Diploma Programme

Chemistry teacher support material

First assessment 2025

International Baccalaureate®
Baccalauréat International
Bachillerato Internacional

Chemistry teacher support material

First assessment 2025

International Baccalaureate®
Baccalauréat International
Bachillerato Internacional

Diploma Programme
Chemistry teacher support material

Published September 2023
Updated July 2024

Published by the International Baccalaureate Organization, a not-for-profit educational foundation of Rue du Pré-de-la-Bichette 1, 1202 Genève, Switzerland.
Website: ibo.org

© International Baccalaureate Organization 2023

The International Baccalaureate Organization (known as the IB) offers four high-quality and challenging educational programmes for a worldwide community of schools, aiming to create a better, more peaceful world. This publication is one of a range of materials produced to support these programmes.

The IB may use a variety of sources in its work and check information to verify accuracy and authenticity, particularly when using community-based knowledge sources such as Wikipedia. The IB respects the principles of intellectual property and makes strenuous efforts to identify and obtain permission before publication from rights holders of all copyright material used. The IB is grateful for permissions received for material used in this publication and will be pleased to correct any errors or omissions at the earliest opportunity.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, without the IB's prior written permission, or as expressly permitted by the Rules for use of IB Intellectual Property.

IB merchandise and publications can be purchased through the IB Store (email: sales@ibo.org). Any commercial use of IB publications (whether fee-covered or commercial) by third parties acting in the IB's ecosystem without a formal relationship with the IB (including but not limited to tutoring organizations, professional development providers, educational publishers and operators of curriculum mapping or teacher resource digital platforms, etc.) is prohibited and requires a subsequent written licence from the IB. Licence requests should be sent to copyright@ibo.org. More information can be obtained on the IB public website.

International Baccalaureate, **Baccalauréat International**, **Bachillerato Internacional** and IB logos are registered trademarks of the International Baccalaureate Organization.

IB mission statement

The International Baccalaureate aims to develop inquiring, knowledgeable and caring young people who help to create a better and more peaceful world through intercultural understanding and respect.

To this end the organization works with schools, governments and international organizations to develop challenging programmes of international education and rigorous assessment.

These programmes encourage students across the world to become active, compassionate and lifelong learners who understand that other people, with their differences, can also be right.

IB learner profile

The aim of all IB programmes is to develop internationally minded people who, recognizing their common humanity and shared guardianship of the planet, help to create a better and more peaceful world.

As IB learners we strive to be:

INQUIRERS
We nurture our curiosity, developing skills for inquiry and research. We know how to learn independently and with others. We learn with enthusiasm and sustain our love of learning throughout life.

KNOWLEDGEABLE
We develop and use conceptual understanding, exploring knowledge across a range of disciplines. We engage with issues and ideas that have local and global significance.

THINKERS
We use critical and creative thinking skills to analyse and take responsible action on complex problems. We exercise initiative in making reasoned, ethical decisions.

COMMUNICATORS
We express ourselves confidently and creatively in more than one language and in many ways. We collaborate effectively, listening carefully to the perspectives of other individuals and groups.

PRINCIPLED
We act with integrity and honesty, with a strong sense of fairness and justice, and with respect for the dignity and rights of people everywhere. We take responsibility for our actions and their consequences.

OPEN-MINDED
We critically appreciate our own cultures and personal histories, as well as the values and traditions of others. We seek and evaluate a range of points of view, and we are willing to grow from the experience.

CARING
We show empathy, compassion and respect. We have a commitment to service, and we act to make a positive difference in the lives of others and in the world around us.

RISK-TAKERS
We approach uncertainty with forethought and determination; we work independently and cooperatively to explore new ideas and innovative strategies. We are resourceful and resilient in the face of challenges and change.

BALANCED
We understand the importance of balancing different aspects of our lives—intellectual, physical, and emotional—to achieve well-being for ourselves and others. We recognize our interdependence with other people and with the world in which we live.

REFLECTIVE
We thoughtfully consider the world and our own ideas and experience. We work to understand our strengths and weaknesses in order to support our learning and personal development.

The IB learner profile represents 10 attributes valued by IB World Schools. We believe these attributes, and others like them, can help individuals and groups become responsible members of local, national and global communities.

International Baccalaureate®
Baccalauréat International
Bachillerato Internacional

© International Baccalaureate Organization 2017
International Baccalaureate® | Baccalauréat International® | Bachillerato Internacional®

The purpose of this teacher support material

Welcome to the Diploma Programme (DP) chemistry teacher support material (TSM). This material is designed to assist both new and experienced teachers to build or revise their course design. It is intended to add insight, inspiration and guidance to the teacher and student journey by:

- supporting experienced and inexperienced teachers alike in structuring and delivering a course
- supporting teachers with the organization of experimental work
- complementing IB professional development.

The TSM is structured to cover generic issues such as the approaches to learning and approaches to teaching and how these relate to chemistry, as well as subject-specific considerations such as nature of science (NOS) and skills in the study of chemistry.

A downloadable change document, *DP chemistry syllabus changes* (Excel), comparing the 2016 syllabus to this new version at the subtopic level is also available.

Acknowledgements

The International Baccalaureate (IB) would like to thank the educators who contributed time and resources to the development of the DP *Chemistry guide* and TSM.

Course overview

This section will help teachers become familiar with the structure of the course.

The course is organized under two main concept areas, structure and reactivity, with students' skills development as an overall integrated aim. The course structure reflects the fact that skills are best developed through a conceptual approach to teaching and learning. This approach suggests that a fundamental knowledge of atomic structure is key to understanding more complex structures and chemical reactivity.

