraviolet light at room temperature
  (ii) alkenes (exemplified by ethene) in terms of combustion and addition reactions with bromine (in CCl_4) and hydrogen (using Ni catalyst)
  (iii) halogenoalkanes (exemplified by bromoethane) in terms of substitution reaction to alcohols (using NaOH(aq), heat) and elimination reactions to alkenes (using NaOH in ethanol and heat)
  (iv) alcohols (exemplified by ethanol) in terms of combustion, oxidation to carboxylic acids (using acidified $K_2Cr_2O_7$ or acidified $KMnO_4$ and heat) and elimination to alkenes (using concentrated H_3PO_4 catalyst and heat)
  (v) aldehydes (exemplified by ethanal) and ketones (exemplified by propanone) in terms of their reduction to primary and secondary alcohols respectively (using $LiAlH_4$, or using H_2(g), Ni catalyst) and oxidation of aldehydes to carboxylic acids (using acidified $K_2Cr_2O_7$ or acidified $KMnO_4$ and heat)
  (vi) carboxylic acids (exemplified by ethanoic acid) in terms of:
   - reaction with alkalis and carbonates to form salts,
   - condensation with alcohols to form esters (in the presence of concentrated H_2SO_4 catalyst), and with amines (exemplified by ethylamine) to form amides (in the presence of dicyclohexylcarbodiimide, DCC)
     [knowledge of structure of DCC is **not** required]
  (vii) esters (exemplified by ethyl ethanoate) and amides (exemplified by ethanamide) in terms of hydrolysis with aqueous acid (or aqueous alkali) and heat
   [detailed conditions involving specific temperature and pressure values are **not** required]
  (viii) amines (exemplified by ethylamine) with aqueous acid to form salts

(h) recognise polymers as macromolecules built up from monomers, with average relative molecular mass of at least 1000 or at least 100 repeat units.

Learning Outcomes
Students should be able to:

(i) classify and explain the difference between addition and condensation polymers

(j) describe proteins as examples of condensation polymers made up of α-amino acids as monomers, forming peptide (amide) bonds.

(k) describe the hydrolysis of proteins using aqueous acid (or aqueous alkali) and heat

(l) describe the specific bonds or interactions that stabilise the three-dimensional structure of a protein: hydrogen bonding, intermolecular forces, ionic linkages
[Knowledge of the specific levels of structure of proteins, including α-helix and β-pleated sheet, is **not** required.]

(m) explain denaturation of proteins by extremes of temperature and pH changes, in terms of disruption of the bonds or interactions that hold the three-dimensional structure of the proteins (see also LO 7(i))

(n) apply knowledge of the loss and formation of three-dimensional structure to interpret real-world phenomena such as heating of egg whites, addition of vinegar to milk
[Students are **not** required to identify the proteins in the substances.]

(o) classify and explain the difference between thermoplastic (linear, as exemplified by poly(ethene)) and thermosetting (cross-linked, as exemplified by poly(diallyl phthalate)) polymers with reference to structure, bonding and the following properties:
  (i) softening behaviour, including capacity to be recycled
  (ii) rigidity
  (iii) strength

(p) describe and explain the types of structure and bonding in relation to the properties and uses as exemplified by the following:
  (i) low density poly(ethene) (LDPE) in plastic bag and high density poly(ethene) (HDPE) in plastic bottles in relation to LDPE being softer and more flexible, and HDPE being harder and stiffer
  (ii) polyester and polyamide as fabric in relation to polyester (exemplified by poly(ethylene terephthalate) (PET)) as a fabric that is slightly less prone to creasing than polyamide (exemplified by nylon 6,6)
  (iii) poly(vinyl alcohol) (PVA) as a water-soluble polymer in eye drops and poly(vinyl chloride) (PVC) as a water-resistant polymer used in raincoats

Learning Outcomes
Students should be able to:

(iv) poly(propene) (PP) container instead of one made from poly(ethylene terephthalate) (PET) to store strongly alkaline cleaning solutions due to hydrolysis of PET

(q) predict physical properties of polymer from its structure

(r) recognise that poly(alkenes) are chemically inert and can therefore be difficult to biodegrade (see also 9(g)(i))

(s) recognise that polyesters and polyamides are generally biodegradable by hydrolysis (see also 9(g)(vii))

(t) recognise that materials are a finite resource and the importance of recycling plastics, considering the economic, environmental and social factors

Students will be expected to be able to predict the reaction products of a given compound in reactions that are chemically similar to those specified in the syllabus.

When describing preparative reactions, students will be expected to quote the reagents, e.g. aqueous NaOH, the essential practical conditions, e.g. reflux, high temperature and pressure, and the identity of each of the major products. Detailed conditions involving specific temperature and pressure values are **not** required.

Detailed knowledge of practical procedures is also **not** required: however, students may be expected to suggest (from their knowledge of the reagents, essential conditions and products) what steps may be needed to purify/extract a required product from the reaction mixture. In equations for organic redox reactions, the symbols [O] and [H] are acceptable.

Students are expected to be able to interpret and use the following types of representations in the description of organic molecules. The examples given are for the compound lactic acid.

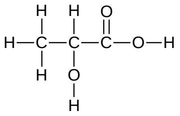
Empirical Formula : simplest ratio of the number of atoms of the elements present in one molecule, e.g. CH_2O

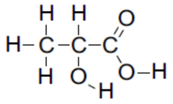
Molecular Formula : actual number of atoms of the elements present in one molecule, e.g. $C_3H_6O_3$

Structural Formula : shows how the constituent atoms of a molecule are joined together with minimal detail, using conventional groups, for an unambiguous structure, e.g. $CH_3CH(OH)CO_2H$

Full Structural or Displayed Formula : detailed structure of molecule showing the relative placing of atoms and the number of bonds between them,

e.g.

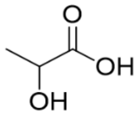




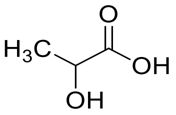
(Note: Where a benzene ring is part of the molecule, a displayed formula for benzene will not be expected to be drawn.)

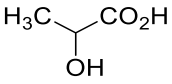
Skeletal Formula : simplified representation of an organic formula derived from the structural formula by removing hydrogen atoms (and their associated bonds) and carbon atoms from alkyl chains, leaving just the carbon-carbon bonds in the carbon skeleton and the associated functional groups.

Skeletal or partial skeletal representations may be used in question papers and are acceptable in students' answers where they are unambiguous, e.g.

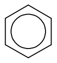


skeletal





partial skeletal

The convention  for representing the aromatic ring is preferred.

SECTION 2B:
CONTENT FOR H2 CHEMISTRY

2B. CONTENT: H2 CHEMISTRY

Core Ideas, Extension Topics and Themes

The topics in H2 Chemistry are organised as two levels underpinned by the Practices of Science:

- Core Ideas: The three Core Ideas of Chemistry are *Matter, Structure and Properties*, and *Transformation*. The concepts in these Core Ideas are inter-related and form the basis for which further learning and understanding of chemical phenomena and reactions is built upon.

- Extension Topics: Concepts in the Core Ideas extend into the learning of different chemical systems such as the chemistry of organic compounds and transition elements.

Core Ideas	Topics
Core Idea 1: Matter	1. Atomic Structure
Core Idea 2: Structure and Properties	2. Chemical Bonding
	3. The Gaseous State
	4. Theories of Acids and Bases
	5. The Periodic Table
Core Idea 3: Transformation	6. The Mole Concept and Stoichiometry
	7. Chemical Energetics: Thermochemistry and Thermodynamics (Gibbs Free Energy and Entropy)
	8. Reaction Kinetics
	9. Chemical Equilibria
Extension Topics:	10. Chemistry of Aqueous Solutions 10.1 Acid-base Equilibria 10.2 Solubility Equilibria
	11. Organic Chemistry 11.1 Introduction 11.2 Isomerism 11.3 Organic Reactions and Mechanisms 11.4 Hydrocarbons 11.5 Halogen Derivatives 11.6 Hydroxy Compounds 11.7 Carbonyl Compounds 11.8 Carboxylic Acids and Derivatives 11.9 Nitrogen Compounds 11.10 Polymers
	12. Electrochemistry
	13. An Introduction to the Chemistry of Transition Elements

- Relevance of Chemistry in the real world through the themes of Environmental Sustainability and Materials: Real-world contexts are weaved into the narratives and learning experiences incorporating the two themes for the different topics can help to draw connections between concepts and everyday life, develop scientific literacy and enable learners to see the impact of chemistry on our society and environment. These contexts are broadly classified under the themes of Environmental Sustainability and Materials. These two interrelated themes are timely in view of climate change and the push for scientific innovation to address global needs and environmental challenges.

Narratives

Narratives describe the Core Ideas and the attendant concepts in a coherent manner. They highlight

- the connections within and across the three Core Ideas in chemistry,
- links between the Core Ideas and Extension Topics,
- links to unifying ideas that cut across science subjects, and
- connections to themes of Environmental Sustainability and Materials.

2.1 SYLLABUS NARRATIVE: THE H2 CHEMISTRY CURRICULUM

The H2 Chemistry curriculum provides students with the opportunity to appreciate the connections between the concepts in the Core Ideas of *Matter*, *Structure and Properties*, and *Transformation*, and to apply these to the study of different chemical systems in the *Extension Topics*. This is illustrated in the H2 Chemistry Content Map on the next page.

Chemistry is about the study of matter, its interactions and transformations. At a macroscopic level, we observe matter and its interactions everywhere in our daily life. The submicroscopic level looks at the structure of matter that gives rise to these interactions. At O-Level, students have been introduced to the fundamental idea that matter is made up of particles and the simple atomic model (electrons in discrete shells around a positively charged nucleus). This allows students to apply the key ideas of conservation of matter and energy in the quantitative treatment of reactions such as stoichiometry and thermochemistry.

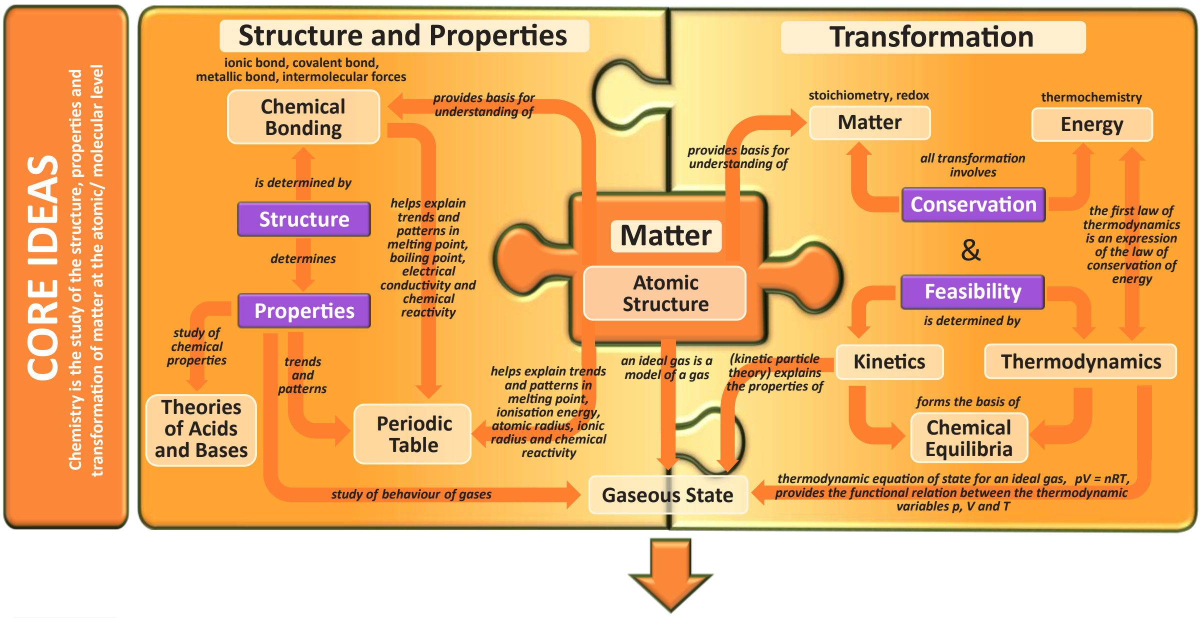
In H2 Chemistry, an in-depth study of the electronic structure of atoms provides the basis for the study of chemical bonding. The Valence Shell Electron Pair Repulsion (VSEPR) model is used to rationalise the three-dimensional structure of molecules, which determines the type of interactions possible and also helps to explain the physical and chemical properties. Knowledge of structure and bonding is also important to study and predict trends in properties of matter and its reactions. Modern organic chemistry is based on the concept that the four valence bonds of a carbon atom are oriented in a tetrahedral configuration, which led to the development of the stereochemical concept. This has important applications, particularly in the pharmaceutical industry as many drugs are active only in one particular enantiomeric form.

Transformation of matter involves the study of the feasibility and the extent of chemical reactions. Considerations of thermodynamics and kinetics account for the feasibility while an understanding in equilibrium explains the extent of chemical reactions. The chemical thermodynamics dimension builds upon prior knowledge of thermochemistry, mainly enthalpy changes (ΔH). Together with entropy changes (ΔS), a mathematical relationship is established which gives the true measure of the thermodynamics feasibility of a reaction – the Gibbs free energy (ΔG). For aqueous redox reactions, the more convenient notion of electrode potential (E) is used, and the resultant cell potential (E_{cell}) gives a measure of thermodynamics feasibility instead. The chemical kinetics facet of a reaction can be understood quantitatively by relating the rate of reaction to the concentration of reactants. The qualitative aspect which deals with the factors affecting rate of reactions will be covered based on the collision theory.

The concepts in chemical thermodynamics and kinetics will form the basis for the study of Chemical Equilibrium. Theoretically all reactions are reversible, and the notion of dynamic equilibrium will be introduced. The concept of equilibrium constant (K) gives a measure of the extent of a reversible reaction. Factors which determine the position of equilibrium will also be examined. Chemical equilibria involving aqueous acids and bases will be dealt with in greater depth, in view of the relevance and prevalence of these concepts which cuts across chemical systems.

Finally, the concepts of structure and bonding, thermodynamics and kinetics are combined and applied in the topics of Organic Chemistry and the Chemistry of Transition Elements. Apart from being major sub-disciplines in Chemistry in their own right, the latter topics contextualise the theoretical principles by providing a wealth of concrete examples of chemical transformations.

H2 Chemistry Content Map



EXTENSION TOPICS

Chemistry of Aqueous Solutions

- acid and base dissociation constant
- ionic product of water
- pH
- buffer solutions
- solubility product
- common ion effect

Organic Chemistry

- introduction (nomenclature, shapes, functional groups)
- isomerism (constitutional and stereoisomerism)
- organic reaction mechanisms (free-radical substitution, electrophilic addition, electrophilic substitution, nucleophilic addition, nucleophilic substitution), terminologies associated with organic reactivities
- functional group reactions (alkanes, alkenes, arenes, halogenoalkanes, halogenoarenes, alcohols, phenols, aldehydes, ketones, carboxylic acids, acyl chlorides, esters, amines, amides, amino acids, nitriles)

Electrochemistry

- standard electrode (redox) potentials
- standard cell potentials and their interpretation
- batteries and fuel cells
- factors affecting electrolysis
- the Faraday constant
- industrial applications of electrolysis

Chemistry of the Transition Elements

- general physical and characteristic chemical properties of the first row transition elements from Sc to Cu
- colour of complexes

2.2 CORE IDEA 1: MATTER

1. [H2] ATOMIC STRUCTURE

5th century BC	**Democritus**	Held that all matter is composed of the smallest indivisible bodies, called atoms (from Greek ἄτομον, atomon, i.e. 'uncuttable', 'indivisible')
4th century BC	**Aristotle**	Proposed a fifth element, aether, from which stars and planets were made, in addition to the four elements, earth, water, air and fire, described earlier by Empedocles
Middle Ages	**Alchemy**	Sought Aristotle's fifth element to effect the transformation of other base metals into precious gold; helped develop many apparatus and experimental techniques still in use today
1661	**Robert Boyle**	Referred to as 'The Father of Chemistry'; defined elements as substances which could not be broken down into nor formed from simpler substances
1774	**Antoine Lavoisier**	Discovered the law of conservation of mass; defined an element as a basic substance that could not be further broken down by the methods of chemistry
1704	**Isaac Newton**	Proposed a mechanical universe with small solid masses in motion
1805	**John Dalton**	Proposed that each element consists of atoms of a single, unique type, and that chemical compounds are formed by combinations of these atoms

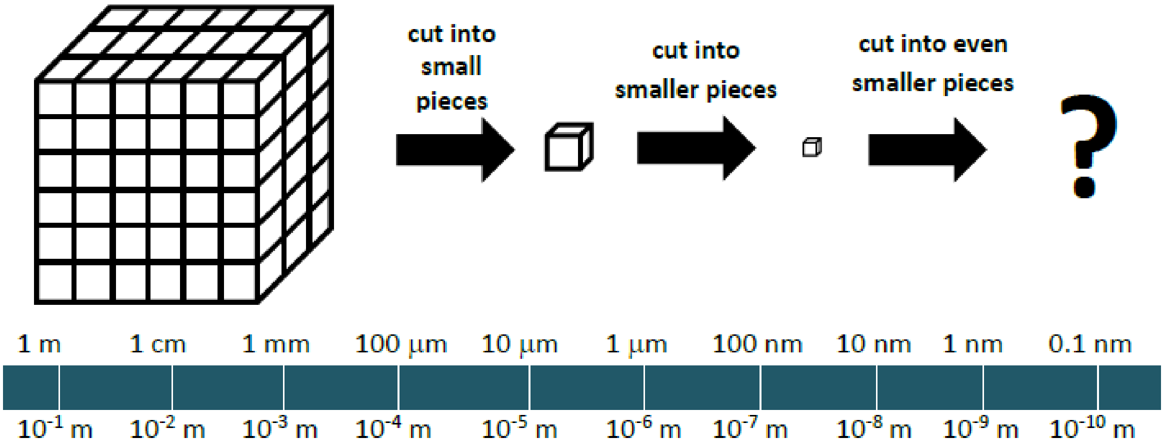
The development of atomic theory has come a long way since John Dalton's work, and our understanding of the nature of matter and the structure of atoms has deepened with the work of scientists such as J. J. Thompson, Ernest Rutherford, Niels Bohr, Louis de Broglie, Erwin Schrödinger and Werner Heisenberg, just to name a few.

Today, the atom is still a basic unit of matter and the current quantum mechanical model of an atom features a dense central nucleus comprising protons and neutrons, surrounded by a cloud of electrons, and we also know that although the electron is a true fundamental particle, the proton and neutron are themselves made up of more elementary particles known as quarks.

In this section, the structure of an atom will be explored for a more in-depth understanding. This forms the basis for subsequent understanding of chemical bonds that give rise to the variety of chemical structures that exhibit a range of physical and chemical properties. In all processes involving the forming and breaking of chemical bonds, matter is conserved – atoms are neither created nor destroyed.

Connections to theme of Materials

In Atomic Structure, we step into the “invisible” sub-microscopic world of materials (substances or matter) around us. There is a limit to which matter can be cut into smaller pieces before it loses its properties and chemical identity. The ancient Greeks used the word atoma (meaning indivisible units) to describe this smallest unit of matter. “Indivisibility” became a central concept of modern atomic theory where the smallest unit of matter that retains its chemical identity is called an atom. All materials around us, be it natural or artificial, are made up of atoms. Atoms are very small, with a diameter about 0.1 nanometer (nm). Atoms are too small to be seen directly through a microscope. Electron microscopes could be used to generate images of micro/nanostructures. The size of a material can influence its properties; properties of a material at nanoscale (generally defined as having a length $\leqslant$ 100 nm) can be very different from its corresponding bulk material at a larger scale dimension.



In this topic, we investigate the electronic structure of atoms, which influences the interactions between matter, as well as interactions between matter and electromagnetic radiation. You will find out more about the latter in H3 Chemistry, which builds on H2 Chemistry foundation on the understanding of discrete energy levels of electrons in an atom.

A simple appreciation of electromagnetic radiation and the interactions of electromagnetic radiation with matter would be useful in helping us explain phenomena in everyday life. There will be also opportunities in the extension topic on transition elements to explore the concept of why some compounds are coloured.