<table>
<tr><th colspan="4">Skills in the study of chemistry</th></tr>
<tr><th colspan="2">Structure
Structure refers to the nature of matter, from simple to more complex forms</th><th colspan="2">Reactivity
Reactivity refers to how and why chemical reactions do or do not occur</th></tr>
<tr><td colspan="4">Structure determines reactivity, which in turn transforms structure.</td></tr>
<tr><td rowspan="5">Structure 1.
Models of the particulate nature of matter</td><td>Structure 1.1—Introduction to the particulate nature of matter</td><td rowspan="5">Reactivity 1.
What drives chemical reactions?</td><td>Reactivity 1.1—Measuring enthalpy changes</td></tr>
<tr><td>Structure 1.2—The nuclear atom</td><td rowspan="2">Reactivity 1.2—Energy cycles in reactions</td></tr>
<tr><td>Structure 1.3—Electron configurations</td></tr>
<tr><td>Structure 1.4—Counting particles by mass: The mole</td><td>Reactivity 1.3—Energy from fuels</td></tr>
<tr><td>Structure 1.5—Ideal gases</td><td>Reactivity 1.4—Entropy and spontaneity (HL)</td></tr>
<tr><td rowspan="4">Structure 2.
Models of bonding and structure</td><td>Structure 2.1—The ionic model</td><td rowspan="4">Reactivity 2.
How much, how fast and how far?</td><td>Reactivity 2.1—How much? The amount of chemical change</td></tr>
<tr><td>Structure 2.2—The covalent model</td><td>Reactivity 2.2—How fast? The rate of chemical change</td></tr>
<tr><td>Structure 2.3—The metallic model</td><td rowspan="2">Reactivity 2.3—How far? The extent of chemical change</td></tr>
<tr><td>Structure 2.4—From models to materials</td></tr>
<tr><td rowspan="4">Structure 3.
Classification of matter</td><td>Structure 3.1—The periodic table: Classification of elements</td><td rowspan="4">Reactivity 3.
What are the mechanisms of chemical change?</td><td>Reactivity 3.1—Proton transfer reactions</td></tr>
<tr><td rowspan="3">Structure 3.2—Functional groups: Classification of organic compounds</td><td>Reactivity 3.2—Electron transfer reactions</td></tr>
<tr><td>Reactivity 3.3—Electron sharing reactions</td></tr>
<tr><td>Reactivity 3.4—Electron-pair sharing reactions</td></tr>
</table>

Conceptual approach

The concept of structure

The topics of Structure 1–3 cover the concept area of structure.

The study of the structure of matter at the submicroscopic level is based largely on models. Although models represent reality in only limited ways, they help us understand and explain what cannot be seen. With new observations and evidence, models of matter have been developed over time—to explain, for example, the existence and behaviour of subatomic particles. Analytical techniques such as spectroscopy have greatly enhanced our knowledge of structure. This knowledge has enabled design and manufacture of materials with specialized purposes, such as breathable plastics, superconductors and new classes of therapeutic drugs.

In "Structure 1—Models of the particulate nature of matter", observations of the particulate nature of matter lead to the study of atoms as the defining unit of elements. The problem of scale, how we quantify what cannot be directly measured, is addressed by introducing the mole as a unit of amount of substance. From the number and arrangement of subatomic particles comes the familiar representation of elements in the periodic table. This enables predictions about the likelihood that atoms will react together, forming bonds.

In "Structure 2—Models of bonding and structure", understanding that atoms have different attractions for electrons leads to an exploration of different types of bonds: ionic, covalent and metallic. When atoms form bonds, the products have structures and properties of infinite variety. In the scientific community, these structures are named in ways that are unambiguous and internationally agreed.

In "Structure 3—Classification of matter", terminology and notation are introduced, based on both the periodic table and the International Union of Pure and Applied Chemistry (IUPAC) system of nomenclature.

The concept of reactivity

The topics of Reactivity 1–3 cover the concept area of reactivity.

The study of reactivity is based on questions that explore chemical change. During chemical reactions, reactants are transformed through the processes of bond breaking and bond making. These reactions happen when the free energy of products is less than that of reactants.

Chemical change is at the heart of industrial processes such as textile manufacturing, drug synthesis and resource extraction. Such processes supply many products for our modern world, but they sometimes make additional, unwanted side products that can have harmful effects on the environment. Many of the negative effects of chemical change can be ameliorated by applying the principles of green chemistry.

In "Reactivity 1—What drives chemical reactions?", investigating temperature changes during reactions leads to an understanding of the direction of energy transfer. Energy cycles are introduced as an application of the first law of thermodynamics and are used to track energy changes as reactants become products. Our dependence on various fuels, with a consideration of their relative benefits and burdens, is considered as an application of energy transfer.

In "Reactivity 2—How much, how fast and how far?", an understanding of the factors that influence the rate and extent of reactions is developed. These factors, which include the role of catalysts, allow for the control of conditions that will produce favourable outcomes. Stoichiometric principles are introduced to quantify changes in mass, and to assess yield and atom economy.

In "Reactivity 3—What are the mechanisms of chemical change?", the focus is on exploration of how reactions happen at the molecular level, and their mechanisms. Mechanisms are classified on the basis of the transfer or sharing of subatomic particles between reactants. In this way, we can see how an understanding of reactivity is based on application of a knowledge of structure.

Structure determines reactivity, which in turn transforms structure.

The teaching sequence

The topics can be taught in many different sequences. Although some knowledge of structure seems essential to build an understanding of reactivity, completing Structure 1–3 first is not necessary. Teachers may choose to follow the study of covalent bonding in Structure 2 with a study of some organic reactions in "Reactivity 3.3—Electron sharing reactions" and "Reactivity 3.4—Electron-pair sharing reactions". A study of equilibria in "Reactivity 2.3—How far? The extent of chemical change" may lead directly to a study of acid and base behaviour in "Reactivity 3.1—Proton transfer reactions". Examples of different possible routes through the syllabus are given in the section "Planning the teaching of the course" in this TSM. Teachers are encouraged to plan their own route according to their circumstances and interests. Wherever possible, teachers are encouraged to use local and global examples to extend students' appreciation and application of the course concepts.

Skills in the study of chemistry

The syllabus aims to encourage a hands-on inquiry approach wherever possible. Guided discovery and learning through seeing and doing is essential. The "Skills in the study of chemistry" section in the DP *Chemistry guide* summarizes the tools and inquiry process students are expected to experience during the course. This includes important laboratory techniques, mathematical and digital skills. Teachers are free to include these skills wherever they choose during the teaching of the course. Some linking questions in the understandings are connected to the "Skills in the study of chemistry" section, and these may prompt application of experimental work that is appropriate to the content. For example, use of distillation and reflux may be included in "Reactivity 3.2—Electron transfer reactions", where oxidation of alcohols is covered, or these skills could equally well be introduced in "Structure 1.1—Introduction to the particulate nature of matter", as part of studying separation and purification methods.

Nature of science (NOS)

It is expected that an awareness of the process of science pervades the course. An introduction to NOS is given in the guide and is covered in more detail in the "Nature of science" section of this TSM. Teachers are encouraged to include relevant examples and anecdotes from past and current scientific developments. Some linking questions in the understandings address NOS, to help prompt thinking about the scientific method.

Data booklet

The IB publishes a *Chemistry data booklet*, which contains the periodic table, relevant equations, constants, and tabulated data, specific to the course. Students must have access to a copy for the duration of the course, so that they can become familiar with its contents. Direct reference is made to the data booklet in the understandings section of the syllabus. This helps to maintain the emphasis on interpretation and application rather than memorization of data. A clean copy of the *Chemistry data booklet* must also be made available to students for all examination papers at both standard level (SL) and higher level (HL).

Syllabus structure and features

This section contains examples of guiding questions and linking questions from the *Chemistry guide* and suggests ways in which they can be incorporated into classroom discussion.

The structure and features of the syllabus are shown here. This diagram illustrates the format of the syllabus and explains the recurring headings from the *Chemistry guide*.

Subtopic name

The **guiding question** frames the subtopic. By studying the subtopic, students will be able to answer the question with increasing depth.

Standard level and higher level: 2 hours

Standard level and higher level must be covered for both SL and HL courses.

Each topic is divided into numbered **Understandings**. The first statement in **bold** is the content statement.

The second statement (and any further such statements) in normal text are the outcomes of learning and teaching.

This box clarifies the requirements and parameters of the skills and understandings students should acquire.

This box outlines **linking questions** from this subtopic to another in chemistry, or to "Skills in the study of chemistry" or "Nature of science". The questions can be asked in either direction. They signpost related concepts and encourage problem-solving beyond the immediate content. Teachers and students are encouraged to create their own linking questions.

Additional higher level content is only for the HL course.

The **recommended hours** should be sufficient to teach this subtopic. They should also be sufficient for assessment of learning, and to cover material from "Skills in the study of chemistry" and "Nature of science".

The time allocated to the experimental programme is in addition to these recommended teaching hours.

Reactivity 3.3—Electron sharing reactions

Guiding question: What happens when a species possesses an unpaired electron?

Standard level and higher level: 2 hours

Reactivity 3.3.1—A radical is a molecular entity that has an unpaired electron. Radicals are highly reactive. Identify and represent radicals, e.g. $\bullet CH_3$ and $Cl\bullet$.	
	Structure 2.1—How is it possible for a radical to be an atom, a molecule, a cation or an anion? Consider examples of each type.

Reactivity 3.3.2—Radicals are produced by homolytic fission, e.g. of halogens, in the presence of ultraviolet (UV) light or heat. Explain, including with equations, the homolytic fission of halogens, known as the initiation step in a chain reaction.	
The use of a single-barbed arrow (fish hook) to show the movement of a single electron should be covered.	Reactivity 1.2—Why do chlorofluorocarbons (CFCs) in the atmosphere break down to release chlorine radicals but typically not fluorine radicals? Structure 2.2—What is the reverse process of homolytic fission? Structure 2.2—Chlorine radicals released from CFCs are able to break down ozone, O_3, but not oxygen, O_2, in the stratosphere. What does this suggest about the relative strengths of bonds in the two allotropes?

Reactivity 3.3.3—Radicals take part in substitution reactions with alkanes, producing a mixture of products. Explain, using equations, the propagation and termination steps in the reactions between alkanes and halogens.	
Reference should be made to the stability of alkanes due to the strengths of the C–C and C–H bonds and their essentially non-polar nature.	Reactivity 2.2—Why are alkanes described as kinetically stable but thermodynamically unstable?

Additional higher level: None for Reactivity 3.3

Guiding questions

Each topic starts with guiding questions. Students may be able to answer the questions in different ways at different stages of their learning, with increasing depth and breadth as their understanding of the topic develops.