1. [H2] Atomic Structure

Guiding Questions

What makes up an atom?

How has the understanding of atomic structure developed and evolved?

What is the evidence showing that the electrons in an atom exist in discrete energy levels?

What do you understand by electronic configuration? How are the electrons arranged in the atoms of a given element?

How are the arrangement of an element's electrons and its position in the Periodic Table related?

Learning Outcomes

Students should be able to:

(a) identify and describe protons, neutrons and electrons in terms of their relative charges and relative masses

(b) deduce the behaviour of beams of protons, neutrons and electrons in an electric field

(c) describe the distribution of mass and charges within an atom

(d) deduce the numbers of protons, neutrons and electrons present in both atoms and ions given proton and nucleon numbers (and charge)

(e) (i) describe the contribution of protons and neutrons to atomic nuclei in terms of proton number and nucleon number
  (ii) distinguish between isotopes on the basis of different numbers of neutrons present

(f) describe the number and relative energies of the s, p and d orbitals for the principal quantum numbers 1, 2 and 3 and also the 4s and 4p orbitals

(g) describe the shapes of s, p and d orbitals (see also Section 13)
[knowledge of wave functions is **not** required]

(h) state the electronic configuration of atoms and ions given the proton number (and charge)

(i) explain the factors influencing the ionisation energies of elements (see the *Data Booklet*) (see also Section 5)

Learning Outcomes Students should be able to:	
(j)	deduce the electronic configurations of elements from successive ionisation energy data
(k)	interpret successive ionisation energy data of an element in terms of the position of that element within the Periodic Table

2.3 CORE IDEA 2: STRUCTURE AND PROPERTIES

[H2] CHEMICAL BONDING
[H2] THE GASEOUS STATE
[H2] THEORIES OF ACIDS AND BASES
[H2] THE PERIODIC TABLE

The concepts covered will provide students with the opportunity to appreciate how the structure of atoms determines the type of bonding and interaction that can take place, and use these concepts to observe and predict the patterns and trends in the chemical and physical properties of matter and its reactions.

The concept of the atomic structure provides the basis for the study of chemical bonding, which builds upon knowledge of how chemical bonds (e.g. ionic bonds, covalent bonds) are formed. By extending this knowledge into an understanding of the electrostatic nature of chemical bonds, this helps in viewing the classification of chemical bonds on a continuum rather than as discrete descriptions. This augments the understanding of intermolecular forces of attraction. The study of the three-dimensional structures of elements and/or their compounds and the types of interactions present explains their chemical and physical properties.

The chemical properties of acids and bases will be covered in greater depth with the introduction of Brønsted and Lewis's definitions of acids and bases. The study of the properties and behaviours of both ideal and real gases will focus on the use of the ideal gas equation to understand the relationship between the different variables (pressure, volume, amount and temperature).

The study of trends and patterns in the chemical and physical properties of elements in the Periodic Table is built upon prior knowledge of Period and Group trends acquired at the secondary science level.

Connections to themes of Environmental Sustainability and Materials

The interactions between matter resulted in a diversity of materials of different structures and properties. Observing patterns in reactivity and how the structure of a substance affects its properties can be useful for designing and synthesizing new materials.

In the past, people have designed materials to last for as long as they could. Reducing corrosion is important for safety as well as pragmatic purposes. For example, it is difficult to keep replacing rusty iron nails in the house. However, when materials are designed not to naturally degrade easily, they pose issues during disposal. So what factors must be considered when we design materials that can last for the duration of use, and yet can be degraded or recycled when they are no longer needed? Design principles for new materials no longer rest upon durability, but include careful considerations on sustainability, in particular biodegradability and recycling.

2. [H2] Chemical Bonding

Guiding Questions

What holds particles together?

What are the different models that describe the forces that hold particles together?

How do these models explain the properties of matter?

How do we determine the shapes of molecules?

Learning Outcomes

Students should be able to:

(a) show understanding that all chemical bonds are electrostatic in nature and describe:
  (i) ionic bond as the electrostatic attraction between oppositely charged ions
  (ii) covalent bond as the electrostatic attraction between a shared pair of electrons and positively charged nuclei
  (iii) metallic bond as the electrostatic attraction between a lattice of positive ions and delocalised electrons

(b) describe, including the use of 'dot-and-cross' diagrams,
  (i) ionic bonding as in sodium chloride and magnesium oxide
  (ii) covalent bonding as in hydrogen; oxygen; nitrogen; chlorine; hydrogen chloride; carbon dioxide; methane; ethene
  (iii) co-ordinate (dative covalent) bonding, as in formation of the ammonium ion and in the Al_2Cl_6 molecule

(c) describe covalent bonding in terms of orbital overlap (limited to s and p orbitals only), giving σ and π bonds (see also Section 11.1)

(d) explain the shapes of, and bond angles in, molecules such as BF_3 (trigonal planar); CO_2 (linear); CH_4 (tetrahedral); NH_3 (trigonal pyramidal); H_2O (bent); SF_6 (octahedral) by using the Valence Shell Electron Pair Repulsion theory

(e) predict the shapes of, and bond angles in, molecules analogous to those specified in (d)

(f) explain and deduce bond polarity using the concept of electronegativity [quantitative treatment of electronegativity is **not** required]

(g) deduce the polarity of a molecule using bond polarity and its molecular shape (analogous to those specified in (d))

(h) describe the following forces of attraction (electrostatic in nature):

Learning Outcomes
Students should be able to:

  - (i) intermolecular forces, based on permanent and induced dipoles, as in $CHCl_3(l)$; $Br_2(l)$ and the liquid noble gases
  - (ii) hydrogen bonding, using ammonia and water as examples of molecules containing –NH and –OH groups

(i) outline the importance of hydrogen bonding to the physical properties of substances, including ice and water

(j) explain the terms *bond energy* and *bond length* for covalent bonds

(k) compare the reactivities of covalent bonds in terms of bond energy, bond length and bond polarity

(l) describe, in simple terms, the lattice structure of a crystalline solid which is:
  - (i) ionic, as in sodium chloride and magnesium oxide
  - (ii) simple molecular, as in iodine
  - (iii) giant molecular, as in graphite and diamond
  - (iv) hydrogen-bonded, as in ice
  - (v) metallic, as in copper

[the concept of the 'unit cell' is **not** required]

(m) describe, interpret and/or predict the effect of different types of structure and bonding on the physical properties of substances

(n) suggest the type of structure and bonding present in a substance from given information

3. [H2] The Gaseous State

Guiding Questions

What is an ideal gas?

What conditions are needed for a gas to behave ideally?

What is the relationship between the pressure, volume, temperature and amount of a gas?

How do the individual components of a gas mixture contribute to the pressure of the mixture?

Learning Outcomes

Students should be able to:

(a) state the basic assumptions of the kinetic theory as applied to an ideal gas

(b) explain qualitatively in terms of intermolecular forces and molecular size:
  (i) the conditions necessary for a gas to approach ideal behaviour
  (ii) the limitations of ideality at very high pressures and very low temperatures

(c) state and use the general gas equation $pV = nRT$ in calculations, including the determination of M_r

(d) use Dalton's Law to determine the partial pressures of gases in a mixture (see also Section 9)

4. [H2] Theories of Acids and Bases

Guiding Questions

What are acids and bases?

What models can be used to classify substances as acids or bases?

Learning Outcomes

Students should be able to:

(a) show understanding of, and apply the Arrhenius theory of acids and bases

(b) show understanding of, and apply the Brønsted–Lowry theory of acids and bases, including the concept of conjugate acids and conjugate bases

(c) show understanding of, and apply the Lewis theory of acids and bases (including non-aqueous system e.g. reaction between BF_3 and NH_3)

5. [H2] The Periodic Table

Guiding Questions

What are the trends and variations in physical and chemical properties in elements and compounds?

How can the trends and variations in atomic, physical and chemical properties be explained?

How can we predict the properties of elements and their compounds?

Learning Outcomes

Students should be able to:

Trends and variations in atomic and physical properties

For elements in the third period (sodium to chlorine), and in Group 2 (magnesium to barium) and Group 17 (chlorine to iodine), students should be able to:

(a) recognise variation in the electronic configurations across a Period and down a Group

(b) describe and explain qualitatively the general trends and variations in atomic radius, ionic radius, first ionisation energy and electronegativity:
  (i) across a Period in terms of shielding and nuclear charge
  (ii) down a Group in terms of increasing number of electron shells, shielding and nuclear charge

(c) interpret the variation in melting point and in electrical conductivity across a Period in terms of structure and bonding in the elements (metallic, giant molecular, or simple molecular)

(d) describe and explain the trend in volatility of the Group 17 elements in terms of instantaneous dipole-induced dipole attraction

Trends and variations in chemical properties

For elements in the third period (sodium to chlorine), students should be able to:

(e) (i) state and explain the variation in the highest oxidation number of the elements in oxides (for Na_2O; MgO; Al_2O_3; SiO_2; P_4O_{10}; SO_3) and chlorides (for NaCl; $MgCl_2$; $AlCl_3$; $SiCl_4$; PCl_5)
  (ii) state and explain the variation in bonding in oxides and chlorides in terms of electronegativity (with the exception of $AlCl_3$)
  (iii) describe the reactions of the oxides with water (for Na_2O; MgO; Al_2O_3; SiO_2; P_4O_{10}; SO_3)
  (iv) describe and explain the acid/base behaviour of oxides (for Na_2O; MgO; Al_2O_3; SiO_2;

Learning Outcomes
Students should be able to:

P_4O_{10}; SO_3) and hydroxides (for NaOH; $Mg(OH)_2$; $Al(OH)_3$), including, where relevant, amphoteric behaviour in reaction with sodium hydroxide (only) and acids

(v) describe and explain the reactions of the chlorides with water (for NaCl; $MgCl_2$; $AlCl_3$; $SiCl_4$; PCl_5)

(vi) suggest the types of structure and bonding present in the oxides and chlorides from observations of their chemical and physical properties

For elements in Group 2 (magnesium to barium) and Group 17 (chlorine to iodine) students should be able to:

(f) describe and deduce from $E^{\ominus}$ values the relative reactivity of elements of:
  (i) Group 2 as reducing agents
  (ii) Group 17 as oxidising agents

(g) describe and explain the trend in thermal stability of:
  (i) Group 2 carbonates in terms of the charge density of the cation and the polarisability of the large anion
  (ii) Group 17 hydrides in terms of bond energies

In addition, students should be able to:

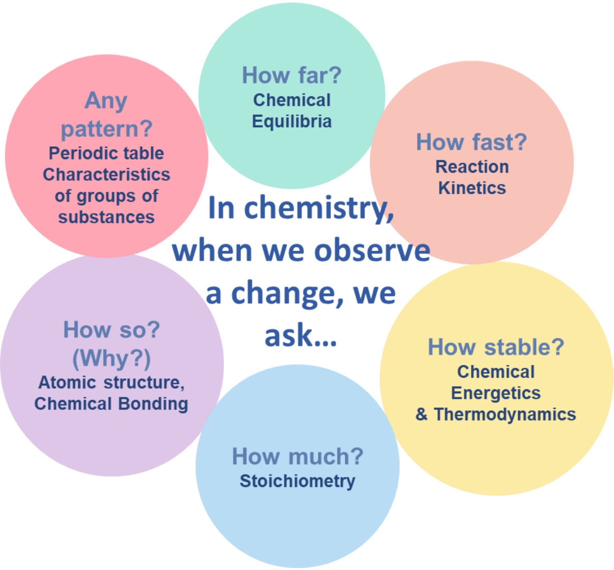
(h) predict the characteristic properties of an element in a given Group by using knowledge of chemical periodicity

(i) deduce the nature, possible position in the Periodic Table, and identity of unknown elements from given information of physical and chemical properties

2.4 CORE IDEA 3: TRANSFORMATION

[H2] THE MOLE CONCEPT AND STOICHIOMETRY
[H2] CHEMICAL ENERGETICS: THERMOCHEMISTRY AND THERMODYNAMICS (GIBBS FREE ENERGY AND ENTROPY)
[H2] REACTION KINETICS
[H2] CHEMICAL EQUILIBRIA

Why does water expand when it cools and turns into ice? How do instant heat packs and instant cold packs work? If a sentence written using an erasable pen is erased, would it be possible to reverse the process to see the sentence again? How do enzymes in laundry detergents remove dirt from clothes? Why can't such biological detergents be used in hot wash cycles in washing machines?



Transformation of matter involves a change in the chemical and/or physical properties of the substance. Chemical transformations involve the reorganisation or transfer of valence electrons among the reactants to form new substances. Physical transformations however, do not result in changes in the elemental composition of the substance, e.g. a change in physical state from a solid to liquid. In all transformations, matter and energy *must* be conserved. The conservation of matter is the basis of **stoichiometric** relationships in a balanced equation where atoms and charges are conserved. Not all transformations can be directly observed, though. While some changes can be observed at the macroscopic level (e.g. changes in colour, state, temperature, smell), others occur at the submicroscopic level without affecting the bulk properties of matter (e.g. processes in **dynamic equilibrium**). Also, not all transformation occurs within the timescale of observation; the rate of change (**kinetics**) needs to be considered. For example, the conversion of diamond to a more stable form, graphite, is so slow that it can never be observed within the life span of a human. Finally, the extent of the transformation will not be complete if the chemical or physical process is reversible. Changes in temperature, concentration or pressure, otherwise known as disturbances to the system, can affect the position of the **equilibrium** of the transformation.

Besides the characteristics of transformations, another fundamental question to ask is this: *Why do transformations take place at all?*

There are many examples in daily life in which changes occur and do not occur. The **structure and properties** of substances influence how they interact with each other and change, but do not guarantee that the change can take place. A deeper understanding involves **energy** as the key consideration for any transformation to take place.

Connections to themes of Environmental Sustainability and Materials

Humans have explored and exploited changes in **materials** around us for our own benefit ever since we mastered the art of starting and maintaining fire. **Thermal energy** is useful to accelerate and activate transformations that involved changes to the structure and properties of materials. However, no matter how hard ancient chemists (alchemists) worked on transmutation of base elements into precious metals (e.g. trying to convert lead into gold) by subjecting materials to intense heat and mechanical forces, none succeeded in their attempts. As alchemists continued their observations and experimentations on materials, they paved the way for modern chemistry and medicine, sometimes through serendipitous discoveries. Gradually, scientists gathered evidence that corroborated theories and laws involving the transformation of matter. For example,

- **Law of conservation of matter:** During any physical or chemical change, the total mass of the products remains equal to the total mass of the reactants.
- **Law of conservation of energy:** The total energy of an isolated system remains constant.

The law of definite proportion[16] and law of multiple proportions[17] paved the way for stoichiometry and mole concept.

Scientists ask many questions as they worked towards optimising processes for desired reactions to proceed quickly with good yield and lowest possible cost. However, as we improve our methods to transform materials into the useful products we desire, we need to consider that resources around us are finite. A **finite resource** is a material that exists in limited quantities that *cannot* be replaced within a short period of time after being used (e.g. fossil fuels). Scientists now need to ask different questions and take on multiple perspectives. They also need to consider that the process of transformation can generate other materials that are not needed, i.e. waste. When materials are changed from one form to another, this can disturb the state of equilibrium or **balance** in the world around us. Reversing some of these changes can be energetically costly, e.g. energy is required to split up water into hydrogen and oxygen gas.

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[16] A chemical compound contains the same elements chemically combined together in the same proportion by mass.

[17] When two elements chemically combine with each other to form two or more compounds, the ratios of the masses of one element that combines with the fixed mass of the other are simple whole numbers.

Example of questions to ask when taking on different perspectives:

Scientific lens:
- If I do this, what can happen?
- What should I do? *Could* I do this?

Moral lens:
- Do I want this to happen?
- What should I do? *Should* I do this?

We need to think about how we can **minimise the impact of our actions on the environment**. Some questions or issues we might wish to think about in the following topics:

- Should optimising percentage yield be the goal of chemical synthesis?
- How might the concept of Reduce, Reuse and Recycle (3Rs) be applied in Chemistry?
- What do we really mean when we say we have a global energy and natural resource crisis?
- What is the best method to increase the rate of a chemical reaction while being environmentally friendly?

6. [H2] The Mole Concept and Stoichiometry

Guiding Questions

What is a mole? Why is it important in chemistry?

What is the significance of a balanced equation?

How can the amount of reactants and products in a chemical reaction be determined?

Learning Outcomes

Students should be able to:

[the term relative formula mass or M_r will be used for ionic compounds]

(a) define the terms *relative atomic*, *isotopic*, *molecular* and *formula mass*

(b) define the term *mole* in terms of the Avogadro constant

(c) calculate the relative atomic mass of an element given the relative abundances of its isotopes

(d) define the terms *empirical* and *molecular formula*

(e) calculate empirical and molecular formulae using combustion data or composition by mass

(f) write and/or construct balanced equations

(g) perform calculations, including use of the mole concept, involving:
  (i) reacting masses (from formulae and equations)
  (ii) volumes of gases (e.g. in the burning of hydrocarbons)
  (iii) volumes and concentrations of solutions

[when performing calculations, students' answers should reflect the number of significant figures given or asked for in the question]

(h) deduce stoichiometric relationships from calculations such as those in (g)

7. [H2] Chemical Energetics: Thermochemistry and Thermodynamics (Gibbs Free Energy and Entropy)

Guiding Questions

What are the energy changes in a chemical or physical process?
Why do some chemical or physical processes take place spontaneously?
How can we predict if a process is spontaneous?
How can we measure or find the energy change in a chemical or physical process?

Learning Outcomes

Students should be able to:

(a) explain that most chemical reactions are accompanied by energy changes, principally in the form of heat usually associated with the breaking and forming of chemical bonds; the reaction can be exothermic (ΔH negative) or endothermic (ΔH positive)

(b) construct and interpret an energy profile diagram, in terms of the enthalpy change of the reaction and of the activation energy (see also Section 8)

(c) explain and use the terms:
  (i) *enthalpy change of reaction* and *standard conditions*, with particular reference to: formation; combustion; hydration; solution; neutralisation; atomisation
  (ii) *bond energy* (ΔH positive, i.e. bond breaking) (see also Section 2)
  (iii) *lattice energy* (ΔH negative, i.e. gaseous ions to solid lattice)

(d) calculate enthalpy changes from appropriate experimental results, including the use of the relationship:

$$\text{heat change} = mc\Delta T$$

(e) explain, in qualitative terms, the effect of ionic charge and of ionic radius on the numerical magnitude of a lattice energy

(f) apply Hess' Law to construct simple energy cycles, e.g. Born-Haber cycle, and carry out calculations involving such cycles and relevant energy terms (including ionisation energy and electron affinity), with particular reference to:
  (i) determining enthalpy changes that cannot be found by direct experiment, e.g. an enthalpy change of formation from enthalpy changes of combustion
  (ii) the formation of a simple ionic solid and of its aqueous solution
  (iii) average bond energies

(g) explain and use the term *entropy*

Learning Outcomes
Students should be able to:

(h) discuss the effects on the entropy of a chemical system by the following:
  (i) change in temperature
  (ii) change in phase
  (iii) change in the number of particles (especially for gaseous systems)
  [quantitative treatment is **not** required]

(i) predict whether the entropy change for a given process or reaction is positive or negative

(j) state and use the equation involving *standard Gibbs free energy change of reaction,* $\Delta G^{\ominus}$:

$$\Delta G^{\ominus} = \Delta H^{\ominus} - T\Delta S^{\ominus}$$

[the calculation of standard entropy change, $\Delta S^{\ominus}$, for a reaction using standard entropies, $S^{\ominus}$, is **not** required]

(k) state whether a reaction or process will be spontaneous by using the sign of $\Delta G^{\ominus}$

(l) understand the limitations in the use of $\Delta G^{\ominus}$ to predict the spontaneity of a reaction

(m) predict the effect of temperature change on the spontaneity of a reaction, given standard enthalpy and entropy changes

8. [H2] Reaction Kinetics

Guiding Questions

What do we mean by rate of reaction? How can we measure it?

What are the factors affecting rate? Why?

How can we determine and express the relationship between rate and concentration mathematically? How are the other factors affecting rate featured in this equation?