The guiding questions can be used to support learning and teaching as:

- **openers** for a subtopic
- suggestions for an **overview** of the content
- **tools** for the assessment of learning
- **stimuli** to help generate further guiding questions.

Each of these approaches is explored below using different examples of guiding questions from the guide.

Guiding questions as openers for a subtopic

The question may provide a prompt for discussions based on students' prior knowledge, either from earlier courses or from subtopics previously studied within the course. These discussions may help suggest ways to introduce the content.

The following two examples outline possible approaches.

Example 1

Structure 3.1—The periodic table: Classification of elements

Guiding question: How does the periodic table help us to predict patterns and trends in the properties of elements?

Prior knowledge

- The definition of "element"
- The periodic table as a classification system
- Common groups of elements, e.g. metals, non-metals
- Physical properties compared to chemical properties

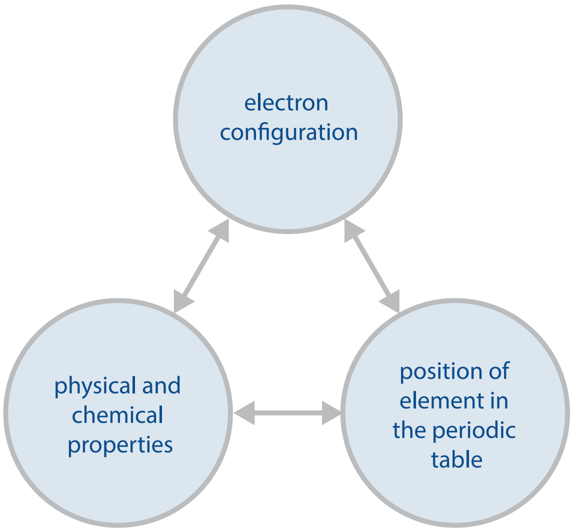
Ideas for opening discussions

- What properties were used historically to organize the elements?
- Why were there problems in using atomic mass to organize the elements?
- What inspired Mendeleev to leave gaps in the table?
- What are some examples of gradual, observable and predictable changes in physical and chemical properties of elements?

Developing understandings

- Explaining what unites elements in the same period, the same group and the same block according to their electron configurations
- Deducing the electron configuration of an atom from its element's position in the periodic table, and vice-versa
- Predicting an element's properties from its position in the periodic table

Connections to help develop understanding of the periodic table



NOS: The periodic table is a key example of organization in chemistry based on structure and reactivity. Early models of the table allowed for the making and testing of predictions, such as the properties of elements that had not yet been discovered.

Extending learning

- Discovery and naming of new elements
- Applications of rare earth elements in touchscreen devices and similar
- Metalloids and semiconductors

Example 2

Reactivity 1.3—Energy from fuels

Guiding question: What are the challenges of using chemical energy to address our energy needs?

Prior knowledge

- Increasing global energy demands resulting from population growth and economic development
- Increasing dependence of society on energy-driven technology
- Sources of energy used globally; different fossil fuels
- Air pollution, including particulates and smog
- Greenhouse gas emissions from combustion
- Problems of battery disposal

Ideas for opening discussions

- What are the differences between renewable and non-renewable energy sources?
- What are some advantages and disadvantages of each?
- What are some of the specific health and environmental impacts of the by-products of combustion?

Developing understandings

- The choice of fuel for a given activity may involve evaluating conflicting considerations. These include availability, energy per unit mass or volume, and the impacts of by-products and waste materials.

NOS: Scientific innovations are responsible for many of the conveniences we enjoy in the modern world, but they can sometimes have unintended consequences. It is also the role of scientists to find solutions to ameliorate any negative effects.

Extending learning

- Ways to reduce global energy demand
- Other aspects of the fossil fuel industry: hydraulic fracturing ("fracking"), building pipelines, oil spills on land and sea, carbon offsets, liquefied natural gas (LNG)
- The global warming potential of different greenhouse gases
- Land use and the "foods vs fuels" debate
- Microbial fuel cells
- Environmental issues related to the mining of ores
- The limited supply of elements such as uranium, lithium and rare earth metals, which will limit the extension of some technologies

Guiding questions as suggestions for an overview of the content

The guiding questions may be used as summaries by teachers to outline the expectations and timelines for the understandings within the subtopic.

Example

Structure 1.4—Counting particles by mass: The mole

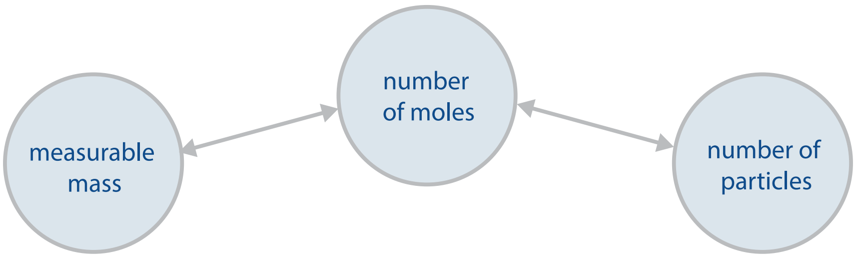
Guiding question: How do we quantify matter on the atomic scale?

The suggested timeline of seven hours for this subtopic includes significant time for practice questions and calculations in each of the understandings. It also includes time for the teaching and learning of practical skills in the study of chemistry.

Developing understandings

- Masses of atoms are too small to measure directly—introducing the Avogadro number and the mole as the unit of amount of substance
- The mole is a link between the number of particles and a measurable mass

Connections to help illustrate progressions of learning



- Quantification of matter, as it applies to:
  - atoms (A_r)
  - molecules or compounds—empirical and molecular formulae (M_r, M)
  - solute concentration in solution
  - gas volumes—Avogadro's law

NOS: The mole is a convenient way to describe numbers of atoms on a scale appropriate to the size of a measurable sample in grams.

Guiding questions as tools for the assessment of learning

The questions could be asked at various times within the study of the subtopics, looking for increasing breadth and depth of comprehension of the syllabus.

Example 1

Structure 1.5—Ideal gases

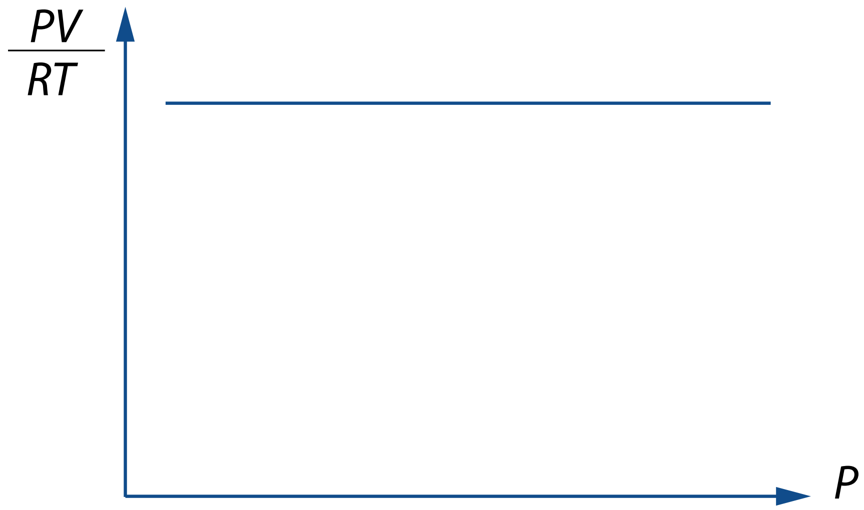
Guiding question: How does the model of ideal gas behaviour help us to predict the behaviour of real gases?

Developing understandings

- Explaining gas properties in terms of the properties of ideal gases only
- Calculations based on gas laws, molar volume, the ideal gas equation and graphical interpretations, such as shown here

Graphical interpretation using the ideal gas law

For a fixed mass of an ideal gas:



- Explaining gas properties considering conditions where assumptions in the model do not fully apply, for example:
  - at higher pressure—the volume of the particles is not negligible
  - at lower temperature—the interparticle forces become non-negligible
- Explaining gas properties considering how the nature of the gas may affect deviations from ideal gas behaviour, for example:
  - larger atomic or molecular volume
  - greater interparticle forces, such as between polar molecules
- Interpreting graphs to predict and explain conditions when either

$$\frac{PV}{RT} < 1$$

$$\frac{PV}{RT} > 1$$

- Collecting and analysing experimental data to calculate the molar mass of a gas from the ideal gas equation, including the evaluation of errors and assumptions

NOS: The ideal gas law is an example of a model that allows for the prediction and explanation of observed properties. Consideration of limitations in the application of the model can help achieve a deeper understanding.

Example 2

Reactivity 2.2—How fast? The rate of chemical change

Guiding question: How can the rate of reaction be controlled?

Developing understandings

- Explaining factors affecting rates of reactions in terms of the collision theory
- Explaining the role of catalysts in terms of reaction profiles showing activation energies
- Interpreting Maxwell–Boltzmann distribution curves to explain the effect of temperature and catalysts on the frequency of successful collisions

In many subtopics, the higher level (HL) course involves content that leads to more in-depth study. HL students should therefore be able to give a more extensive response to the guiding question by the end of the unit.

- Explaining the role of the rate-determining step in controlling the rate of the reaction
- Explaining the effect of concentration on reaction rate by analysing rate equations showing the order of reaction with respect to each reactant
- Explaining how the temperature dependence of the rate constant (in the Arrhenius equation) affects the rate of reaction

NOS: Explanations based on the kinetic molecular theory and collision theory are qualitative until this point.

Explanations based on application of the Arrhenius equation give a quantitative model to explain the effect of temperature change on reaction rate. This leads to testable predictions—data can be generated that lend support to the theory (HL).

Guiding questions as stimuli to generate further guiding questions

Teachers and students may consider additional guiding questions, which may be included at different points in the coverage of the subtopic. Such questions may be used to help learning and teaching in any of the ways described above.

Example 1

Structure 2.4—From models to materials

Guiding question: What role do bonding and structure have in the design of materials?

The relationship between structure and properties could be considered from the other direction, working backwards from the desired properties to the structure.

- How can application of the bonding triangle help to determine the components for materials with specific desired properties?

For example, a material that needs to be light, strong and an electrical conductor could have the structure of an alloy, a combination of more than one metal.

Example 2

Reactivity 3.4—Electron-pair sharing reactions

Guiding question: What happens when reactants share their electron pairs with others?

A different guiding question could aim to bring the wide range of examples of electron-pair donors and electron-pair acceptors into focus.

- What are the common features of electron-pair donors and of electron-pair acceptors?

Linking questions

Linking questions are found within many of the understandings. They are designed to promote networking across the syllabus and may suggest:

- links between different subtopics
- references to skills in the study of chemistry
- references to the overarching NOS theme in chemistry.