What can we infer about the mechanism of a reaction from the order of reaction? Why do many reactions not occur in a single step?

What are the general types of catalysts? How are they similar and how do their modes of action differ?

Learning Outcomes

Students should be able to:

(a) explain and use the terms: *rate of reaction*; *rate equation*; *order of reaction*; *rate constant*; *half-life of a reaction*; *rate-determining step*; *activation energy*; *catalysis*

(b) construct and use rate equations of the form rate = $k[A]^m[B]^n$ (limited to simple cases of single-step reactions and of multi-step processes with a rate-determining step, for which m and n are 0, 1 or 2), including:
  (i) deducing the order of a reaction by the initial rates method
  (ii) justifying, for zero- and first-order reactions, the order of reaction from concentration-time graphs
  (iii) verifying that a suggested reaction mechanism is consistent with the observed kinetics
  (iv) predicting the order that would result from a given reaction mechanism
  (v) calculating an initial rate using concentration data
  [integrated forms of rate equations are **not** required]

(c) (i) show understanding that the half-life of a first-order reaction is independent of concentration
  (ii) use the half-life of a first-order reaction in calculations

(d) calculate a rate constant using the initial rates method

(e) devise a suitable experimental technique for studying the rate of a reaction, from given information

(f) explain qualitatively, in terms of frequency of collisions, the effect of concentration changes on the rate of a reaction

Learning Outcomes
Students should be able to:

(g) show understanding, including reference to the Boltzmann distribution, of what is meant by the term *activation energy*

(h) explain qualitatively, in terms both of the Boltzmann distribution and of collision frequency, the effect of temperature change on a rate constant (and hence, on the rate) of a reaction

(i)
- (i) explain that, in the presence of a catalyst, a reaction has a different mechanism, i.e. one of lower activation energy, giving a larger rate constant
- (ii) interpret this catalytic effect on a rate constant in terms of the Boltzmann distribution

(j) outline the different modes of action of homogeneous and heterogeneous catalysis, including:
- (i) the Haber process
- (ii) the catalytic removal of oxides of nitrogen in the exhaust gases from car engines (see also Section 11.4)
- (iii) the catalytic role of atmospheric oxides of nitrogen in the oxidation of atmospheric sulfur dioxide
- (iv) catalytic role of Fe^{2+} in the $I^-/S_2O_8^{2-}$ reaction

(k) describe enzymes as protein molecules that act as biological catalysts with high specificity (in the reactions that they catalyse and in their choice of substrates as exemplified by the lock-and-key model), temperature sensitivity and pH sensitivity
[Knowledge of the levels of structure of proteins and the details of the denaturation process are **not** required.]

9. [H2] Chemical Equilibria

Guiding Questions

What are the characteristics of a system that has reached dynamic equilibrium? How can we describe such a system at equilibrium?
Why would systems tend towards a state of equilibrium?
What happens when a system at equilibrium is disturbed?
What are the factors to consider for optimal yield in a reversible reaction?

Learning Outcomes
Students should be able to:

(a) explain, in terms of rates of the forward and reverse reactions, what is meant by a *reversible reaction* and *dynamic equilibrium*

(b) state Le Chatelier's Principle and apply it to deduce qualitatively (from appropriate information) the effects of changes in concentration, pressure or temperature, on a system at equilibrium

(c) deduce whether changes in concentration, pressure or temperature or the presence of a catalyst affect the value of the equilibrium constant for a reaction

(d) deduce expressions for equilibrium constants in terms of concentrations, K_c, and partial pressures, K_p
[treatment of the relationship between K_p and K_c is **not** required]

(e) calculate the values of equilibrium constants in terms of concentrations or partial pressures from appropriate data

(f) calculate the quantities present at equilibrium, given appropriate data (such calculations will not require the solving of quadratic equations)

(g) describe and explain the conditions used in the Haber process, as an example of the importance of an understanding of chemical equilibrium in the chemical industry

2.5 EXTENSION TOPICS

[H2] CHEMISTRY OF AQUEOUS SOLUTIONS
[H2] ORGANIC CHEMISTRY
[H2] ELECTROCHEMISTRY
[H2] AN INTRODUCTION TO THE CHEMISTRY OF TRANSITION ELEMENTS

Concepts in the Core Ideas will extend into the learning of different chemical systems such as the chemistry of organic compounds and transition elements.

Since water is the most common solvent on Earth, there are many chemical reactions in the natural world that occur in aqueous solutions. Hence, it is important to explore aqueous chemical reactions in the topic of Chemistry of Aqueous Solutions. Some of the more important aqueous chemical reactions are acid-base, precipitation and complexation. This topic builds on students' understanding of the Theories of Acids and Bases (Core Idea 2: Structure and Properties), which is largely qualitative in nature, to a more quantitative approach to the understanding of acid-base Equilibria (Core Idea 3: Transformation). Precipitation reactions require both quantitative and qualitative understanding of dissolution and precipitation of sparingly soluble solids and the factors affecting these reactions (Core Idea 3: Transformation).

Connections to theme of Environmental Sustainability

This topic presents a good opportunity to delve deeper into ideas that cuts across science disciplines, and issues that threaten biodiversity and our existence.

Maintaining **balance**, where the system is in equilibrium or a steady state, is important in living things as well as ecosystems. **Diversity** is an important part of maintaining balance in the ecosystem. The variety of living and non-living things around us interact with one another. Interactions within and between **systems** meant that the fates of systems are intertwined.

Our everyday activities, for example from power generation, transport, agricultural practices, industries, contribute to anthropogenic CO_2 released to the environment. The rate of CO_2 emission is much greater than CO_2 removal through plants, even with reforestation efforts and improvements in technology. This is worrying as CO_2 is a greenhouse gas that contributes to enhanced global warming – the rise in global average temperature near the earth's surface. This is one of the leading causes of climate change.

How is this related to aqueous systems and the topics on acid-base and solubility equilibria? The rapid increase in atmospheric CO_2 disturbed the equilibrium of the carbon cycle, which inadvertently affected the acid-base equilibrium of our oceans – the largest aqueous system that covers more than 70% of earth's surface. Our oceans play a major role in regulating atmospheric carbon dioxide. The oceans, with pH about 8.2, absorb atmospheric CO_2 gas, which is acidic in nature. It has a natural buffering capacity, where the carbonate/hydrogencarbonate equilibria is sustained by calcium carbonate minerals in the deep ocean floor and marine organisms with shells or exoskeletons rich in calcium carbonate. The rapid increase in atmospheric concentration of CO_2 over the last 200 years (as well as warmer temperatures) has shifted the equilibrium. The pH of surface ocean waters has decreased by 0.1 pH units, which is about 30% increase in acidity[18]. Ocean acidification impacts the marine ecosystem adversely. This in turn affects humans and other animals who rely on the ocean for food. **So, what actions can we take to restore the equilibrium in our oceans?**

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[18] https://edu.rsc.org/feature/ocean-acidification/2020203.article

10. [H2] Chemistry of Aqueous Solutions

10.1 Acid-base Equilibria

This topic deals with acid-base equilibria in aqueous solution. Hence, the Brønsted–Lowry definitions of acid/base are primarily used in the understanding of the pH of solutions (See Section 4: Theories of Acids and Bases).

Learning Outcomes

Students should be able to:

(a) explain qualitatively the differences in behaviour between strong and weak acids and bases in terms of the extent of dissociation

(b) explain the terms pH; K_a; pK_a; K_b; pK_b; K_w and apply them in calculations, including the relationship $K_w = K_aK_b$

(c) calculate [$H^+(aq)$] and pH values for strong acids, weak monobasic (monoprotic) acids, strong bases, and weak monoacidic bases
[Calculations involving weak acids/bases will **not** require solving of quadratic equations]

(d) describe the changes in pH during acid-base titrations and explain these changes in terms of the strengths of the acids and bases

(e) explain the choice of suitable indicators for acid-base titrations, given appropriate data

(f) (i) explain how buffer solutions control pH
(ii) describe and explain the uses of buffer solutions, including the role of CO_3^{2-}/HCO_3^- in maintaining pH in oceans, and how the rapid increase in atmospheric carbon dioxide gas contributed to ocean acidification

(g) calculate the pH of buffer solutions, given appropriate data

10.2 Solubility Equilibria

Learning Outcomes

Students should be able to:

(a) show understanding of, and apply, the concept of solubility product, K_{sp}

(b) calculate K_{sp} from concentrations and *vice versa*

(c) discuss the effects on the solubility of ionic salts by the following:
  - (i) common ion effect
  - (ii) formation of complex ion, as exemplified by the reactions of halide ions with aqueous silver ions followed by aqueous ammonia (see also Section 13)

11. [H2] Organic Chemistry

What is Organic Chemistry?

Organic chemistry is the study of the structure, properties, composition, reactions and preparation of carbon-containing compounds, which include not only hydrocarbons (compounds containing carbon and hydrogen only) but also compounds with any number of other elements, such as nitrogen, oxygen, halogens, phosphorus, silicon and sulfur, in addition to hydrogen. It is one of the major branches of chemistry.

Carbon, with a ground state electronic configuration of $1s^2\ 2s^2\ 2p^2$, has four valence electrons (Core Idea 1: Matter) and is able to form single, double and triple bonds with a variety of other atoms. Carbon is also unique among the elements in its unsurpassable ability to self-link into chains or rings of different sizes, giving rise to the millions of organic compounds known.

History of Organic Chemistry

Like other branches of Science, the development of Organic Chemistry occurred over a long period of time, during which the knowledge acquired through observation is organised and rationalised using different theories and models.

Antiquity	**Romans and Egyptians**	Used organic chemicals in ancient times such as dyes, medicines and poisons from nature, although the chemical compositions were unknown. E.g. indigotin from the indigo and woad plants
1807	**Jöns Jakob Berzelius**	The first person to make the distinction between organic compounds (those containing carbon) and inorganic compounds. However, being a vitalist, he subscribed to the notion that 'all organic compounds can arise with the operation of vital force inherent to living cells'
1828	**Friedrich Wöhler**	Synthesised the organic compound, urea (H_2NCONH_2), fortuitously while heating the inorganic salt, ammonium cyanate (NH_4NCO)
1850s–1900s	**Pierre Eugène Marcellin Berthelot**	Showed that all classes of organic compounds could be synthesised
1858	**August Kekulé and Archibald Scott Couper**	Independently developed the valence theory of carbon for the understanding of structures in organic chemistry
1862	**Emil Erlenmeyer**	The first person to suggest that double and triple bonds could form between carbon atoms
1864	**Alexander Crum Brown**	The first person to draw ethene with the C=C unit to represent the double bond
1874	**Jacobus Henricus van't Hoff**	Accounted for the phenomenon of optical activity by assuming that the bonds around carbon atoms were arranged in a tetrahedral manner. Awarded the first Nobel Prize in Chemistry in 1901
1916	**Gilbert Newton Lewis**	Introduced the concept of a covalent bond formed by the sharing of a pair of electrons, and the formulation of the Lewis structure

The history of organic chemistry can be traced back to antiquity when medicine men extracted chemicals from plants and animals to treat their tribe members. Science was still unheard of then and they simply kept records of the useful properties and uses of things like willow bark, which was used as a painkiller. (It is now known that willow bark contains salicin, which can be converted to salicyclic acid and subsequently, acetylsalicyclic acid, the ingredient in aspirin.)

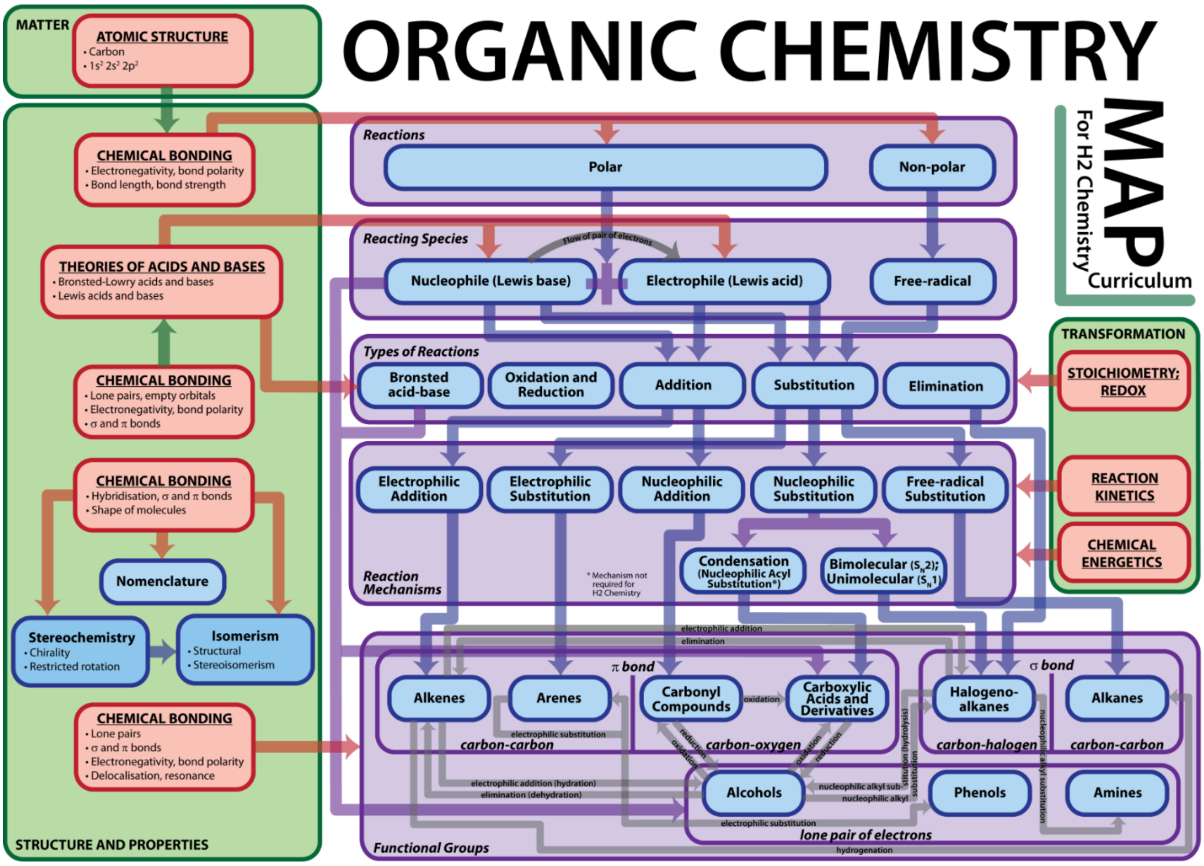
Organic chemistry was first made a branch of modern chemistry by Jöns Jakob Berzelius in the early 1800s. He classified chemical compounds into two main groups: those originating from living or once-living matter, which he termed **organic**, and those originating from mineral or non-living matter, which he termed **inorganic**. Berzelius, similar to most chemists of that era, believed that organic compounds could only come from living organisms mediated by some vital force, known as **vitalism**.

In 1828, Friedrich Wöhler discovered that the organic compound urea could be made by heating ammonium cyanate, an inorganic salt. This observation demonstrated for the very first time that an organic compound could be synthesised from an inorganic source, which led eventually to the rejection of vitalism as a scientific theory.

Wöhler's observation represents a milestone in the history of science for two reasons. First, it challenged the idea of vitalism. Second, this also marked the discovery of **isomerism** – the phenomenon of two or more different chemical structures (ammonium cyanate and urea) based on the same chemical formula (N_2H_4CO).
Chemists began their quest for ways to rationalise isomerism, which in turn led to theories pertaining to the structure and bonding of chemical compounds. By the 1860s, chemists like Kekulé and Couper separately published papers on relating the chemical formula of a compound to the ways the atoms are linked, that a carbon atom forms four bonds and carbon atoms can bond to one another. By the 1900s chemists like Lewis and Pauling developed models to understand the nature of the chemical bond, particularly the **covalent bond** for organic chemistry. The number of known organic compounds also increased exponentially throughout this time.

By the 20th century, organic chemistry has found applications in materials chemistry, pharmacology, chemical engineering and petro-chemistry, amongst many others. Millions of new substances were discovered or synthesised during this period, and today over 98% of all known compounds are organic.

Chemistry of the different functional groups.
The study of organic chemistry at the A-Level, as shown in the Organic Chemistry Map below, includes the **chemistry of the different functional groups** and understanding of the **general principles of organic reaction mechanisms**.



Functional groups are specific groups of atoms attached to a carbon backbone and they dictate the chemical and physical properties of molecules. These are also the sites of reactivity in organic compounds. For each of the functional groups, besides looking at the characteristic physical properties of the homologous series, synthetic methods to install the functional group in molecules will be examined. Characteristic reactions of the different functional groups will also be explored.

The reaction of one functional group lends itself to the construction of another functional group, and vice versa. The recognition of such functional group interconversion is invaluable to the study of organic chemistry. At the A-Level, most reactions involve the simple conversion of one functional group to another, which can usually be performed in either direction readily. For instance, secondary alcohols can be oxidised to give ketones, which can in turn be reduced back to secondary alcohols.

Good knowledge and understanding of the reactions of functional groups can be applied to the synthesis of desired molecular architectures and the structural elucidation of unknown compounds.

Strengthening understanding of organic chemistry through emphasising mechanistic principles

The characteristic reaction of each functional group can be understood in terms of the nature of the reacting species and the type of reaction involved, which are related to the **organic structure and bonding** (Core Idea 2: Structure and Properties), as can be seen in the Organic Chemistry Map. Mechanistically, most reactions in organic chemistry are **polar** in nature (with the exception of those involving free radicals), entailing the flow of pair(s) of electrons from a *nucleophilic*/Lewis basic (electron-rich) site to an *electrophilic*/Lewis acidic (electron-poor) site.

Specifically, the mechanisms of five of the general types of reactions will be discussed in detail, namely free-radical substitution (exemplified by alkanes), electrophilic addition (exemplified by alkenes), electrophilic aromatic substitution (exemplified by arenes), nucleophilic substitution (exemplified by halogenoalkanes) and nucleophilic addition (exemplified by carbonyl compounds), which can be understood on the basis of both kinetic and energetic considerations (Core Idea 3: Transformation).

Connections to themes of Environmental Sustainability and Materials

With the knowledge of Organic Chemistry, organic molecules that have specific structures and therefore, properties, can be designed and synthesised in the laboratory through careful control of the reagents and conditions used. An example of organic molecules whose properties have enabled their use in many applications as well as brought convenience and possibilities to our lives is plastics, a material that is part of a bigger class of organic compounds known as organic polymers.

Plastics are ubiquitous in our everyday life. They have the properties of being waterproof, lightweight, chemically inert, versatile, durable and are not easily biodegraded in the environment. In the food supply chain, the properties of plastics enable them to be used as food packaging which helps to extend shelf-life of food and which supports safe handling and distribution of food, thus contributing to minimising food wastage[19]. In the healthcare sector, plastics have contributed to improved hygiene such as in the form of sterile single-use materials like syringes and disposable face masks, amongst many other medical devices and uses[20]. Plastics are also components in electrical products such as mobile phones and laptops. Its lightweight property has also led to use of plastics in transportation, contributing to reduced carbon emissions[21].

However, plastic waste and their disposal, especially single-use plastics, has also led to growing environmental concerns such as pollution of oceans, posing a threat to marine lives

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[19] Dora, M., Iacovidou, E. (2019, June 27). Commentary: Why some plastic packaging is necessary. ChannelNewsAsia.

[20] Gibbens, S. (2019, October 4). Can medical care exist without plastic?. National Geographic. Retrieved 31 Dec 2024 from https://www.nationalgeographic.com/science/2019/10/can-medical-care-exist-without-plastic/

[21] Royal Society of Chemistry Materials Chemistry Division. (2019, April 24). Sustainable Plastics – the role of Chemistry. Retrieved October 18, 2020, from https://www.rsc.org/globalassets/04-campaigning-outreach/policy/environment-health-safety-policy/plastics-sustainability.pdf

and human health[22]. In addition, a major source of chemical feedstock to manufacture common plastics comes from crude oil, a finite resource[23].