In seeking to answer these questions, students are encouraged to make connections across the syllabus to illustrate the interconnectedness of concepts and the holistic nature of the subject.

Teachers are encouraged to pose their own linking questions.

Students are expected to demonstrate networked knowledge as modelled through linking questions within the external assessment.

The linking questions can be used to support learning and teaching:

- as direct links between different subtopics
- to integrate skills in the study of chemistry
- to integrate NOS
- for applications of chemistry in a real-world context.

Each of these approaches is explored in this section using different examples of linking questions from the *Chemistry guide*. Note that each response answer is just one example of how a linking question might be answered.

Linking questions as connections between different subtopics

Linking questions can help to connect different areas of study where content overlaps. These questions are two-way links, which means that the related content can be covered in either subtopic.

Example 1

Reactivity 1.3.5—Linking question to Reactivity 3.2

What are the main differences between a fuel cell and a primary (voltaic) cell?

Guidance on the link

Voltaic cells are studied in Reactivity 3.2 as part of the study of electron transfer/redox reactions, while fuel cells are studied in "Reactivity 1.3—Energy from fuels". As both are important sources of energy derived from electron transfer, there is a link between them.

Response

Fuel cells use the oxidation of a fuel (e.g. H_2, CO, CH_4) to generate electrical energy, whereas a voltaic cell converts the energy released from a spontaneous redox reaction to electrical energy. Fuel cells rely on a continuous supply of reactants to release energy, whereas voltaic cells function until the fixed amount of reactants is used.

Ideas for context

- Advantages and disadvantages of different energy sources, including specific energy and density
- Side products
- Renewable and non-renewable sources
- Waste and waste disposal

Example 2

Structure 2.3.2—Linking question to Structure 2.4

What are the features of metallic bonding that make it possible for metals to form alloys?

Guidance on the link

The physical properties of metals are explained in "Structure 2.3—The metallic model" in terms of the delocalized electrons in their outer energy levels. An application of this is that metals can form alloys with different properties, as described in "Structure 2.4—From models to materials".

Response

Metallic bonding is non-directional as the delocalized electrons are not held in a fixed position. The cation lattice can accommodate ions of different sizes. Therefore, the ions of different metals can be scattered through the structure in the alloy, bonded with the delocalized electrons.

Ideas for context

Although there is no expectation to learn specific combinations of metals in alloys, some features of alloys in common applications, and their advantages over pure metals, could be considered.

Examples include aircraft construction, statues, coins, solder, electrical wiring and stainless steel.

Linking questions to integrate skills in the study of chemistry

Some linking questions refer to the “Skills in the study of chemistry” section. These link to the tools or the inquiry process. This section is in the DP *Chemistry guide* and summarizes the laboratory and practical experiences students must gain during the course.

Although teachers could include these skills within any topic, linking questions aim to be a prompt or a suggestion for appropriate experimental work that can enhance learning in a topic.

Example 1

Reactivity 3.2.2—Linking question to Tool 1, Inquiry 2

Why are some redox titrations described as “self-indicating”?

Guidance on the link

Tool 1 (Experimental techniques) includes redox titration as a specified applied technique. Inquiry 2 (Collecting and processing data) can be applied to experiments involving titration.

Redox titrations may be less familiar than acid–base titrations, but they are similarly used to measure the concentration of a substance in solution. Including redox titrations in the study of “Reactivity 3.2—Electron transfer reactions” is a good application of redox half-equations and balanced equations.

Specific examples of redox titrations with “built-in” colour change will help to make the point here. For example, in the reaction between $KMnO_4$(aq) and $FeSO_4$(aq), as Mn is reduced from oxidation state +7 to +2, the colour changes from deep purple to almost colourless. (HL students will be able to relate this to changes of colour according to transition metals’ oxidation states.) Students will benefit from seeing the abrupt colour change at equivalence first-hand—either in an investigation, a demonstration or an online simulation. The contrast can be made with acid–base titrations, where an indicator is added to signal the equivalence point, because the reactants themselves do not change colour.

Response

If one of the reactants in a redox titration changes colour as it changes oxidation state, a colour change will occur abruptly when the oxidizing agent and reducing agent are present in stoichiometrically equivalent amounts. This colour change can therefore be used to determine the equivalence point of the reaction without the addition of an indicator.

Ideas for context

Redox titrations are used for assay and quality control in:

- the food and beverages industry
- water and environmental analyses
- the pharmaceutical industry.

Example 2

Reactivity 1.3.2—Linking question to Inquiry 2

What might be observed when a fuel such as methane is burned in a limited supply of oxygen?

Guidance on the link

The study of fuels in “Reactivity 1.3—Energy from fuels” includes comparison of the products of complete and incomplete combustion of organic compounds. By linking to Inquiry 2 (Collecting and processing data), this linking question emphasizes the observations or qualitative data that accompany these reactions. In the laboratory, students may notice carbon deposits when Bunsen or alcohol burners heat substances in insufficient oxygen. Practical considerations include possible changes in mass due to deposition on crucibles or glassware during heating, which is a common source of experimental error.

Response

A smoky flame and deposits of soot (impure carbon particles) on surfaces might be observed.

Ideas for context

The incomplete combustion of hydrocarbons, which has many health and environmental effects, includes the release of:

- carbon monoxide, which is toxic at higher concentrations
- particles of unburned carbon, which cause damage to plants and human respiratory systems, and reacts with nitrogen oxides to produce smog.