Just as Chemistry has played a role in the development of plastics which improve our lives, Chemistry could play a part in mitigating the environmental consequences that arise from the use of plastics. These include designing biodegradable plastics, bio-based plastics or plastics that can be broken down at the end of its useful lifespan to recover its monomers to reuse. It can also include improving on the manufacturing processes to reduce materials and energy use, recycling plastics efficiently and ensuring safe degradation of plastic waste, such as using non-toxic reagents, amongst many other possibilities[24].

Organic Chemistry can collectively play a role in the design and synthesis of useful materials such as the plastics that we are familiar with, as well as alternative plastics that are easier to degrade, recycle or produce less toxic waste, thereby contributing to sustainability. For instance, the study of organic reaction mechanisms provides a foundation for understanding how polymers are formed and how they degrade in the natural environment. This can lead to the design and synthesis of plastics using suitable reagents and conditions to facilitate an environmentally friendly degradation method for plastics. This would also require a good understanding of organic reactions and the factors that influence reactivities of organic molecules, reactions, and mechanisms. How the properties of plastics can be controlled at the molecular level[25] also enables an appreciation of the role of structure in influencing the properties of matter (Core Idea 2: Structure and Properties).

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[22] Parker, L. (2024, Sept 24). The world’s plastic pollution crisis explained. National Geographic. Retrieved 31 Dec 2024 from https://www.nationalgeographic.com/environment/habitats/plastic-pollution/

[23] Millet, H., Vangheluwe, P., Block, C., Sevenster, A., Garcia, L., Antonopoulos, R. (2018). The Nature of Plastics and Their Societal Usage. In Harrison, R.M., Hester, R.E (Eds.) Plastics and the Environment (pp. 1-20). Royal Society of Chemistry

[24] The Royal Society of Chemistry. (2020). Science to enable sustainable plastics. A white paper from the 8th Chemical Sciences and Society Summit. rsc.li/progressive-plastics-report

[25] Morrison, R. T., Boyd, R. N. (1987). Macromolecules. Polymers and Polymerisation. In Organic Chemistry (pp. 1233-1260). Allyn and Bacon, Inc.

11.1 [H2] Introduction

Guiding Questions

What are organic compounds?
What are the main classes of organic compounds?
What determines the shapes of molecules?

Learning Outcomes

Students should be able to:

(a) interpret, and use the nomenclature, general formulae and displayed formulae of the following classes of compound:
  (i) hydrocarbons (alkanes, alkenes and arenes)
  (ii) halogen derivatives (halogenoalkanes and halogenoarenes)
  (iii) hydroxyl compounds (alcohols and phenols)
  (iv) carbonyl compounds (aldehydes and ketones)
  (v) carboxylic acids and derivatives (acyl chlorides and esters)
  (vi) nitrogen compounds (amines, amides, amino acids and nitriles)

(b) describe sp^3 hybridisation, as in ethane molecule, sp^2 hybridisation, as in ethene and benzene molecules, and sp hybridisation, as in ethyne molecule

(c) explain the shapes of, and bond angles in, the ethane, ethene, benzene, and ethyne molecules in relation to σ and π carbon-carbon bonds

(d) predict the shapes of, and bond angles in, molecules analogous to those specified in (c)

Students are expected to be able to interpret and use the following types of representations in the description of organic molecules. The examples given are for the compound (+)-lactic acid.

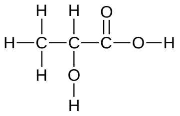
Empirical Formula : simplest ratio of the number of atoms of the elements present in one molecule, e.g. CH_2O

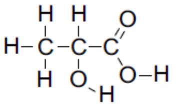
Molecular Formula : actual number of atoms of the elements present in one molecule, e.g. $C_3H_6O_3$

Structural Formula : shows how the constituent atoms of a molecule are joined together with minimal detail, using conventional groups, for an unambiguous structure, e.g. $CH_3CH(OH)CO_2H$

Full Structural or Displayed Formula : detailed structure of molecule showing the relative placing of atoms and the number of bonds between them,

e.g.

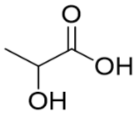




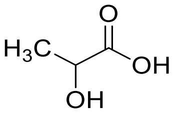
(Note: Where a benzene ring is part of the molecule, a displayed formula for benzene will not be expected to be drawn.)

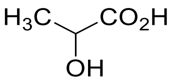
Skeletal Formula : simplified representation of an organic formula derived from the structural formula by removing hydrogen atoms (and their associated bonds) and carbon atoms from alkyl chains, leaving just the carbon-carbon bonds in the carbon skeleton and the associated functional groups.

Skeletal or partial skeletal representations may be used in question papers and are acceptable in students' answers where they are unambiguous, e.g.

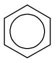


skeletal

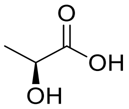




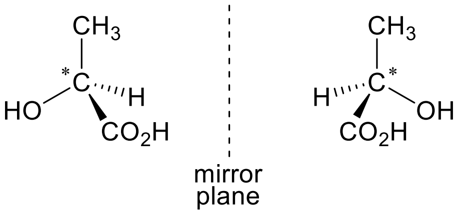
partial skeletal

The convention  for representing the aromatic ring is preferred.

Stereochemical Formula : show spatial arrangement of bonds, atoms and groups in a molecule in 3-D,

e.g. 

When drawing a pair of enantiomers, students should indicate the three-dimensional structures according to the convention used in the example below.



11.2 [H2] Isomerism

Guiding Questions

What is isomerism? What are the different types of isomerism?
What are the structural criteria for exhibition of the different types of isomerism?
How do the physical and chemical properties of different types of isomers differ?

Learning Outcomes

Students should be able to:

(a) describe constitutional (structural) isomerism

(b) describe *cis-trans* isomerism in alkenes, and explain its origin in terms of restricted rotation due to the presence of π bonds
[use of *E*, *Z* nomenclature is **not** required]

(c) explain what is meant by a chiral centre

(d) deduce whether a given molecule is chiral based on the presence or absence of chiral centres and/or a plane of symmetry

(e) recognise that an optically active sample rotates plane-polarised light and contains chiral molecules

(f) recognise that enantiomers have identical physical properties except in the direction in which they rotate plane-polarised light
[usage of the term diastereomers is **not** required]

(g) recognise that enantiomers have identical chemical properties except in their interactions with another chiral molecule

(h) recognise that different stereoisomers exhibit different biological properties, for example in drug action

(i) deduce the possible isomers for an organic molecule of known molecular formula

(j) identify chiral centres and/or *cis-trans* isomerism in a molecule of given structural formula

11.3 [H2] Organic Reactions and Mechanisms

Guiding Questions

What are some terms commonly used in the description of organic reactions and reactivities?
What are the main types of organic reactions?
What are the characteristics of common functional groups (electron-rich and electron-poor sites) in organic molecules and what type of reagents do they react with?
How do electrons flow in polar organic reactions?

Learning Outcomes
Students should be able to:

(a) interpret, and use the following terminology associated with organic reactions:
  (i) functional group
  (ii) degree of substitution: primary, secondary, tertiary, quaternary
  (iii) homolytic and heterolytic fission
  (iv) carbocation
  (v) free radical
  (vi) electrophile (Lewis acid), nucleophile (Lewis base)
  (vii) addition, substitution, elimination, condensation, hydrolysis
  (viii) oxidation and reduction
  [in equations for organic redox reactions, the symbols [O] and [H] are acceptable]

(b) interpret, and use the following terminology associated with organic reactivities:
  (i) delocalisation
  (ii) electronic effect (electron-donating and electron-withdrawing effect)
  (iii) steric effect (steric hindrance)

(c) explain the general unreactivity of alkanes, including towards polar reagents

(d) explain the general reactivity of alkenes towards electrophilic reagents/ electrophiles

(e) explain, in terms of delocalisation of π electrons, the difference between benzene and alkene:
  (i) reactivity towards electrophiles
  (ii) preference of benzene to undergo substitution rather than addition reaction

(f) interpret the different reactivities of halogenoalkanes, with particular reference to hydrolysis, and to the relative strengths of the carbon halogen bonds

(g) explain the unreactivity of chlorobenzene compared to halogenoalkanes towards nucleophilic substitution, in terms of the delocalisation of the lone pair of electrons on the halogen and steric hindrance

(h) explain the reactivity of carbonyl compounds towards nucleophilic reagents, such as hydrogen cyanide

(i) apply (a) and (b) to the understanding of mechanisms in terms of organic structure and bonding

(j) recognise that the mechanisms of polar reactions involve the flow of electrons from electron-rich to electron-poor sites

(k) describe the mechanism of free-radical substitution with particular reference to the initiation, propagation and termination reactions, exemplified by reaction of ethane with chlorine

(l) describe the mechanism of electrophilic addition in alkenes, using bromine (Br_2 (in CCl_4)) with ethene as an example

(m) (i) describe the mechanism of electrophilic substitution in arenes, using the mono-bromination of benzene as an example
(ii) describe the effect of the delocalisation of electrons in arenes in such reactions

(n) describe and explain the mechanisms of nucleophilic substitutions in halogenoalkanes:
(i) S_N1, in terms of stability of the carbocation intermediates
(ii) S_N2, in terms of steric hindrance in the halogenoalkanes

(o) describe the mechanism of the nucleophilic addition reactions of hydrogen cyanide with aldehydes and ketones

In each of the sections, 11.4 to 11.10, students will be expected to be able to predict the reaction products of a given compound in reactions that are chemically similar to those specified.

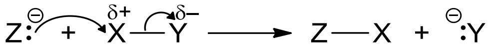
In their study of organic chemistry, students may wish to group the organic reactions in terms of the mechanisms in the syllabus where possible. Students may wish to compare and contrast the different mechanisms.

When describing preparative reactions, students will be expected to quote the reagents, e.g. aqueous NaOH, the essential practical conditions, e.g. reflux, high temperature and pressure, and the identity of each of the major products. Detailed conditions involving specific temperature and pressure values are **not** required.

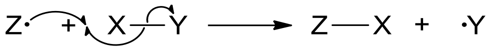
Detailed knowledge of practical procedures is also **not** required; however, students may be expected to suggest (from their knowledge of the reagents, essential conditions and products) what steps may be needed to purify/extract a required product from the reaction mixture. In equations for organic redox reactions, the symbols [O] and [H] are acceptable.

Students are expected to be able to interpret and use the curly arrow notation to represent the movement of electrons in organic reaction mechanisms.

For the movement of a *pair* of electrons (**full arrow**):



For the movement of a *single* unpaired electron (**half arrow**):



11.4 [H2] Hydrocarbons

Guiding Questions

Alkanes

Why are alkanes generally unreactive, particularly towards polar reagents? (see 11.3)

Which class of reagents do alkanes react with and why? (see 11.3)

What type of reactions do alkanes undergo and why?

How do alkanes react with halogens?

Alkenes

Which classes of reagents do alkenes react with and why? (see 11.3)

What types of reactions do alkenes undergo and why?

How do alkenes react with electrophiles?

What is the major product obtained when an unsymmetrical alkene reacts with hydrogen halide and why?

Arenes

How does the reactivity of benzene compare with that of alkene and why? (see 11.3)

Which class of reagents does benzene react with and why? (see 11.3)

What types of reactions does benzene undergo and why?

How does benzene react with an electrophile?

What types of reactions do the alkyl side-chains of arenes undergo and why?

How does the substituent on mono-substituted arenes determine the reactivity towards, and the substitution position of, an incoming electrophile?

Learning Outcomes

Students should be able to:

(a) describe the chemistry of alkanes as exemplified by the following reactions of ethane:
  (i) combustion
  (ii) free-radical substitution by chlorine and by bromine in the presence of ultraviolet light at room temperature (see also 11.3(c), 11.3(k))

(b) describe the chemistry of alkenes as exemplified, where relevant, by the following reactions of ethene:
  (i) electrophilic addition of steam ($H_2O(g)$ with H_3PO_4 catalyst), hydrogen halides ($HX(g)$) and halogens (X_2 (aq) or X_2 (in CCl_4)) (see also 11.3(d), 11.3(l))
  (ii) reduction via catalytic hydrogenation, using $H_2(g)$ and Ni catalyst (catalytic addition of hydrogen; see also 8(j))
  (iii) oxidation by cold, alkaline solution of manganate(VII) ions to form the diol

Learning Outcomes
Students should be able to:

  - (iv) oxidation by hot, acidified solution of manganate(VII) ions leading to the rupture of the carbon-to-carbon double bond in order to determine the position of alkene linkages in larger molecules

(c) apply Markovnikov's rule to the addition of hydrogen halides to unsymmetrical alkenes, and explain the composition of products in terms of the stability of carbocation intermediates

(d) describe the chemistry of the benzene ring as exemplified by the following reactions of benzene and methylbenzene (see also Section 4, 11.3(e) and 11.3(m)(i)):
  - (i) electrophilic substitution reactions with chlorine using $AlCl_3$ as catalyst and with bromine using $AlBr_3$ as catalyst (recognise the use of Lewis acid as catalysts)
  - (ii) nitration with a mixture of concentrated nitric acid and concentrated sulfuric acid, with the reaction mixture maintained at 30°C for methylbenzene and 50°C for benzene (recognise concentrated sulfuric acid as a Brønsted-Lowry acid catalyst)
  - (iii) Friedel-Crafts alkylation with halogenoalkanes using $AlCl_3$ or $AlBr_3$ as catalyst (recognise the use of Lewis acid as catalysts)

(e) describe the chemistry of the alkyl side-chain of benzene ring as exemplified by the following reactions of methylbenzene:
  - (i) free-radical substitution by chlorine and by bromine in the presence of ultraviolet light at room temperature
  - (ii) complete oxidation to give benzoic acid using hot alkaline $KMnO_4$ and then dilute acid, or using hot acidified $KMnO_4$

(f) predict whether halogenation will occur in the side-chain or aromatic nucleus in arenes depending on reaction conditions

(g) apply the knowledge of positions of substitution in the electrophilic substitution reactions of mono-substituted arenes

(h) recognise the environmental consequences of:
  - (i) carbon monoxide, oxides of nitrogen and unburnt hydrocarbons arising from the internal combustion engine and of their catalytic removal
  - (ii) gases that contribute to the enhanced greenhouse effect

11.5 [H2] Halogen Derivatives

Guiding Questions

Halogenoalkanes
How are halogenoalkanes synthesised?
Which classes of reagents do halogenoalkanes react with and why? (see 11.3)
What types of reactions do halogenoalkanes undergo and why?
How do halogenoalkanes react with nucleophiles? What are the factors that determine the mechanism of nucleophilic substitution?
How does the reactivity compare among different halogenoalkanes?

Halogenoarenes
How are halogenoarenes synthesised?
How does the reactivity of a halogenoarene compare with that of a halogenoalkane towards nucleophilic reagents? (see 11.3)

Learning Outcomes
Students should be able to:

(a) recall the chemistry of halogenoalkanes as exemplified by:
  (i) the following nucleophilic substitution reactions of bromoethane:
    - hydrolysis using NaOH(aq) and heat;
    - formation of nitriles using KCN in ethanol and heat;
    - formation of primary amines by reaction with ammonia in ethanol heated under pressure
  (ii) the elimination of hydrogen bromide from 2-bromopropane using NaOH in ethanol and heat

(b) explain the stereochemical outcome in nucleophilic substitution involving optically active substrates (see also 11.3 (n)):
  (i) inversion of configuration in S_N2 mechanism
  (ii) racemisation in S_N1 mechanism

(c) suggest characteristic reactions to differentiate between:
  (i) different halogenoalkanes (see also 11.3(f))
  (ii) halogenoalkanes and halogenoarenes (see also 11.3(g))
  e.g. hydrolysis, followed by testing of the halide ions

(d) explain the uses of fluoroalkanes and fluorohalogenoalkanes in terms of their relative chemical inertness

Learning Outcomes
Students should be able to:

(e) recognise the effect of chlorofluoroalkanes (CFCs) on the ozone layer, and that their proposed replacements, hydrofluoroalkanes (HFCs) and hydrochlorofluoroalkanes (HCFCs), have significant environmental impact too

[the mechanistic details of how CFCs and HCFCs deplete the ozone layer are **not** required]

11.6 [H2] Hydroxy Compounds

Guiding Questions

How are alcohols synthesised?
Which classes of reagents do alcohols react with and why? What types of reactions do alcohols undergo and why?
Which classes of reagents do phenols react with and why? What types of reactions do phenols undergo and why?
How does the reactivity of phenol compare to that of benzene towards electrophiles?
How do we compare the relative acidity of hydroxy compounds?

Learning Outcomes
Students should be able to:

(a) recall the chemistry of alcohols, exemplified by ethanol:
  (i) combustion
  (ii) nucleophilic substitution to give halogenoalkanes using hydrogen halides, HX or PCl_5
  (iii) reaction with sodium
  (iv) oxidation to
    - carbonyl compounds using acidified $K_2Cr_2O_7$, heat with distillation
    - carboxylic acids using primary alcohols, acidified $KMnO_4$ and heat (under reflux)
    - carboxylic acids using primary alcohols, acidified $K_2Cr_2O_7$ and heat (under reflux)
  (v) dehydration to alkenes using concentrated H_3PO_4 catalyst and heat

(b) suggest characteristic distinguishing reactions for the different classes of alcohols (primary, secondary and tertiary alcohols), e.g. mild oxidation

(c) deduce the presence of a $CH_3CH(OH)–$ group in an alcohol from its reaction with warm alkaline aqueous iodine to form tri-iodomethane

(d) recall the chemistry of phenol, as exemplified by the following reactions:
  (i) with bases
  (ii) with sodium
  (iii) nitration of the benzene ring (using dilute HNO_3) to form a mixture of 2-nitrophenol and 4-nitrophenol, and bromination of the benzene ring (using aqueous Br_2) to form 2,4,6-tribromophenol

Learning Outcomes Students should be able to:
(e) explain the relative acidities of water, phenol and ethanol in aqueous medium (interpret as Brønsted-Lowry acids)

11.7 [H2] Carbonyl Compounds

Guiding Questions

How are carbonyl compounds synthesised?
Which class of reagents do carbonyl compounds react with and why? What types of reactions do carbonyl compounds undergo and why?
How do carbonyl compounds react with HCN in nucleophilic addition?

Learning Outcomes
Students should be able to:

(a) describe the formation of aldehydes and ketones from, and their reduction to, primary and secondary alcohols respectively (using $LiAlH_4$, or using $H_2(g)$, Ni catalyst)

(b) describe the reactions of hydrogen cyanide (using KCN catalyst) with aldehydes and ketones (see also 11.3 (o))

(c) describe the use of 2,4-dinitrophenylhydrazine (2,4-DNPH) to detect the presence of carbonyl compounds

(d) deduce the nature (aldehyde or ketone) of an unknown carbonyl compound from the results of simple tests (i.e. warming in Fehling's and Tollens' reagents; ease of oxidation)

(e) deduce the presence of a $CH_3CO–$ group in a carbonyl compound from its reaction with warm alkaline aqueous iodine to form tri-iodomethane

11.8 [H2] Carboxylic Acids and Derivatives

Guiding Questions

Carboxylic acids
How are carboxylic acids synthesised?
What types of reactions do carboxylic acids undergo and why?

Acid derivatives
How are acyl chlorides and esters synthesised?
What types of reactions do acyl chlorides and esters undergo and why?
How does the ease of hydrolysis of acyl chlorides compare with that of alkyl and aryl chlorides?

How do we compare the acidity of organic compounds in aqueous medium?

Learning Outcomes
Students should be able to:

(a) describe the formation of carboxylic acids from
- primary alcohols using acidified $KMnO_4$ or acidified $K_2Cr_2O_7$, and heat (under reflux)
- aldehydes using acidified $KMnO_4$ or acidified $K_2Cr_2O_7$, and heat (under reflux)
- nitriles by heating with dilute acid (or dilute alkali followed by acidification)

(b) describe the reactions of carboxylic acids in the formation of:
   (i) salts via reaction with metals, alkalis or carbonates
   (ii) esters via condensation with alcohols (using concentrated H_2SO_4 catalyst and heat), using ethyl ethanoate as an example
   (iii) acyl chlorides via reaction with PCl_5, using ethanoyl chloride as an example
   (iv) primary alcohols, via reduction with $LiAlH_4$, using ethanol as an example

(c) explain the acidity of carboxylic acids and of chlorine-substituted ethanoic acids in terms of their structures

(d) describe the hydrolysis of acyl chlorides with water

(e) describe the condensation reactions of acyl chlorides with alcohols, phenols and primary amines

(f) explain the relative ease of hydrolysis of acyl chlorides, alkyl chlorides and aryl chlorides

Learning Outcomes

Students should be able to:

(g) describe the formation of esters from the condensation reaction of acyl chlorides, using phenyl benzoate as an example

(h) describe the acid and base hydrolysis of esters using aqueous acid (or aqueous alkali) and heat

11.9 [H2] Nitrogen Compounds

Guiding Questions

Amines
How are amines synthesised?
What types of reactions do amines undergo and why?

Phenylamines
How are phenylamines synthesised?
What types of reactions do phenylamines undergo and why?
What are the effects of the delocalisation of the lone pair of electrons on nitrogen of phenylamine into the benzene ring?

Amides
How are amides synthesised?
Why are amides neutral?
What types of reactions do amides undergo and why?

Amino acids
What are the properties of amino acids?
What types of reactions do amino acids undergo and why?

How do we compare the basicity of organic nitrogen compounds?

Learning Outcomes
Students should be able to:

(a) describe the formation of amines as exemplified by

- ethylamine through reduction of amide using $LiAlH_4$ and nitrile using $LiAlH_4$ or H_2(g), Ni catalyst
  (see also Section 11.5)
- phenylamine through the reduction of nitrobenzene using Sn and concentrated HC*l* with heating, followed by NaOH(aq)

(b) describe the reaction of amines in the formation of salts

(c) describe and explain the basicity of primary, secondary and tertiary amines in the gaseous phase (interpret as Lewis bases)

(d) explain the relative basicities of ammonia, ethylamine and phenylamine, in aqueous medium, in terms of their structures

Learning Outcomes

Students should be able to:

(e) describe the reaction of phenylamine with aqueous bromine

(f) describe the formation of amides from the condensation reaction between RNH_2 and $R'COCl$

(g) explain why an amide is neutral in terms of delocalisation of the lone pair of electrons on nitrogen

(h) describe the chemistry of amides, exemplified by the following reactions:
   (i) hydrolysis using aqueous acid (or aqueous alkali) and heat
   (ii) reduction to amines with $LiAlH_4$

(i) describe the acid/base properties of amino acids

11.10 [H2] Polymers

Guiding Questions

What are polymers?
How are polymers formed and what are their uses?
How does the structure of the polymer chain affect their biodegradability?

Learning Outcomes
Students should be able to:

(a) recognise polymers as macromolecules built up from monomers, with average relative molecular mass of at least 1000 or at least 100 repeat units

(b) classify and explain the difference between addition polymers (as exemplified by poly(alkenes)) and condensation polymers (as exemplified by polyesters and polyamides)

(c) describe proteins as an example of condensation polymers made up of α-amino acids as monomers, forming peptide (amide) bonds.

(d) describe the hydrolysis of proteins using aqueous acid (or aqueous alkali) and heat

(e) recognise that poly(alkenes) are chemically inert and can therefore be difficult to biodegrade (see also 11.3(c))

(f) recognise that polyesters and polyamides are generally biodegradable by hydrolysis (see also 11.8(h) and 11.9(h)(i))

(g) recognise that materials are a finite resource and the importance of recycling plastics, considering the economic, environmental and social factors

12. [H2] Electrochemistry

Electrochemistry involves the study of redox reactions, where electrode potential (E) and the resultant cell potential (E_{cell}) are used as measures of thermodynamic feasibility (Core Idea 3: Transformation). These redox reactions involve transfer of electrons, which would require understanding of concepts in Atomic Structure (Core Idea 1: Matter). In all these reactions, **matter** and **energy** are conserved (Core Idea 3: Transformation). Not all redox reactions are thermodynamically feasible; in electrolytic systems, energy needs to be provided to drive the redox reactions (Core Idea 3: Transformation).

Connections to themes of Environmental Sustainability and Materials

With the knowledge of electrochemistry, scientists were able to design **systems** that allow electron movement to **store and/or transfer energy** to drive reactions as well as power appliances and machines. The enhancement of desired properties of materials via electrochemical methods, such as corrosion resistant properties in anodised aluminium, have improved our daily lives significantly. Cells and batteries are examples of electrochemical cells that allow us to power our mobile devices, personal mobility devices (PMDs) etc. Whether it is the primary cells (single use cells such as alkaline batteries or button cells found in heart pace-makers), secondary cells (rechargeable ones such as the lead-acid cells found in car batteries or the lithium ion batteries found in your mobile phones) or fuel cells (e.g. hydrogen/oxygen fuel cells that have found uses in space shuttles and some electric vehicles), these electrochemical cells operate through redox reactions where exchange of electrons occurs as chemical reactions takes place.

While scientific knowledge allows us to create more useful materials from existing resources, we need to acknowledge that resources are finite and *cannot* be replaced within a short period of time after being used. For instance, we need to continually extract lithium to produce rechargeable lithium batteries[26] and these batteries have a limited lifetime. Eventually, they have to be disposed of in hazardous-waste landfills. Thus, we need to play our part in mitigating potential environmental consequences that arise because of our use of such materials. The next time before each purchase, you could ask yourself “Do I really need this?”. Pause, and consider whether you could reduce consumption, reuse/donate items that are still in working condition and recycle/repurpose items for better use[27,28].

With new challenges faced by the world from climate change, there are ongoing efforts to harness energy from alternative sources which are renewable or cleaner than burning fossil fuels. To help promote sustainable living, governments around the world are adopting cleaner and quieter transport system. Singapore is committed in the adoption for cleaner vehicles, as we observe from the changes in legislation, infrastructure, the rise of electric vehicle sharing services and the widening charging network in Singapore. How are electric vehicles

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[26] https://edu.rsc.org/resources/lithium-separation-mining-and-battery-power-11-14-years/4012765.article

[27] https://www.nea.gov.sg/our-services/towards-zero-waste

[28] https://www.nea.gov.sg/our-services/waste-management/3r-programmes-and-resources/e-waste-management

more environmentally friendly than vehicles that run on internal combustion engine? What limitations would there be in the implementation of electric vehicles? Are there other possible alternatives that can be a source of energy for the transportation sector?

As we continue to develop more advanced methods and technologies to improve our lives, we must also continue to remember the impact it has on the environment, in addition to other aspects such as safety to human health.

12. [H2] Electrochemistry

Guiding Questions

Electrochemical cell
What happens in a redox reaction?
How can the tendency of a substance to be reduced or oxidised be measured?
What are the factors affecting electrode potential?
How can the direction and feasibility of a redox reaction be predicted, and what are the limitations?

Electrolytic cell
What are the factors affecting the discharge of a substance during electrolysis?
How can we calculate the amount of substance liberated during electrolysis?
What are some industrial applications of electrolysis?
What are the differences between an electrochemical cell and an electrolytic cell?

Learning Outcomes
Students should be able to:

(a) describe and explain redox processes in terms of electron transfer and/or of changes in oxidation number (oxidation state)

(b) define the terms:
  (i) *standard electrode (redox) potential*
  (ii) *standard cell potential*

(c) describe the standard hydrogen electrode

(d) describe methods used to measure the standard electrode potentials of:
  (i) metals or non-metals in contact with their ions in aqueous solution
  (ii) ions of the same element in different oxidation states

(e) calculate a standard cell potential by combining two standard electrode potentials

(f) use standard cell potentials to:
  (i) explain/deduce the direction of electron flow from a simple cell
  (ii) predict the spontaneity of a reaction

(g) understand the limitations in the use of standard cell potentials to predict the spontaneity of a reaction

Learning Outcomes
Students should be able to:

(h) construct redox equations using the relevant half-equations (see also Section 13)

(i) state and apply the relationship $\Delta G^{\ominus} = -nFE^{\ominus}$ to electrochemical cells, including the calculation of $E^{\ominus}$ for combined half reactions

(j) predict qualitatively how the value of an electrode potential varies with the concentration of the aqueous ion

(k) state the possible advantages of developing other types of cell, e.g. the H_2/O_2 fuel cell and improved batteries (as in electric vehicles) in terms of smaller size, lower mass and higher voltage

(l) state the relationship, $F = Le$, between the Faraday constant, the Avogadro constant and the charge on the electron

(m) predict the identity of the substance liberated during electrolysis from the state of electrolyte (molten or aqueous), position in the redox series (electrode potential) and concentration

(n) calculate:
    (i) the quantity of charge passed during electrolysis
    (ii) the mass and/or volume of substance liberated during electrolysis

(o) explain, in terms of the electrode reactions, the industrial processes of:
    (i) the anodising of aluminium
    (ii) the electrolytic purification of copper
    [technical details are **not** required]

13. [H2] An Introduction to the Chemistry of Transition Elements

An understanding of the concepts in Atomic Structure (Core Idea 1: Matter), Chemical Bonding and The Periodic Table (Core Idea 2: Structure and Properties) and Reaction Kinetics and Chemical Equilibrium (Core Idea 3: Transformation) is extended to the study of the Chemistry of Transition Elements. In this topic, students will learn about the chemical and physical properties of the first-row transition elements and compare them with the main group metals.

Connections to themes of Materials and Environmental Sustainability

The understanding of the **structure and properties** of transition elements and their compounds has enabled scientists to harness them into useful **materials** in many industries (such as construction and medicine) as well as in our daily lives.

One example of the use of transition elements and their compounds is in catalysis. Catalytic processes have enhanced the economic viability of industrial applications because of its potential to improve **energy-efficiency**[29]. For instance, the use of iron as a catalyst in the Haber process has allowed the manufacture of ammonia to be economically feasible. Other than reducing energy demand, the role of catalysis has become increasingly more important especially in quest towards environmentally friendly practices and socioeconomic sustainable solutions, due to the use of less chemicals, which would otherwise generate more waste[30]. This has driven the concerns on their renewability and future availability, especially if the rates of their extraction were to increase in the future.

It should also be noted that some of these transition metals can also be toxic to humans and the environment if not handled properly during disposal. One possible way to mitigate this would be through toxic waste control management. Individuals can also do our part through recycling of e-waste as such waste can potentially contain these metals (See also topic on Electrochemistry).

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[29] Jacob R. Ludwig, Corinna S. Schindler, Catalyst: Sustainable Catalysis, Chem, Volume 2, Issue 3, 2017, Pages 313-316, ISSN 2451-9294, https://doi.org/10.1016/j.chempr.2017.02.014.

[30] Tabanelli, Tommaso, Daniele Cespi, and Raffaele Cucciniello. 2021. "Sustainable and Environmental Catalysis" Catalysts 11, no. 2: 225. https://doi.org/10.3390/catal11020225

13. [H2] An Introduction to the Chemistry of Transition Elements

Guiding Questions

What are transition elements?
What are the characteristic properties of transition elements? How are these properties similar or different from a typical s-block element?
Are there any trends/patterns in the properties of transition elements?
What are some examples/applications of transition elements/their compounds?

Learning Outcomes
Students should be able to:

For 1st set of transition elements from scandium to copper

(a) explain that a transition element is a d block element whose atom has an incomplete d subshell, or which can give rise to cations with an incomplete d subshell

(b) state the electronic configuration of a first row transition element and its ions (see also 1(h))

(c) explain why atomic radii and first ionisation energies of the transition elements are relatively invariant

(d) contrast, qualitatively, the melting point and density of the transition elements with those of calcium as a typical s block element

(e) describe the tendency of transition elements to have variable oxidation states

(f) predict from a given electronic configuration, the likely oxidation states of a transition element

(g) describe and explain the use of Fe^{3+}/Fe^{2+}, MnO_4^-/Mn^{2+} and $Cr_2O_7^{2-}/Cr^{3+}$ as examples of redox systems (see also Section 12)

(h) predict, using $E^{\ominus}$ values, the likelihood of redox reactions (see also 12f(ii))

(i) define the terms *ligand* and *complex* as exemplified by the complexes of copper(II) ions with water, ammonia and chloride ions as ligands
(including the transition metal complexes found in the Qualitative Analysis Notes)

(j) explain qualitatively that ligand exchange may occur, as exemplified by the formation

Learning Outcomes
Students should be able to:

of the complexes in (i), including the colour changes involved, and CO/O_2 exchange in haemoglobin

(k) describe, using the shape and orientation of the d orbitals, the splitting of degenerate d orbitals into two energy levels in octahedral complexes

(l) explain, in terms of d orbital splitting and d-d transition, why transition element complexes are usually coloured
[knowledge of the relative order of ligand field strength is **not** required]

(m) explain how some transition elements and/or their compounds can act as catalysts (see also 8(j))

SECTION 2C:
CONTENT FOR H3 CHEMISTRY

2C. CONTENT: H3 CHEMISTRY

The syllabus for H3 Chemistry builds on that for H2 Chemistry and includes the whole of the H2 Chemistry syllabus. Only content that is not already part of the H2 Chemistry syllabus is specifically set out here.

Students who offer H3 Chemistry should have a strong foundation in H2 Chemistry. They are also expected to tackle more sophisticated problems than students who only offer H2 Chemistry, especially because of the expanded scope.

Additional Content in H3 Chemistry and Themes

- The Additional Content in H3 complement the H2 curriculum with a stronger focus on applications.

Additional Content	Topics
1. Spectroscopic Techniques	1.1 Basic Principles of Spectroscopy 1.2 Ultraviolet/visible Spectroscopy 1.3 Infrared (IR) Spectroscopy 1.4 Nuclear Magnetic Resonance (NMR) Spectroscopy 1.5 Mass Spectrometry
2. Molecular Stereochemistry	2. Molecular Stereochemistry
3. Further Organic Mechanisms	3.1 Basic Physical Organic Chemistry 3.2 Nucleophilic Substitution 3.3 Elimination

- Relevance of Chemistry in the real world through the themes of Environmental Sustainability and Materials: Real-world contexts are weaved into the narratives and learning experiences incorporating the two themes for the different topics can help to draw connections between concepts and everyday life, develop scientific literacy and enable learners to see the impact of chemistry on our society and environment. These contexts are broadly classified under the themes of Environmental Sustainability and Materials. These two interrelated themes are timely in view of climate change and the push for scientific innovation to address global needs and environmental challenges.

Narratives

Narratives describe the Core Ideas and the attendant concepts in a coherent manner. They highlight

- the connections within and across the three Core Ideas in chemistry,
- links between the Core Ideas and Extension Topics,
- links to unifying ideas that cut across science subjects, and
- connections to themes of environmental sustainability and materials.

2.1 SYLLABUS NARRATIVE: THE H3 CHEMISTRY CURRICULUM

H3 Chemistry is built on H2 Chemistry, anchored by the three Core Ideas, *Matter*, *Structure and Properties* and *Transformation*. Throughout the study of H3 Chemistry, explicit links will be made to the Core Ideas, deepening students' understanding of their knowledge in these Core Ideas and the Practices of Science.

Spectroscopic Techniques, Molecular Stereochemistry and Further Organic Mechanisms have been chosen to complement the H2 curriculum with a stronger focus on applications. The additional content draws strong links to the core ideas and extension topics in H2 and meaningfully expands the content scope, providing the opportunity for students to apply relevant concepts and skills from H2 to tackle a more diverse range of problems. Students will engage in analysis, synthesis and integration of concepts for a wider and deeper appreciation and understanding of the discipline of chemistry.

2.2 ADDITIONAL CONTENT 1: SPECTROSCOPIC TECHNIQUES

1. [H3] SPECTROSCOPIC TECHNIQUES

Spectroscopy involves the study of the interaction between matter and electromagnetic radiation. While we are unable to "see" matter at the atomic level, spectroscopy provides a method for the structural identification of organic and inorganic compounds. There are various spectroscopic techniques involving electromagnetic radiation of different frequencies. Spectroscopy is widely used in modern research and its applications span across all fields of science and society.

The study of spectroscopy will broaden students' perspective on analytical chemistry – the branch of chemistry that looks into methods for determining the structure, chemical composition, or purity of matter. Analytical methods can range from qualitative (obtaining information about the identity of the atomic or molecular species, or the functional groups in the sample) to quantitative (obtaining numerical information as to the relative amount of one or more of the components in the sample).

Spectroscopy is a natural extension of H2 Chemistry, providing complementary methods of qualitative and quantitative analysis to the classical wet-lab methods that students encounter in H2 Chemistry. For example, qualitative methods include identification of unknown ions or compounds by qualitative analysis, separation by precipitation, crystallisation, distillation, extraction or chromatography. Quantitative methods include gravimetric and titrimetric methods. The introduction of spectroscopy helps to expand the problem space, building on students' knowledge across the core ideas (matter, structure and properties, transformation – kinetic monitoring) and extension topics (organic chemistry, transition elements).

How spectroscopy is relevant to students

In modern day chemistry, advancements in technology have led to new instrumental methods that allow for greater precision, sensitivity, selectivity, and speed of analysis. Chemical analysis could also be performed with a smaller sample size and some methods are also non-destructive. This is useful when there are limited samples (e.g. from a crime scene[31]) or if the sample is rare (e.g. an art piece[32]). Generally, there should be sufficient analyte concentration present to produce an analytical signal that can reliably be distinguished from "analytical noise," the signal produced in the absence of analyte[33]. Classical methods are useful when

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[31] Find out more about forensic science and medicine from the Health Sciences Authority website: https://www.hsa.gov.sg/about-us/applied-sciences

[32] Read about how science can help in art and conservation research at the Netherlands Institute for Conservation, Art and Science: http://www.nicas-research.nl/

[33] D. A. A. and T.Pry (2008). Limit of Blank, Limit of Detection and Limit of Quantitation. Clin Biochem Rev., Aug; 29(Suppl 1): S49–S52.
Retrieved from: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2556583/

the analyte concentration is high, but instrumental techniques will be more appropriate for lower analyte concentration.

Students should appreciate that while these new instrumental techniques are convenient and accurate; the role of the scientist has not been relegated to a “machine operator”. A single spectrum usually does not provide sufficient information, and a combination of analytical methods is often employed for structural elucidation. The scientist has to play a critical role in terms of selecting the appropriate analytical methods based on the context. Following that, the data has to be analysed and interpreted, and various bits of information have to be fitted together to obtain a conclusion about the nature of the substance.

The inclusion of this topic aims to give students insight into the physical background of spectroscopic techniques, and the skills to interpret various spectra. Students will be expected to justify their conclusions based on the spectra and other provided information through reasoning and logical argument.

Connections to theme of Environmental Sustainability

The study of spectroscopic techniques presents a good opportunity to delve into ideas which cut across science disciplines, and issues that threaten biodiversity and our existence. For example, expanding upon ideas from the H2 curriculum, students are challenged to consider the role which polyatomic gases play in the greenhouse effect, in terms of their infrared absorption and deepen their thinking from an environmental perspective.