Linking questions to integrate NOS

Some linking questions make reference to the overarching NOS theme, which is described in more detail in the DP *Chemistry guide*. These are designed to stimulate links to aspects of NOS in other parts of the course.

Example 1

Structure 1.2.2—Linking question to NOS and Reactivity 2.2

How can isotope tracers provide evidence for a reaction mechanism?

Guidance on the link

This linking question applies the study of isotopes in "Structure 1.2—The nuclear atom" to the use of radioactive isotopes in research. Although the HL course covers reaction mechanisms in more depth (e.g. "Reactivity 2.2—How fast? The rate of chemical change"), the basic idea that a reaction is a sequence of steps involving bond making and bond breaking is important for the standard level (SL) course, too. There are examples of this in "Reactivity 3—What are the mechanisms of chemical change?"

The link to NOS is based on a consideration of this question: what constitutes evidence for a particular mechanism? The steps in a reaction cannot usually be directly observed, so any evidence is indirect. Evaluating a mechanism therefore involves checking that it is consistent with all data, including from kinetic studies and from the overall stoichiometry. Mechanisms can be disproved when they do not satisfy one of these criteria. But can it be said that a proposed mechanism is proven to be correct? Specific examples might be useful here.

- In studying the mechanism of photosynthesis ("Reactivity 1.3—Energy from fuels"), use of the heavy isotope ^{18}O showed that the oxygen released as a product came from the reactant H_2O, not from CO_2. This indicated that the reaction mechanism must involve splitting water molecules.
- In the study of the condensation reaction in esterification (HL "Structure 2.4—From models to materials"), ^{18}O in labelled alcohol is detected in the ester product, not in the water. What might this suggest about the reaction mechanism?

Links could also be made to analytical techniques in HL "Structure 3.2—Functional groups: Classification of organic compounds" for the detection of isotopes in intermediates and products.

Response

Isotope tracers are used to "label" a substance so that it can be detected at the different steps of a reaction. This is possible because the isotope tracer's chemical behaviour is the same as its more common isotope, the "label": but the tracer can be detected because of its distinct mass and, in some cases, its radioactivity. Data from isotope tracer studies may provide evidence for a proposed reaction mechanism, but supporting data (e.g. from kinetic studies) are also needed. Mechanisms cannot be observed directly, so all evidence is indirect. This may lead to a proposed mechanism that is consistent with the data, but not to certainty.

Ideas for context

Other applications of isotope tracers include:

- geological dating
- measuring distribution of substances in organisms and waste
- monitoring fluid flow and detecting leaks
- medical diagnosis and treatment.

Example 2

Structure 2.2.8—Linking question to NOS

How can advances in technology lead to changes in scientific definitions, e.g. the updated IUPAC definition of the hydrogen bond?

Guidance on the link

This link to NOS considers how technology often limits the data we can collect. Greater instrument sensitivity—especially in spectroscopy—has expanded those limits, and we can now detect effects not measured previously, such as weak intermolecular forces of attraction. The definition of the hydrogen bond has been broadened to include these weaker attractive forces; it no longer focuses entirely on molecules in which H is bonded to N, O or F. Instead, hydrogen bond formation is now considered when H is covalently bonded to any electronegative element, if there is evidence of bond formation between H and a nearby electronegative atom. This can include molecules where Cl, S and even C (if bonded to electronegative atoms, such as in $CHCl_3$) are bonded to hydrogen. The strength of these hydrogen bonds diminishes with the decreasing electronegativity of the element bonded to hydrogen.

Memorizing definitions is not the intention here, and students will not be asked to do so in assessment. The emphasis should be on explaining the origins of the hydrogen bond in terms of shifts in electron density within and between molecules, and identifying hydrogen bonds according to this updated definition.

The paper that led to the change in the IUPAC definition of a hydrogen bond is at http://publications.iupac.org/pac/pdf/2011/pdf/8308x1619.pdf (Arunan et al., 2011).

Response

The updated definition of the hydrogen bond includes weaker interactions than were previously detectable. Hydrogen bonds are now described in situations where H, covalently bonded to an electronegative atom (not just F, N and O), shows evidence of bond formation with a nearby electronegative atom, for example in HCl, H_2S and $CHCl_3$. This broader definition is possible because more advanced technology has led to the detection and measurement of weaker forces of attraction, providing evidence of bond formation.

Ideas for context

- Hydrogen bonding. For example:
  - anomalous properties of water—high boiling point, expansion of H_2O on freezing
  - intramolecular hydrogen bonds in DNA and proteins; replication of DNA
  - receptor–ligand interactions in drugs and materials science.
- Advances in technology, more precise measurements and the possibility of tighter regulation. For example:
  - legal concentration limits of alcohol for driving or for operating machinery
  - drug testing in sports
  - detecting lower concentrations of pollutants in air and water.

Many linking questions, while focusing on linking different subtopics, also provide opportunities to consider aspects of NOS. The example above demonstrates this, scrutinizing the assumptions and limitations of models.

Example 3

HL Structure 2.2.14—Linking question to Structure 3.1 and Reactivity 3.2

What are the different assumptions made in the calculation of formal charge and of oxidation states for atoms in a species?