1.1 [H3] Basic Principles of Spectroscopy

Learning Outcomes

Students should be able to:

(a) understand basic molecular orbital (MO) theory, involving:
  (i) atomic and molecular orbitals
  (ii) bonding, anti-bonding and non-bonding orbitals
  (iii) molecular orbitals with σ and π symmetry

(b) understand that molecular orbitals represent discrete electronic energy levels in molecules [see also 1.1 e(ii)]

(c) apply linear combination of atomic orbitals (LCAO) principles to obtain the shape and relative energies of molecular orbitals in the following:
  (i) simple homonuclear diatomic molecules such as H_2, O_2, and F_2
  (ii) benzene and linear polyenes (molecular orbitals of π symmetry only)
  [quantitative treatment of LCAO is **not** required]

(d) construct and interpret molecular orbital diagrams, and identify the highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) for the following:
  (i) simple homonuclear diatomic molecules such as H_2, O_2, and F_2
  (ii) benzene and linear polyenes (molecular orbitals of π symmetry only)
  [knowledge of orbital mixing between orbitals of the same symmetry is **not** required]

(e) understand the following in relation to the fundamental principles of spectroscopy:

  (i) properties of electromagnetic radiation
  - the electromagnetic spectrum (with range of wavelengths for different types of radiation used in spectroscopy)
  - the photon as a discrete packet (quantum) of electromagnetic energy
  - the relationship between wavelength, frequency and speed of light, including the use of the equation, $E = hf$

  (ii) the quantisation of energy in relation to
  - electronic, vibrational and rotational energy levels
  - nuclear energy levels in applied magnetic field

  (iii) energy level transitions associated with the absorption and emission of photons with energy matching the energy gap

1.2 [H3] Ultraviolet/visible Spectroscopy

Learning Outcomes

Students should be able to:

(a) explain that ultraviolet/visible absorption in organic molecules requires electronic transitions ($\sigma \rightarrow \sigma^*$, $n \rightarrow \sigma^*$, $\pi \rightarrow \pi^*$, $n \rightarrow \pi^*$ transitions; forbidden and allowed transitions) between energy levels in chromophores which contain a double or triple bond, a delocalised system, or a lone pair of electrons

[detailed knowledge of instrumentation is **not** required]

(b) predict whether a given organic molecule will absorb in the ultraviolet/visible region by identifying the chromophore

(c) explain qualitatively how increasing conjugation in an organic molecule decreases the gap between energy levels and hence shifts the absorption towards longer wavelength

(d) use the Beer-Lambert Law, absorbance = $\lg(I_o/I) = \varepsilon c l$, where ε is taken merely as a constant characteristic of the substance concerned, to calculate the concentration of a given species (either organic or inorganic) in solution

(e) apply ultraviolet/visible spectroscopy to quantitative analysis of a given species (either organic or inorganic) in solution

1.3 [H3] Infrared (IR) Spectroscopy

Learning Outcomes

Students should be able to:

(a) explain the origin of IR spectroscopy in simple molecules in terms of:
  (i) stretching vibrations
  (ii) bending vibrations
  [detailed knowledge of instrumentation is **not** required]

(b) predict the number of IR absorptions for a given simple molecule (e.g. CO_2 or SO_2), and identify the molecular vibrations which give rise to them

(c) identify characteristic IR absorptions in the IR spectrum of a compound which may contain different functional groups
  [absorptions of common functional groups will be provided in the *Data Booklet*]

(d) suggest structures for a compound from its IR spectrum

(e) predict the characteristic IR absorptions that will be present in the IR spectrum of a compound, given its structure

(f) describe qualitatively, in terms of their IR absorption, the role of polyatomic gases (e.g. CO_2, H_2O, CHF_3) in the greenhouse effect

1.4 [H3] Nuclear Magnetic Resonance (NMR) Spectroscopy

Learning Outcomes

Students should be able to:

(a) outline the basic principles of NMR with reference to:
  (i) nuclear spin
  (ii) the process of absorption of energy
  [quantitative calculations of transitional energy are **not** required; detailed knowledge of instrumentation is **not** required]

(b) understand the following features and use them in the interpretation and prediction of ^1H NMR spectra:
  (i) chemical shift
  (ii) deuterated solvents in the identification of labile protons
  (iii) the number of ^1H NMR signals: equivalent and non-equivalent protons
  (iv) peak area (integration) and proton counting
  (v) spin-spin splitting: first order spin-spin coupling; multiplicity

(c) explain the use of the δ scale with tetramethylsilane (TMS) as the reference

(d) explain the factors affecting chemical shift
  (i) electronegativity: inductive effect of substituents, including shielding and deshielding effects
  (ii) anisotropic effects
  (iii) hydrogen bonding

1.5 [H3] Mass Spectrometry

Learning Outcomes

Students should be able to:

(a) outline the basic principles of mass spectrometry, with reference to:
  (i) ionisation and fragmentation
  (ii) mass/charge ratio, *m/z*
  [detailed knowledge of instrumentation is **not** required]

(b) understand the following features and use them in the interpretation and prediction of mass spectra:
  (i) molecular ion peak
  (ii) isotopic abundances including the use of (M+1) peak caused by ^{13}C and (M+2) and (M+4) peaks for the identification of halogen compounds
  (iii) major fragment ions
  [fragment ions obtained from rearrangements are **not** included]

2.3 ADDITIONAL CONTENT 2: MOLECULAR STEREOCHEMISTRY

[H3] MOLECULAR STEREOCHEMISTRY

Stereochemistry involves studying the static and dynamic aspects of three-dimensional shapes of molecules, and provides a foundation for understanding structure and reactivity. This topic serves to deepen and broaden the understanding of stereochemistry through introducing alternative symbolic representations and various ways of classification and naming molecules. Students can also appreciate how stereochemistry is useful in probing reaction mechanisms, and be able to relate to it in different contexts, including inorganic molecules and biological systems.

2. [H3] Molecular Stereochemistry

Learning Outcomes

Students should be able to:

(a) (i) use stereochemical projections, including Newman projections, to represent molecules

(ii) interpret stereochemical projections of molecules

[knowledge of Fischer projections is **not** required]

(b) apply their understanding of the following types of isomerism to explain the stereochemistry of molecules, including saturated ring systems:

(i) conformational isomerism, including energy barriers to rotation and interconversion

(ii) *cis-trans* isomerism, including *E, Z* nomenclature

(iii) enantiomerism and diastereomerism

- *R*, *S* configuration
- optical activity
- optical purity as the excess of one enantiomer, including calculation of optical purity by the equation:

$$\text{optical purity} = \frac{[\alpha]_{\text{obs}}}{[\alpha]_{\text{pure material}}} \times 100\%$$

(c) recognise that transition element complexes can also exhibit stereoisomerism:

(i) *cis-trans* isomerism, e.g. square planar complexes such as $[Pt(NH_3)_2Cl_2]$ and octahedral complexes such as $[Co(NH_3)_4(H_2O)_2]^{2+}$

(ii) enantiomerism, e.g. $[Ni(H_2NCH_2CH_2NH_2)_3]^{2+}$ and $[Ni(H_2NCH_2CH_2NH_2)_2(H_2O)_2]^{2+}$

[Identification of fac-mer isomerism is **not** required.]

2.4 ADDITIONAL CONTENT 3: FURTHER ORGANIC MECHANISMS

[H3] FURTHER ORGANIC MECHANISMS

Further organic mechanisms involve studying the relationships between structure, bonding and reactivity in organic systems, leading to the quantitative, molecular level understanding of their properties. Further organic mechanisms serve as a meaningful link between the concepts of energetics and kinetics from the core idea of 'Transformation', and chemical bonding from the core idea of 'Structure and Properties'. It also enhances the bridging of the traditional 'physical chemistry' and 'organic chemistry' divide. Building on students' knowledge from H2 Chemistry, this expands the problem space meaningfully and introduces more complexities to the problems to be analysed.

As such, students can reflect on the practices of science and better appreciate the rigour of scientific research, which contributes to the accumulation of scientific knowledge today. The fundamental linkage between structure and reactivity also has clear links to other applications in bioorganic chemistry, organometallic chemistry and material science, and is relevant to modern research approaches such as developing electronic organic materials and optimising enzymatic reactions.

3.1 [H3] Basic Physical Organic Chemistry

Learning Outcomes Students should be able to:
(a) understand and apply the Hammond postulate to the study of reaction mechanisms

3.2 [H3] Nucleophilic Substitution

Learning Outcomes Students should be able to:
(a) explain how the relative rate of nucleophilic substitution is affected by the nature of the: (i) nucleophile (ii) leaving group (iii) substituents
(b) describe and compare the mechanisms and kinetics of S_N1 and S_N2 reactions, in terms of: (i) the energy profile and rate law, including steady state approximation in S_N1

Learning Outcomes

Students should be able to:

[mathematical treatment of steady state is **not** required]
  (ii) stereochemistry, including ion pair interactions in S_N1
  (iii) substituent effects

(c) explain the factors affecting competition between S_N1 and S_N2 mechanisms
[solvent effects are **not** required]

3.3 [H3] Elimination

Learning Outcomes

Students should be able to:

(a) understand and apply the following concepts to the study of elimination reactions:
  (i) syn- and anti-elimination; and its effect on stereoselectivity
  (ii) regioselectivity: Zaitsev (thermodynamic) and Hofmann (kinetic) product(s)

(b) describe and compare the mechanisms and kinetics of E1 and E2 reactions, in terms of:
  (i) the energy profile and rate law
  (ii) regioselectivity

(c) explain the E2/S_N2 competition, in terms of
  (i) substrate effects
  (ii) base effects

SECTION 3:
PEDAGOGY

3. PEDAGOGY

3.1 INSPIRING STUDENTS THROUGH PEDAGOGICAL PRACTICES

Pedagogy is the intentional practice of teaching informed by educational theories, research and practice. They refer to classroom strategies, teaching actions and teacher-student interactions to help students learn and achieve the outcomes of the curriculum. It is guided by our core beliefs about teaching and learning as articulated in the Singapore Curriculum Philosophy.

Teachers are key in facilitating a variety of learning experiences, drawing on the *Knowledge Bases* and adopting the *Pedagogical Practices*, as described in the *Singapore Teaching Practice* (*STP*). Apt use of pedagogies considering student profile and the nature of the lesson can help our students develop 21CC and work towards the realisation of MOE's Desired Outcomes of Education (DOEs).

3.2 PRACTICAL WORK AS AN INTEGRAL PART OF SCIENCE LEARNING

The excitement of scientific investigation brings to life the theory and underpinning knowledge of many fundamental scientific concepts,[34] as they link the domain of observables and objects to the domain of scientific ideas (see **Table 3.1**).[35]

Table 3.1: Linking the domains of "observables" & "scientific ideas" through practical work

N	Type of Practical	A	P	Main Learning Objective
1	**Modelling** experiment (Model Development)	I	✓	Modelling a physical phenomenon
2	**Planning** (and doing) experiment	I	-	Planning (and conducting) an investigation
3	**Design Challenge** (Model Deployment)	D	-	Solving a problem or challenge given a physical setup
4	**Confirmatory** Experiment	D	✓	Practicing procedures & Confirming theory

A: Approach; P: Procedure; I: Inductive; D: Deductive

Depending on students' readiness and learning objectives, the level of inquiry in a science practical lesson can vary in terms of degree of complexity (see **Table 3.2**). An activity can be inquiry-based when students conduct the analysis and draw their own conclusions or design their own solutions. Scaffolding for students is instrumental in helping them advance their competencies in scientific inquiry, e.g. they could start from structured inquiry before

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[34] Holman, J. (2009). Good Practical Science. Gatsby Foundation.

[35] Millar, R., & Abrahams, I. (2009). Practical work: making it more effective. *School Science Review, 91(334)*, 59

progressing to higher levels of inquiry such as open-ended investigations. In such cases, students are required to design all or part of the experimental procedures, decide on what data to record, analyse and interpret the data on their own. This encourages greater autonomy and deeper practices of science in students.

Table 3.2: Continuum of strategies in terms of amount of information given to the student[36]

Degree of complexity	**How much information is given to the student?**		
	Question?	**Methods?**	**Solution?**
Level 4 Open Inquiry *(Student formulates questions and designs experimental procedures)*	×	×	×
Level 3 Guided Inquiry *(Student designs or selects the experimental procedures)*	✓	×	×
Level 2 Structured Inquiry *(Teachers prescribed the experimental procedures)*	✓	✓	×
Level 1 Confirmation *(Results are known in advance)*	✓	✓	✓

In practical work, students learn to address challenges inherent in observing the physical world, including troubleshooting equipment used to make observations. The use of graphing software (e.g. Excel spreadsheets) allows convenient visualisation and analysis of data. Planning and conducting their mini-investigative projects individually or in small groups also provide many opportunities for students to harness digital tools in the process of recording data, analysing results, and presenting their findings.

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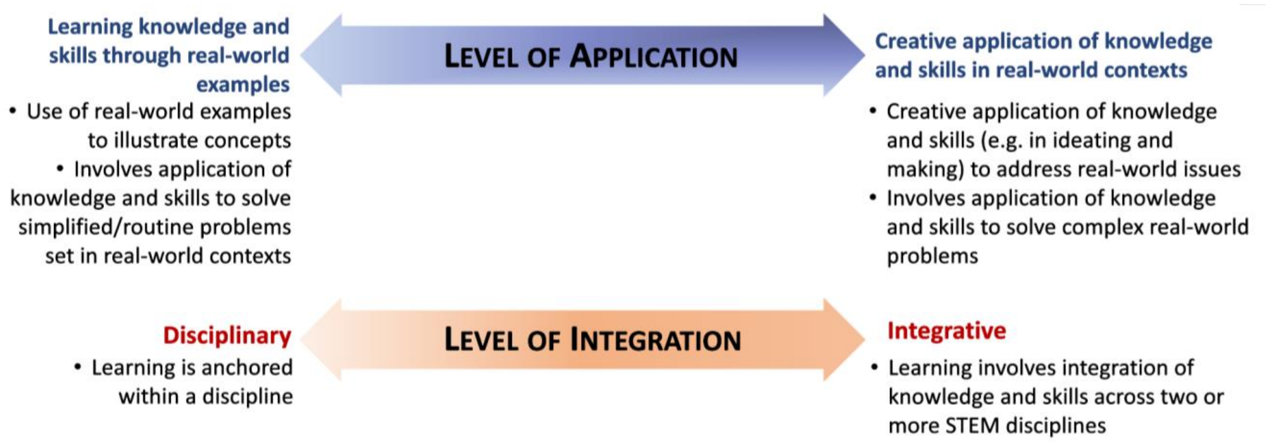
[36] Adapted from Bell, R. L., Smetana, L., & Binns, I. (2005). Simplifying inquiry instruction. *The Science Teacher*, 72(2), 30–33

3.3 SCIENCE LEARNING BEYOND THE BOUNDARIES THROUGH STEM LES

Given how scientists work in areas where subject boundaries are becoming more blurred and interdisciplinary work is increasing important, it would be helpful to teach and learn science that allow students to apply science in real-world contexts and to make connections to other subjects. The design of STEM LEs could be unpacked at two levels along a continuum: 1) level of application and 2) level of integration (see **Figure 3.1**). While the extent of curriculum integration could vary, an example of an interdisciplinary curriculum is one where there is a common theme, cross-cutting concept, project or unit across several subjects. Teachers could also make use of real-world contexts to illustrate concepts and applications, and expose students to problems that involve multiple solutions.



Learning knowledge and skills through real-world examples
- Use of real-world examples to illustrate concepts
- Involves application of knowledge and skills to solve simplified/routine problems set in real-world contexts

Creative application of knowledge and skills in real-world contexts
- Creative application of knowledge and skills (e.g. in ideating and making) to address real-world issues
- Involves application of knowledge and skills to solve complex real-world problems

Disciplinary
- Learning is anchored within a discipline

Integrative
- Learning involves integration of knowledge and skills across two or more STEM disciplines

Figure 3.1: Two design considerations for STEM LEs

SECTION 4: ASSESSMENT

4. ASSESSMENT

Assessment is the process of gathering and analysing evidence about student learning. This information is used to make decisions about students, curricula and programmes. Assessments designed with a clarity of purpose and the provision of timely and targeted feedback can help students move their learning forward in an effective manner.

a. Assessment is an integral to the teaching and learning process. Assessment is a part of teaching and learning, and must be closely aligned with curriculum objectives, content and pedagogy. In a classroom where assessment is used to support learning, there is no divide between teaching and assessment. Everything that happens in the classroom, and everything that students do (e.g., questions they ask, responses to learning activities), become sources of information that help teachers assess what students know and can do. The teacher will analyse these sources of information to make teaching decisions which enhance the quality of learning and address learning gaps. Hence, assessment becomes an ongoing, cyclical process that is woven into the minute-to-minute and day-to-day life in the classroom.

b. Assessment begins with clarity of purpose. Assessment tasks should be fit for purpose and based on sound educational principles. Summative assessment serves to provide information on students' mastery of content knowledge and skills, while formative assessment is carried out for the purpose of enhancing teaching and learning. A balanced assessment system should comprise both summative assessment and formative assessment. Whether implemented as formal examinations or infused in classroom learning activities, assessment should support meaningful learning. Decisions on 'what' to assess and 'how' to assess should be based on a clear purpose, in relation to the learning outcomes.

c. Assessment provides feedback to move learning forward and improve teaching practices. Assessment information should allow both teachers and students to make continuous improvement to teaching and learning. In addition to interpreting assessment information and adapting instructional practices accordingly to address learning gaps, teachers also need to guide students to understand and use assessment information to improve their learning. This will help engender ownership of learning to students and boost their motivation to learn. As students learn to self-assess and self-regulate, they will be equipped to become self-directed learners who are able to learn for life. Assessment information should produce both quantitative and qualitative descriptions of learners' performance that are useful to teachers and students.

4.1 A-LEVEL EXAMINATION

Candidates will be assumed to have knowledge and understanding of Chemistry at O-Level, as a single subject or as part of a balanced science course.

This syllabus is designed to place less emphasis on factual material and greater emphasis on the understanding and application of scientific concepts and principles. This approach has been adopted in recognition of the need for students to develop skills that will be of long term value in an increasingly technological world rather than focusing on large quantities of factual material which may have only short term relevance.

Experimental work is an important component and should underpin the teaching and learning of Chemistry.

Assessment Objectives

In the syllabus documents, the assessment objectives for the theory papers are grouped into two categories:

- Assessment Objective A (AOA) – Knowledge with understanding
- Assessment Objective B (AOB) – Handling, applying and evaluating information

For H2 Chemistry, an assessment objective is added for the practical paper:

- Assessment Objective C (AOC) – Experimental skills and investigations

The assessment objectives listed below reflect those parts of the Aims and Practices of Science that will be assessed.

A Knowledge with understanding

Candidates should be able to demonstrate knowledge and understanding in relation to:

1. scientific phenomena, facts, laws, definitions, concepts, theories
2. scientific vocabulary, terminology, conventions (including symbols, quantities and units)
3. scientific instruments and apparatus, including techniques of operation and aspects of safety
4. scientific quantities and their determination
5. scientific and technological applications with their social, economic and environmental implications.

The syllabus content defines the factual knowledge that candidates may be required to recall and explain. Questions testing these objectives will often begin with one of the following words: *define*, *state*, *describe*, *explain* or *outline* (see the *Glossary of Terms*).

B Handling, applying and evaluating information

Candidates should be able (in words or by using symbolic, graphical and numerical forms of presentation) to:

1. locate, select, organise and present information from a variety of sources
2. handle information, distinguishing the relevant from the extraneous
3. manipulate numerical and other data and translate information from one form to another
4. analyse and evaluate information so as to identify patterns, report trends and conclusions, and draw inferences
5. present reasoned explanations for phenomena, patterns and relationships
6. apply knowledge, including principles, to novel situations
7. bring together knowledge, principles, concepts and skills from different areas of chemistry, and apply them in a particular context
8. evaluate information and hypotheses
9. construct arguments to support hypotheses or to justify a course of action
10. demonstrate an awareness of the limitations of Chemistry theories and models

These assessment objectives cannot be precisely specified in the syllabus content because questions testing such skills may be based on information that is unfamiliar to the candidates. In answering such questions, candidates are required to use principles and concepts that are within the syllabus and apply them in a logical, reasoned or deductive manner to a novel situation. Questions testing these objectives will often begin with one of the following words: *predict*, *suggest*, *construct*, *calculate* or *determine* (see the Glossary of Terms).

C Experimental skills and investigations *(for H2 Chemistry only)*

Candidates should be able to:

1. follow a detailed set or sequence of instructions and use techniques, apparatus and materials safely and effectively
2. make, record and present observations and measurements with due regard for precision and accuracy
3. interpret and evaluate observations and experimental data
4. identify a problem, devise and plan investigations, select techniques, apparatus and materials
5. evaluate methods and techniques and suggest possible improvements.

GLOSSARY OF TERMS USED IN CHEMISTRY PAPERS

It is hoped that the glossary (which is relevant only to science subjects) will prove helpful to candidates as a guide, i.e. it is neither exhaustive nor definitive. The glossary has been deliberately kept brief not only with respect to the number of terms included but also to the descriptions of their meanings. Candidates should appreciate that the meaning of a term must depend in part on its context.

1. *Define* (*the term(s)...*) is intended literally, only a formal statement or equivalent paraphrase being required.

2. *What do you understand by/What is meant by (the term(s)...)* normally implies that a definition should be given, together with some relevant comment on the significance or context of the term(s) concerned, especially where two or more terms are included in the question. The amount of supplementary comment intended should be interpreted in the light of the indicated mark value.

3. *State* implies a concise answer with little or no supporting argument, e.g. a numerical answer that can be obtained ‘by inspection’.

4. *List* requires a number of points, generally each of one word, with no elaboration. Where a given number of points is specified, this should not be exceeded.

5. *Explain* may imply reasoning or some reference to theory, depending on the context.

6. *Describe* requires candidates to state in words (using diagrams where appropriate) the main points of the topic. It is often used with reference either to particular phenomena or to particular experiments. In the former instance, the term usually implies that the answer should include reference to (visual) observations associated with the phenomena.

   In other contexts, *describe and give an account of* should be interpreted more generally, i.e. the candidate has greater discretion about the nature and the organisation of the material to be included in the answer. *Describe and explain* may be coupled in a similar way to *state and explain.*

7. *Discuss* requires candidates to give a critical account of the points involved in the topic.

8. *Outline* implies brevity, i.e. restricting the answer to giving essentials.

9. *Predict* implies that the candidate is not expected to produce the required answer by recall but by making a logical connection between other pieces of information. Such information may be wholly given in the question or may depend on answers extracted in an early part of the question.

10. *Deduce* is used in a similar way as *predict* except that some supporting statement is required, e.g. reference to a law/principle, or the necessary reasoning is to be included in the answer.

11. *Comment* is intended as an open-ended instruction, inviting candidates to recall or infer points of interest relevant to the context of the question, taking account of the number of marks available.

12. *Suggest* is used in two main contexts, i.e. either to imply that there is no unique answer (e.g. in chemistry, two or more substances may satisfy the given conditions describing an ‘unknown’), or to imply that candidates are expected to apply their general knowledge to a ‘novel’ situation, one that may be formally ‘not in the syllabus’.

13. *Find* is a general term that may variously be interpreted as calculate, measure, determine etc.

14. *Calculate* is used when a numerical answer is required. In general, working should be shown, especially where two or more steps are involved.

15. *Measure* implies that the quantity concerned can be directly obtained from a suitable measuring instrument, e.g. length, using a rule, or angle, using a protractor.

16. *Determine* often implies that the quantity concerned cannot be measured directly but is obtained by calculation, substituting measured or known values of other quantities into a standard formula, e.g. relative molecular mass.

17. *Estimate* implies a reasoned order of magnitude statement or calculation of the quantity concerned, making such simplifying assumptions as may be necessary about points of principle and about the values of quantities not otherwise included in the question.

18. *Sketch,* when applied to graph work, implies that the shape and/or position of the curve need only be qualitatively correct, but candidates should be aware that, depending on the context, some quantitative aspects may be looked for, e.g. passing through the origin, having an intercept, asymptote or discontinuity at a particular value.

    In diagrams, sketch implies that a simple, freehand drawing is acceptable: nevertheless, care should be taken over proportions and the clear exposition of important details.

19. *Construct* is often used in relation to chemical equations where a candidate is expected to write a balanced equation, not by factual recall but by analogy or by using information in the question.

20. *Compare* requires candidates to provide both the similarities and differences between things or concepts.

21. *Classify* requires candidates to group things based on common characteristics.

22. *Recognise* is often used to identify facts, characteristics or concepts that are critical (relevant/appropriate) to the understanding of a situation, event, process or phenomenon.

4.2 ASSESSMENT FOR H1 CHEMISTRY

Candidates may not simultaneously offer chemistry at the H1 and H2 levels, though they must offer H2 Chemistry in order to take H3 Chemistry.

[H1 CHEMISTRY] SCHEME OF ASSESSMENT

All candidates are required to enter for Papers 1 and 2.

Paper	Type of Paper	Duration	Weighting (%)	Marks
1	Multiple Choice	1 h	33	30
2	Structured Questions	2 h	67	80

Paper 1 (1 h, 30 marks)
This paper will consist of 30 compulsory multiple choice questions. Four to six items will be of the multiple completion type.

All questions will include 4 options.

Paper 2 (2 h, 80 marks)
This paper consists of two sections. All answers will be written in spaces provided on the Question Paper.

Section A (60 marks)
A variable number of structured questions including data-based questions, all compulsory. The data-based question(s) constitute(s) 15-20 marks for this paper. The data-based question(s) provide(s) a good opportunity to test higher order thinking skills such as handling, applying, and evaluating information.

Section B (20 marks)
Candidates will be required to answer **one** out of two questions. Each question will carry 20 marks.

These questions will require candidates to integrate knowledge and understanding from different areas and topics of the chemistry syllabus.

Weighting of Assessment Objectives

Assessment Objectives		Weighting (%)	Assessment Components
A	Knowledge with understanding	45	Papers 1, 2
B	Handling, applying and evaluating information	55	Papers 1, 2

[H1 CHEMISTRY] ADDITIONAL INFORMATION

Data Booklet

A *Data Booklet* is available for use in the theory papers.

Nomenclature

Candidates will be expected to be familiar with the nomenclature used in the syllabus. The proposals in "*Signs*, *Symbols* and *Systematics*" (The Association for Science Education Companion to 16-19 Science, 2000) will generally be adopted although the traditional names sulfate, sulfite, nitrate, nitrite, sulfurous and nitrous acids will be used in question papers. Sulfur (and all compounds of sulfur) will be spelt with f (not with ph) in question papers, however candidates can use either spelling in their answers.

Units and significant figures

Candidates should be aware that misuse of units and/or significant figures, i.e. failure to quote units where necessary, the inclusion of units in quantities defined as ratios or quoting answers to an inappropriate number of significant figures, is liable to be penalised.

Disallowed Subject Combinations

Candidates may not simultaneously offer Chemistry at H1 and H2 levels.

[H1 CHEMISTRY] MATHEMATICAL REQUIREMENTS

It is assumed that candidates will be competent in the techniques described below.

Make calculations involving addition, subtraction, multiplication and division of quantities.

Make approximate evaluations of numerical expressions.

Express small fractions as percentages, and vice versa.

Calculate an arithmetic mean.

Transform decimal notation to power of ten notation (standard form).

Use calculators to evaluate logarithms (for pH calculations), squares, square roots, and reciprocals.

Change the subject of an equation (most such equations involve only the simpler operations but may include positive and negative indices and square roots.)

Substitute physical quantities into an equation using consistent units so as to calculate one quantity. Check the dimensional consistency of such calculations, e.g. the units of a rate constant k.

Solve simple algebraic equations.

Comprehend and use the symbols/notations $<$, $>$, $\approx$, $/$, Δ, $\equiv$, $\bar{x}$ (or $\langle x \rangle$).

Test tabulated pairs of values for direct proportionality by a graphical method or by constancy of ratio.

Select appropriate variables and scales for plotting a graph, especially to obtain a linear graph of the form $y = mx + c$.

Determine and interpret the slope and intercept of a linear graph.

Choose by inspection a straight line that will serve as the 'least bad' linear model for a set of data presented graphically.

Understand (i) the slope of a tangent to a curve as a measure of rate of change, (ii) the 'area' below a curve where the area has physical significance, e.g. Boltzmann distribution curves.

Comprehend how to handle numerical work so that significant figures are neither lost unnecessarily nor used beyond what is justified.

Estimate orders of magnitude.

Formulate simple algebraic equations as mathematical models, e.g. construct a rate equation, and identify failures of such models.

Calculators

Any calculator used must be on the Singapore Examinations and Assessment Board list of approved calculators.

[H1 CHEMISTRY] SUMMARY OF KEY QUANTITIES AND UNITS

The list below is intended as a guide to the more important quantities which might be encountered in teaching and used in question papers. The list is not exhaustive.

Quantity	Usual symbols	Unit
Base quantities		
amount of substance	n	mol
electric current	I	A
length	l	m
mass	m	kg, g
thermodynamic temperature	T	K
time	t	s
Other quantities		
acid dissociation constant	K_a	mol dm^{-3}
atomic mass	m_a	g, kg
Avogadro constant	L, N_A	mol^{-1}
base dissociation constant	K_b	mol dm^{-3}
bond energy	–	kJ mol^{-1}
concentration	c	mol dm^{-3}
density	ρ	kg m^{-3}, g dm^{-3}, g cm^{-3}
electric potential difference	V	V
electromotive force	E	V
electron affinity	–	kJ mol^{-1}
elementary charge	e	C
enthalpy change of reaction	ΔH	J, kJ
equilibrium constant	K, K_p, K_c	as appropriate
Faraday constant	F	C mol^{-1}
frequency	v, f	Hz
half-life	$T_{½}$, $t_{½}$	s
heat capacity	C	J K^{-1}
ionic product, solubility product	K, K_{sp}	as appropriate
ionic product of water	K_w	mol^2 dm^{-6}
ionisation energy	I	kJ mol^{-1}
lattice energy	–	kJ mol^{-1}
molar gas constant	R	J K^{-1} mol^{-1}
molar mass	M	g mol^{-1}
mole fraction	x	–
molecular mass	m	g, kg
neutron number	N	–
nucleon number	A	–
number of molecules	N, N_A	–
number of molecules per unit volume	n	m^{-3}
order of reaction	n, m	–
partition coefficient	K	–
Planck constant	h	J s
pH	pH	–
pressure	p	Pa
proton number	Z	–
rate constant	k	as appropriate
relative $\left\{\begin{array}{l}\text{atomic}\\\text{isotopic}\end{array}\right\}$ mass	A_r	–
relative molecular mass	M_r	–

specific heat capacity	c	J g^{-1} K^{-1}, kJ kg^{-1} K^{-1}
speed of electromagnetic waves	c	m s^{-1}
(standard) $\left\{\begin{array}{l}\text{electrode}\\ \text{redox}\end{array}\right\}$ potential	($E^{\ominus}$) E	V
standard enthalpy change of reaction	$\Delta H^{\ominus}$	J mol^{-1}, kJ mol^{-1}
temperature	θ, t	°C
volume	V, v	m^3, dm^3
wavelength	λ	m, mm, nm

4.3 ASSESSMENT FOR H2 CHEMISTRY

Candidates may not simultaneously offer chemistry at the H1 and H2 levels, though they must offer H2 Chemistry in order to take H3 Chemistry.

[H2 CHEMISTRY] SCHEME OF ASSESSMENT

All candidates are required to enter for Papers 1, 2, 3 and 4.

Paper	Type of Paper	Duration	Weighting (%)	Marks
1	Multiple Choice	1 h	15	30
2	Structured Questions	2 h	30	75
3	Structured Questions	2 h	35	75
4	Practical	2 h and 30 min	20	50

Paper 1 (1 h, 30 marks)
This paper consists of 30 compulsory multiple choice questions. Five to eight items will be of the multiple completion type.

All questions will include 4 options.

Paper 2 (2 h, 75 marks)
This paper consists of a variable number of structured questions including data-based questions. All questions are compulsory and answered on the question paper. The data-based question(s) constitute(s) 20-25 marks for this paper.

The data-based question(s) provide(s) good opportunity to test higher order thinking skills such as handling, applying, and evaluating information. Some questions will also require candidates to integrate knowledge and understanding from different areas and topics of the chemistry syllabus.

Paper 3 (2 h, 75 marks)
This paper consists of two sections:

- Section A is worth 55 marks consisting of 3-4 structured questions, all compulsory. Each question constitutes 15-25 marks.
- Section B is worth 20 marks consisting of *two* questions, each of 20 marks. Candidates are to answer any *one* question.

These questions will require candidates to integrate knowledge and understanding from different areas and topics of the chemistry syllabus.

Paper 4 (2 h and 30 min, 50 marks)
This paper will assess appropriate aspects of assessment objectives C1 to C5 in the following skill areas:

- Planning (P)
- Manipulation, measurement and observation (MMO)
- Presentation of data and observations (PDO)
- Analysis, conclusions and evaluation (ACE)

The assessment of Planning (P) will have a weighting of 4%. The assessment of skill areas MMO, PDO and ACE will have a weighting of 16%.

The scope of the practical paper is indicated in the Practical Assessment section. The assessment of PDO and ACE may also include questions on data-analysis which do not require practical equipment and apparatus.

Candidates will **not** be permitted to refer to books and laboratory notebooks during the assessment.

Weighting of Assessment Objectives

Assessment Objectives		Weighting (%)	Assessment Components
A	Knowledge with understanding	36	Papers 1, 2, 3
B	Handling, applying and evaluating information	44	Papers 1, 2, 3
C	Experimental skills and investigations	20	Paper 4

[H2 CHEMISTRY] ADDITIONAL INFORMATION

Data Booklet

A *Data Booklet* is available for use in the theory papers. The Qualitative Analysis Notes will be made available for use in the practical assessment.

Nomenclature

Candidates will be expected to be familiar with the nomenclature used in the syllabus. The proposals in "*Signs, Symbols and Systematics*" (The Association for Science Education Companion to 16-19 Science, 2000) will generally be adopted although the traditional names sulfate, sulfite, nitrate, nitrite, sulfurous and nitrous acids will be used in question papers. Sulfur (and all compounds of sulfur) will be spelt with f (not with ph) in question papers, however candidates can use either spelling in their answers.

Unit and significant figures

Candidates should be aware that misuse of units and/or significant figures, i.e. failure to quote units where necessary, the inclusion of units in quantities defined as ratios or quoting answers to an inappropriate number of significant figures, is liable to be penalised.

Disallowed Subject Combinations

Candidates may not simultaneously offer Chemistry at H1 and H2 levels.

[H2 CHEMISTRY] PRACTICAL ASSESSMENT

Scientific subjects are, by their nature, experimental. It is therefore important that, wherever possible, the candidates carry out appropriate practical work to support the learning of this subject and to develop the expected practical skills.

Paper 4 Practical Paper

This paper is designed to assess a candidate's competence in those practical skills which can realistically be assessed within the context of a formal practical assessment.

Candidates will be assessed in the following skill areas:

(a) Planning (P)
Candidates should be able to
- define the question/problem using appropriate knowledge and understanding
- give a clear logical account of the experimental procedure to be followed
- describe how the data should be used in order to reach a conclusion
- assess the risks of the experiment and describe precautions that should be taken to keep risks to a minimum

(b) Manipulation, measurement and observation (MMO)
Candidates should be able to
- demonstrate a high level of manipulative skills in all aspects of practical activity
- make and record accurate observations with good details and measurements to an appropriate degree of precision
- make appropriate decisions about measurements or observations
- recognise anomalous observations and/or measurements (where appropriate) with reasons indicated

(c) Presentation of data and observations (PDO)
Candidates should be able to
- present all information in an appropriate form
- manipulate measurements effectively in order to identify trends/patterns
- present all quantitative data to an appropriate number of decimal places/significant figures

(d) Analysis, conclusions and evaluation (ACE)
Candidates should be able to
- analyse and interpret data or observations appropriately in relation to the task
- draw conclusion(s) from the interpretation of experimental data or observations and underlying principles
- make predictions based on their data and conclusions
- identify significant sources of errors, limitations of measurements and/or experimental procedures used, and explain how they affect the final result(s)

- state and explain how significant errors/limitations may be overcome or reduced, as appropriate, including how experimental procedures may be improved

One, or more, of the questions may incorporate some assessment of Skill P, set in the context of the syllabus content, requiring candidates to apply and integrate knowledge and understanding from different sections of the syllabus. It may also require the treatment of given experimental data to draw a relevant conclusion and analyse a proposed plan.

The assessment of skills MMO, PDO and ACE will also be set mainly in the context of the syllabus content. The assessment of PDO and ACE may also include questions on data-analysis which do not require practical equipment and apparatus.

Candidates should be able to use appropriate apparatus/equipment to record a range of measurements such as mass, time, volume and temperature. In addition, candidates are expected to have been exposed to a range of experimental techniques in the following areas:

1) Titration, e.g. acid-base titration (with suitable indicators such as methyl orange, screened methyl orange, thymolphthalein and thymol blue), redox titration, iodimetric titration, indirect titration, including the preparation of standard solutions. Other types of titrations may also be required, where appropriate, sufficient working details will be given.

2) Gravimetric analysis, e.g. volatilisation gravimetry

3) Gas collection. Candidates would not be required to carry out gas collection experiments involving displacement of water or using gas syringes during the practical examination.

4) Thermochemistry, including thermometric titration

5) Chemical kinetics, e.g. continuous and initial rate methods

6) Qualitative inorganic analysis involving an element, a compound or a mixture. Systematic analysis will **not** be required. Candidates should be familiar with the reactions of cations, reactions of anions and test for gases as detailed in the Qualitative Analysis Notes. Candidates would **not** be required to carry out tests involving hexane, sulfur dioxide gas, nitrite ions or sulfite ions.
   Reactions involving ions not included in the Qualitative Analysis Notes may be tested: in such cases, candidates will **not** be expected to identify the ions but only to draw conclusions of a general nature.

   Candidates should **not** attempt tests, other than those specified, on substances, except when it is appropriate to test for a gas.

7) Qualitative organic analysis requiring a knowledge of simple organic reactions as outlined in Section 11.4 to 11.10, e.g. test-tube reactions indicating the presence of unsaturation (C=C), alcoholic, phenolic, carbonyl, carboxyl and amino groups, may be set. Candidates should be familiar with the tests for organic compounds as detailed in the Qualitative Analysis Notes.

Candidates would **not** be required to carry out tests involving phosphorus (V) chloride, phenol or 2,4-dinitrophenylhydrazine.

8) Simple organic synthesis and purification, including use of water bath, setting up and use of reflux and distillation apparatus. Conducting a large scale organic synthesis involving reflux, distillation and purification would not be expected during the practical examination.

This is not intended to be an exhaustive list.

Candidates are **not** allowed to refer to notebooks, textbooks or any other information in the practical examination. Qualitative Analysis Notes will be included in the question paper for the use of candidates in the examination.

Within the Scheme of Assessment, Paper 4 is weighted to 20% of the Higher 2 assessment. It is therefore recommended that the schemes of work include learning opportunities that apportion a commensurate amount of time for the development and acquisition of practical skills.

Apparatus List

This list given below has been drawn up in order to give guidance to Centres concerning the apparatus that is expected to be generally available for examination purposes. The list is not intended to be exhaustive; in particular, items (such as Bunsen burners, tripods) that are commonly regarded as standard equipment in a chemical laboratory are not included.

Unless otherwise stated, the rate of allocation is “per candidate”.

two burettes, 50 cm^3
two pipettes, 25 cm^3
one pipette, 10 cm^3
teat/dropping pipettes
one pipette filler
two conical flasks within the range 150 cm^3 to 250 cm^3
two conical flasks, 100 cm^3
volumetric flask, 250 cm^3
two measuring cylinders, 10 cm^3
measuring cylinders, 25 cm^3, 50 cm^3 and 100 cm^3
two filter funnels
two porcelain crucibles, approximately 15 cm^3, with lids
one pipe-clay triangle
one evaporating basin, at least 30 cm^3
beakers, squat form with lip: 100 cm^3, 250 cm^3
thermometers: –10 ^oC to +110 ^oC at 1 ^oC
–5 ^oC to +50 ^oC at 0.2 ^oC
a polystyrene, or other plastic beaker of approximate capacity 150 cm^3
test-tubes (some of which should be Pyrex or hard glass), approximately 125 mm x 15 mm
boiling tubes, approximately 150 mm x 25 mm
stopwatch to measure to an accuracy of about 1 s
balance, single-pan, direct reading, 0.01 g or better (1 per 8–12 candidates)
stands and clamps suitable for burettes and pipettes
wash bottle

The apparatus and material requirements for Paper 4 will vary year on year. Centres will be notified in advance of the details of the apparatus and materials required for each practical examination.

Reagents

This list given below has been drawn up in order to give guidance to Centres concerning the standard reagents that are expected to be generally available for examination purposes. The list is not intended to be exhaustive and Centres will be notified in advance of the full list of all the reagents that are required for each practical examination.

aqueous sodium hydroxide (approximately 2.0 mol dm^{-3})
aqueous ammonia (approximately 2.0 mol dm^{-3})
hydrochloric acid (approximately 2.0 mol dm^{-3})
nitric acid (approximately 2.0 mol dm^{-3})
sulfuric acid (approximately 1.0 mol dm^{-3})
aqueous silver nitrate (approximately 0.05 mol dm^{-3})
aqueous barium nitrate (approximately 0.2 mol dm^{-3})
limewater (a saturated solution of calcium hydroxide)
aqueous potassium manganate(VII) (approximately 0.02 mol dm^{-3})
aqueous potassium iodide (approximately 0.1 mol dm^{-3})
aluminium foil
red and blue litmus paper or Universal Indicator paper

Qualitative Analysis Notes

[ppt. = precipitate]

(a) Reactions of aqueous cations

cation	***reaction with***	
	NaOH(aq)	**NH_3(aq)**
aluminium, Al^{3+}(aq)	white ppt. soluble in excess	white ppt. insoluble in excess
ammonium, NH_4^+(aq)	ammonia produced on heating	–
barium, Ba^{2+}(aq)	no ppt. (if reagents are pure)	no ppt.
calcium, Ca^{2+}(aq)	white ppt. with high [Ca^{2+}(aq)]	no ppt.
chromium(III), Cr^{3+}(aq)	grey-green ppt. soluble in excess giving dark green solution	grey-green ppt. insoluble in excess
copper(II), Cu^{2+}(aq),	pale blue ppt. insoluble in excess	blue ppt. soluble in excess giving dark blue solution
iron(II), Fe^{2+}(aq)	green ppt., turning brown on contact with air insoluble in excess	green ppt., turning brown on contact with air insoluble in excess
iron(III), Fe^{3+}(aq)	red-brown ppt. insoluble in excess	red-brown ppt. insoluble in excess
magnesium, Mg^{2+}(aq)	white ppt. insoluble in excess	white ppt. insoluble in excess
manganese(II), Mn^{2+}(aq)	off-white ppt., rapidly turning brown on contact with air insoluble in excess	off-white ppt., rapidly turning brown on contact with air insoluble in excess
zinc, Zn^{2+}(aq)	white ppt. soluble in excess	white ppt. soluble in excess

(b) Reactions of anions

anion	*reaction*
carbonate, CO_3^{2-}	CO_2 liberated by dilute acids
chloride, $Cl^-(aq)$	gives white ppt. with $Ag^+(aq)$ (soluble in $NH_3(aq)$)
bromide, $Br^-(aq)$	gives pale cream ppt. with $Ag^+(aq)$ (partially soluble in $NH_3(aq)$)
iodide, $I^-(aq)$	gives yellow ppt. with $Ag^+(aq)$ (insoluble in $NH_3(aq)$)
nitrate, $NO_3^-(aq)$	NH_3 liberated on heating with $OH^-(aq)$ and Al foil
nitrite, $NO_2^-(aq)$	NH_3 liberated on heating with $OH^-(aq)$ and Al foil; NO liberated by dilute acids (colourless NO → (pale) brown NO_2 in air)
sulfate, $SO_4^{2-}(aq)$	gives white ppt. with $Ba^{2+}(aq)$ (insoluble in excess dilute strong acids)
sulfite, $SO_3^{2-}(aq)$	SO_2 liberated with dilute acids; gives white ppt. with $Ba^{2+}(aq)$ (soluble in dilute strong acids)

(c) Tests for gases

gas	*test and test result*
ammonia, NH_3	turns damp red litmus paper blue
carbon dioxide, CO_2	gives a white ppt. with limewater (ppt. dissolves with excess CO_2)
chlorine, Cl_2	bleaches damp litmus paper
hydrogen, H_2	“pops” with a lighted splint
oxygen, O_2	relights a glowing splint
sulfur dioxide, SO_2	turns aqueous acidified potassium manganate(VII) from purple to colourless

(d) Colour of halogens

halogen	*colour of element*	*colour in aqueous solution*	*colour in hexane*
chlorine, Cl_2	greenish yellow gas	pale yellow	pale yellow
bromine, Br_2	reddish brown gas / liquid	orange	orange-red
iodine, I_2	black solid / purple gas	brown	purple

(e) Tests for organic compounds

Organic compounds	Reactions
alkene	decolourises orange Br_2(aq)
chloroalkane	heat with NaOH(aq), white ppt. formed on adding dilute HNO_3, followed by Ag^+(aq)
bromoalkane	heat with NaOH(aq), pale cream ppt. formed on adding dilute HNO_3, followed by Ag^+(aq)
iodoalkane	heat with NaOH(aq), yellow ppt. formed on adding dilute HNO_3, followed by Ag^+(aq)
alcohol	• forms white fumes with solid PCl_5 • decolourises purple acidified $KMnO_4$(aq) on heating (for primary and secondary alcohols) • gives pale yellow ppt. with alkaline I_2(aq) on warming (for alcohols with $CH_3CH(OH)–$ group)
phenol	decolourises orange Br_2(aq) and forms a white ppt
carbonyl compounds (aldehydes and ketones)	• gives orange ppt. with 2,4-dinitrophenylhydrazine • gives pale yellow ppt. with alkaline I_2(aq) on warming (for carbonyl compounds with $CH_3CO–$ group) • gives red-brown ppt. with Fehling's solution on warming (for aliphatic aldehydes) • gives silver mirror with Tollens' reagent on warming (for aldehydes)
carboxylic acid	• CO_2 liberated by Na_2CO_3(aq) • gives white fumes with solid PCl_5
phenylamine	decolourises orange Br_2(aq) and forms a white ppt
primary amide	NH_3 liberated on heating with NaOH(aq)

[H2 CHEMISTRY] MATHEMATICAL REQUIREMENTS

It is assumed that candidates will be competent in the techniques described below.

Make calculations involving addition, subtraction, multiplication and division of quantities.

Make approximate evaluations of numerical expressions.

Express small fractions as percentages, and vice versa.

Calculate an arithmetic mean.

Transform decimal notation to power of ten notation (standard form).

Use calculators to evaluate logarithms, squares, square roots, and reciprocals.

Change the subject of an equation. (Most such equations involve only the simpler operations but may include positive and negative indices and square roots.)

Substitute physical quantities into an equation using consistent units so as to calculate one quantity. Check the dimensional consistency of such calculations, e.g. the units of a rate constant *k*.

Solve simple algebraic equations.

Comprehend and use the symbols/notations $<$, $>$, $\approx$, $/$, Δ, $\equiv$, $\bar{x}$ (or $\langle x \rangle$).

Test tabulated pairs of values for direct proportionality by a graphical method or by constancy of ratio.

Select appropriate variables and scales for plotting a graph, especially to obtain a linear graph of the form $y = mx + c$.

Determine and interpret the slope and intercept of a linear graph.

Choose by inspection a straight line that will serve as the 'least bad' linear model for a set of data presented graphically.

Understand (i) the slope of a tangent to a curve as a measure of rate of change, (ii) the 'area' below a curve where the area has physical significance, e.g. Boltzmann distribution curves.

Comprehend how to handle numerical work so that significant figures are neither lost unnecessarily nor used beyond what is justified.

Estimate orders of magnitude.

Formulate simple algebraic equations as mathematical models, e.g. construct a rate equation, and identify failures of such models.

Calculators

Any calculator used must be on the Singapore Examinations and Assessment Board list of approved calculators.

[H2 CHEMISTRY] SUMMARY OF KEY QUANTITIES AND UNITS

The list below is intended as a guide to the more important quantities which might be encountered in teaching and used in question papers. The list is not exhaustive.

Quantity	**Usual symbols**	**Units**
Base quantities		
amount of substance	n	mol
electric current	I	A
length	l	m
mass	m	kg, g
thermodynamic temperature	T	K
time	t	s
Other quantities		
acid dissociation constant	K_a	mol $\mathrm{dm^{-3}}$
atomic mass	$\mathrm{m_a}$	g, kg
Avogadro constant	L, $\mathrm{N_A}$	$\mathrm{mol^{-1}}$
base dissociation constant	K_b	mol $\mathrm{dm^{-3}}$
bond energy	–	kJ $\mathrm{mol^{-1}}$
concentration	c	mol $\mathrm{dm^{-3}}$
density	ρ	kg $\mathrm{m^{-3}}$, g $\mathrm{dm^{-3}}$, g $\mathrm{cm^{-3}}$
electric potential difference	V	V
electromotive force	E	V
electron affinity	–	kJ $\mathrm{mol^{-1}}$
elementary charge	e	C
enthalpy change of reaction	ΔH	J, kJ
equilibrium constant	K, K_p, K_c	as appropriate
Faraday constant	F	C $\mathrm{mol^{-1}}$
frequency	v, f	Hz
half-life	$T_{½}$, $t_{½}$	s
heat capacity	C	J $\mathrm{K^{-1}}$
ionic product, solubility product	K, K_sp	as appropriate
ionic product of water	K_w	$\mathrm{mol^2\ dm^{-6}}$
ionisation energy	I	kJ $\mathrm{mol^{-1}}$
lattice energy	–	kJ $\mathrm{mol^{-1}}$
molar gas constant	R	J $\mathrm{K^{-1}\ mol^{-1}}$
molar mass	M	g $\mathrm{mol^{-1}}$
mole fraction	x	–
molecular mass	m	g, kg
neutron number	N	–
nucleon number	A	–
number of molecules	N, N_A	–
number of molecules per unit volume	n	$\mathrm{m^{-3}}$
order of reaction	n, m	–
partition coefficient	K	–
Planck constant	h	J s
pH	pH	–
pressure	p	Pa
proton number	Z	–
rate constant	k	as appropriate
relative $\left\{\begin{array}{l}\text{atomic}\\ \text{isotopic}\end{array}\right\}$ mass	A_r	–
relative molecular mass	M_r	–

specific heat capacity	c	J g^{-1} K^{-1}, kJ kg^{-1} K^{-1}
speed of electromagnetic waves	c	m s^{-1}
(standard) $\left\{\begin{matrix}\text{electrode}\\ \text{redox}\end{matrix}\right\}$ potential	$(E^{\ominus})$ E	V
standard enthalpy change of reaction	$\Delta H^{\ominus}$	J mol^{-1}, kJ mol^{-1}
standard entropy change of reaction	$\Delta S^{\ominus}$	J K^{-1} mol^{-1}, kJ K^{-1} mol^{-1}
standard Gibbs free energy change of reaction	$\Delta G^{\ominus}$	J mol^{-1}, kJ mol^{-1}
temperature	θ, t	°C
volume	V, v	m^3, dm^3
wavelength	λ	m, mm, nm

4.4 ASSESSMENT FOR H3 CHEMISTRY

Candidates must simultaneously offer H2 Chemistry in order to offer H3 Chemistry.

[H3 CHEMISTRY] SCHEME OF ASSESSMENT

Candidates will take a 2h 30 min paper (100 marks total). This paper consists of two sections and will include questions that require candidates to integrate knowledge and understanding from different sections in the syllabus.

Section A (60 marks)
This section will consist of a variable number of compulsory structured questions including 1 or 2 stimulus-based questions. The stimulus-based question(s) constitute(s) 15–20 marks for this paper.

Section B (40 marks)
Candidates will be required to answer two out of three structured questions. Each question will carry 20 marks.

Weighting of Assessment Objectives

Assessment Objectives		Weighting (%)
A	Knowledge with understanding	25
B	Handling, applying and evaluating information	75

[H3 CHEMISTRY] ADDITIONAL INFORMATION

Required Subject Combinations

Candidates should simultaneously offer H2 Chemistry.

Data Booklet

A *Data Booklet* is available for use in the examination paper.

Nomenclature

Candidates will be expected to be familiar with the nomenclature used in the syllabus. The proposals in "*Signs, Symbols and Systematics*" (The Association for Science Education Companion to 16–19 Science, 2000) will generally be adopted although the traditional names sulfate, sulfite, nitrate, nitrite, sulfurous and nitrous acids will be used in question papers. Sulfur (and all compounds of sulfur) will be spelt with f (not with ph) in question papers, however candidates can use either spelling in their answers.

Unit and significant figures

Candidates should be aware that misuse of units and/or significant figures, i.e. failure to quote units where necessary, the inclusion of units in quantities defined as ratios or quoting answers to an inappropriate number of significant figures, is liable to be penalised.

[H3 CHEMISTRY] MATHEMATICAL REQUIREMENTS

It is assumed that candidates will be competent in the techniques described below.

Make calculations involving addition, subtraction, multiplication and division of quantities.
Make approximate evaluations of numerical expressions.
Express small fractions as percentages, and vice versa.
Calculate an arithmetic mean.
Transform decimal notation to power of ten notation (standard form).
Use calculators to evaluate logarithms, squares, square roots, and reciprocals.
Change the subject of an equation. (Most such equations involve only the simpler operations but may include positive and negative indices and square roots.)
Substitute physical quantities into an equation using consistent units so as to calculate one quantity. Check the dimensional consistency of such calculations, e.g. the units of a rate constant k.
Solve simple algebraic equations.
Comprehend and use the symbols/notations $<$, $>$, $\approx$, /, Δ, $\equiv$, $\bar{x}$ (or $\langle x \rangle$).
Test tabulated pairs of values for direct proportionality by a graphical method or by constancy of ratio.
Select appropriate variables and scales for plotting a graph, especially to obtain a linear graph of the form $y = mx + c$.
Determine and interpret the slope and intercept of a linear graph.
Choose by inspection a straight line that will serve as the 'least bad' linear model for a set of data presented graphically.
Understand (i) the slope of a tangent to a curve as a measure of rate of change, (ii) the 'area' below a curve where the area has physical significance, e.g. Boltzmann distribution curves.
Comprehend how to handle numerical work so that significant figures are neither lost unnecessarily nor used beyond what is justified.
Estimate orders of magnitude.
Formulate simple algebraic equations as mathematical models, e.g. construct a rate equation, and identify failures of such models.

Calculators

Any calculator used must be on the Singapore Examinations and Assessment Board list of approved calculators.

[H3 CHEMISTRY] SUMMARY OF KEY QUANTITIES AND UNITS

The list below is intended as a guide to the more important quantities which might be encountered in teaching and used in question papers. The list is not exhaustive.

Quantity	**Usual symbols**	**Units**
Base quantities		
amount of substance	n	mol
electric current	I	A
length	l	m
mass	m	kg, g
thermodynamic temperature	T	K
time	t	s
Other quantities		
acid dissociation constant	K_a	mol dm^{-3}
atomic mass	m_a	g, kg
Avogadro constant	L, N_A	mol^{-1}
base dissociation constant	K_b	mol dm^{-3}
bond energy	–	kJ mol^{-1}
chemical shift	δ	-
concentration	c	mol dm^{-3}
density	ρ	kg m^{-3}, g dm^{-3}, g cm^{-3}
electric potential difference	V	V
electromotive force	E	V
electron affinity	–	kJ mol^{-1}
elementary charge	e	C
enthalpy change of reaction	ΔH	J, kJ
equilibrium constant	K, K_p, K_c	as appropriate
Faraday constant	F	C mol^{-1}
frequency	v, f	Hz
half-life	$T_{1/2}$, $t_{1/2}$	s
heat capacity	C	J K^{-1}
ionic product, solubility product	K, K_{sp}	as appropriate
ionic product of water	K_w	mol^{2} dm^{-6}
ionisation energy	I	kJ mol^{-1}
lattice energy	–	kJ mol^{-1}
molar absorption coefficient	ε	mol^{-1} dm^{3} cm^{-1}
molar gas constant	R	J K^{-1} mol^{-1}
molar mass	M	g mol^{-1}
mole fraction	x	–
molecular mass	m	g, kg
neutron number	N	–
nucleon number	A	–
number of molecules	N, N_A	–
number of molecules per unit volume	n	m^{-3}
order of reaction	n, m	–
partition coefficient	K	–
Planck constant	h	J s

pH	pH	–
pressure	p	Pa
proton number	Z	–
rate constant	k	as appropriate
relative $\left\{\begin{matrix}\text{atomic}\\ \text{isotopic}\end{matrix}\right\}$ mass	A_r	–
relative molecular mass	M_r	–
specific heat capacity	c	J g^{-1} K^{-1}, kJ kg^{-1} K^{-1}
specific rotation	[α]	–
speed of electromagnetic waves	c	m s^{-1}
(standard) $\left\{\begin{matrix}\text{electrode}\\ \text{redox}\end{matrix}\right\}$ potential	$(E^{\ominus})\ E$	V
standard enthalpy change of reaction	$\Delta H^{\ominus}$	J mol^{-1}, kJ mol^{-1}
standard entropy change of reaction	$\Delta S^{\ominus}$	J K^{-1} mol^{-1}, kJ K^{-1} mol^{-1}
standard Gibbs free energy change of reaction	$\Delta G^{\ominus}$	J mol^{-1}, kJ mol^{-1}
temperature	θ, t	°C
volume	V, v	m^3, dm^3
wavelength	λ	m, mm, nm

4.5 DATA BOOKLET

Please refer to this link for the Data Booklet.

SECTION 5:
TEXTBOOK AND REFERENCES

5. TEXTBOOK AND REFERENCES

Cambridge International AS and A Level Chemistry by Peter Cann and Peter Hughes, published by Hodder Education

Cambridge International AS and A Level Chemistry Coursebook with Digital Access by Lawrie Ryan and Roger Norris, published by Cambridge University Press

Chemistry in Context (7th Edition) by Graham Hill and John Holman, published by Oxford University Press

Experiments and Exercises in Basic Chemistry (7th Edition) by Steve Murov and Brian Stedjee, published by Wiley

Why Chemical Reactions Happen? By James Keeler and Peter Wothers, published by Oxford University Press

Oxford Chemistry Primers: Foundations of Organic Chemistry by M. Hornby & J. Peach, published by Oxford University Press

Oxford Chemistry Primers: Structure and Reactivity in Organic Chemistry by H. Maskill, published by Oxford University Press

Oxford Chemistry Primers: Mechanisms of Organic Chemistry by H. Maskill, published by Oxford University Press

The Language of Mathematics in Science: A Guide for Teachers of 11–16 Science by R. Boohan, published by the Association for Science Education. ISBN 9780863574559 https://www.ase.org.uk/mathsinscience

For H3 Chemistry:

Chemical Structure and Reactivity, an integrated approach (2nd Edition) By James Keeler and Peter Wothers, published by Oxford University Press

A Primer to Mechanism in Organic Chemistry by P. Sykes, published by Longman Scientific & Technical

Advanced Organic Chemistry (5th Edition) Part (a) and Part (b) by F.A. Carey & R.J. Sundberg, published by Springer

Introduction to Spectroscopy (5th Edition) by D.L. Pavia, G.M. Lampman, G.S. Kriz & J.A. Vyvyan, published by Cengage Learning

R Spectroscopy (2nd Edition): An Introduction by H. Günzler & H.M. Heise, published by Wiley-VCH

March’s Advanced Organic Chemistry: Reactions, Mechanisms, and Structure (8th Edition) by M. Smith, published by Wiley

Modern Physical Organic Chemistry by E.V. Anslyn & D.A. Dougherty, published by University Science

NMR Spectroscopy: Basic Principles, Concepts and Applications in Chemistry (3rd Edition) by H. Günther, published by Wiley-VCH

Organic Mechanisms: Reactions, Stereochemistry and Synthesis (English edition) by R. Bruckner, M. Harmata & K. Beifuss, published by Springer

Organic Spectroscopy by L.D.S. Yadav, published by Kluwer

Organic Synthesis: The Disconnection Approach (2nd Edition) by S. Warren & P. Wyatt, published by Wiley

Oxford Chemistry Primers: Foundations of Organic Chemistry by M. Hornby & J. Peach, published by Oxford University Press

Oxford Chemistry Primers: Structure and Reactivity in Organic Chemistry by H. Maskill, published by Oxford University Press

Oxford Chemistry Primers: Mechanisms of Organic Chemistry by H. Maskill, published by Oxford University Press

Perspectives on Structure and Mechanism in Organic Chemistry (2nd Edition) by F.A. Carroll, published by Wiley

The Art of Writing Reasonable Organic Reaction Mechanisms (3rd Edition) by R.B. Grossman, published by Springer

UV Spectroscopy: Techniques, Instrumentation, Data handling by B.J. Clark, T. Frost & M.A. Russell, published by Chapman & Hall

The Language of Mathematics in Science: A Guide for Teachers of 11–16 (2016) Science by R. Boohan, published by the Association for Science Education. ISBN 9780863574559 https://www.ase.org.uk/mathsinscience

Teachers are encouraged to choose texts for class use that they feel will be of interest to their students and will support their own teaching style.

Many publishers are also producing videos and software appropriate for A-Level Chemistry students.