Guidance on the link

The linking question leads to the comparison of two concepts that otherwise would likely be taught separately: formal charge (in HL "Structure 2.2—The covalent model" (2.2.14)) and oxidation state (in "Structure 3.1—The periodic table: Classification of elements" and "Reactivity 3.2—Electron transfer reactions"). Both serve as electron record-keeping tools. The numbers for formal charge and oxidation state assigned to atoms are not "real": they do not represent true charges in a molecule but are based on agreed conventions. They are opposites in how they represent the distribution of bonded electrons.

- Oxidation state—"winner takes all" (full charge separation as a result of electronegativity differences between bonded atoms)
- Formal charge—"equal sharing" (electrons are equally distributed regardless of the electronegativity difference of the bonded atoms)

As these assumptions do not distinguish between partial and complete transfer of electrons in bonds, these concepts do not have a structural basis and therefore have limitations.

Response

Oxidation states are assigned to each atom in a molecule assuming that charge separation has occurred between two bonded elements according to the difference in their electronegativities. Formal charge assigns a charge value to each atom in a molecule assuming there is no charge separation between bonded atoms. Oxidation states are usually used to track changes in redox reactions; formal charges are used to determine the relative stability for different models of molecular structure.

Ideas for context

- Oxidation state
    - In chemical nomenclature this is sometimes known as the oxidation number. In chemical names, such as for coordination compounds, Roman numerals are used to denote the oxidation state of the transition element with a variable oxidation number. For example, $FeCl_3$ is iron(III) chloride.
    - It is used in balancing redox equations and identifying redox change in reactions.
- Formal charge
    - This is used to determine the most stable Lewis structure—the one with the lowest formal charge, as charge separation requires energy.
    - Where two alternative Lewis structures have the same values for formal charge, the preferred structure places the negative charge on the more electronegative atom.

Linking questions to apply chemistry in a real-world context

Some linking questions make an explicit connection to applications of chemistry in our world, and include an environmental, ethical, social or economic focus. These questions are designed to prompt similar questions promoting links to relevant topical issues throughout the course.

Example 1

Reactivity 3.2.1—Linking question to Structure 2.3

The surface oxidation of metals is often called corrosion. What are some of the consequences of this process?

Guidance on the link

It is estimated that 3% of the world's economic output is spent dealing with corrosion. It could be considered a case study of oxidation as covered in "Reactivity 3.2—Electron transfer reactions", in the context of metallic bonding described in "Structure 2.3—The metallic model". Although the formation of rust from iron is the most obvious example, it is worth considering the oxidation products of other metals, such as copper. The widespread impact of corrosion can likely be observed first-hand in a local context.

The chemistry of corrosion effectively reverses the reduction process by which metals are refined from their ores. It occurs because of the greater chemical stability of the oxidized forms of the metal.

Response

Corrosion is the deterioration of the surface of a metal resulting from its oxidation by contact with air or water. A common example is iron, which loses its strength when it oxidizes, forming rust at the surface. The widespread problems of corrosion include:

- loss of structural strength in buildings, vehicles, bridges
- leakage in pipes and chemical plants

- fires resulting from corroded electrical contacts; these threaten the safe disposal of nuclear waste, with health and financial implications.

Ideas for context

Ways of mitigating the effects of corrosion include:

- applying protective coatings such as paint
- using alloys such as stainless steel and nickel-based alloys
- galvanization (sacrificial protection)
- cathodic protection.

Example 2

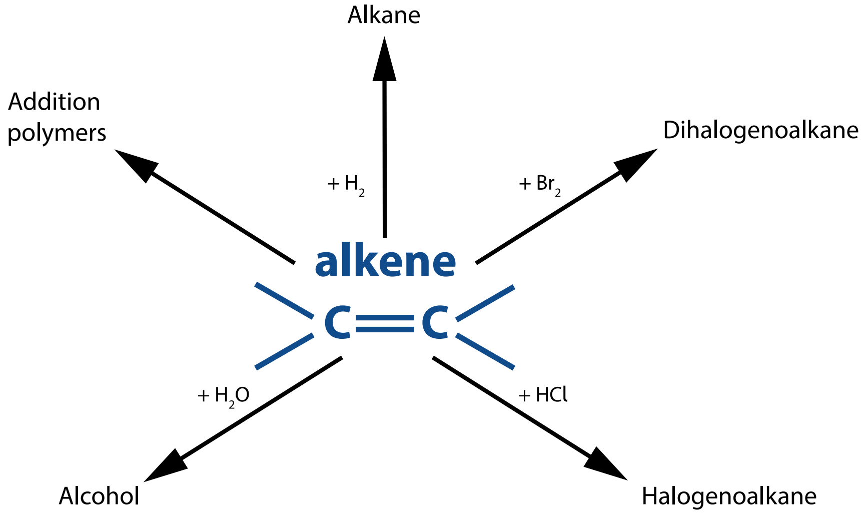
Reactivity 3.4.5—Linking question to Structure 2.4

Why are alkenes sometimes known as "starting molecules" in industry?

Guidance on the link

The electron density of the carbon–carbon double bond in alkenes explains their reactivity in electrophilic addition reactions. As the double bond breaks, new atoms or groups attach to the carbon atoms, forming different classes of compounds. Examples of these reactions are given in "Reactivity 3.4—Electron-pair sharing reactions" (3.4.5), and form the basis of synthetic pathways, linked to the development of new materials in "Structure 2.4—From models to materials".

Synthetic pathways from alkenes



Response

Alkenes can undergo many different addition reactions when the carbon–carbon double bond is broken. Compounds formed include alkanes, alcohols, halogenoalkanes, dihalogenoalkanes and addition polymers. These molecules may then react further to form many different compounds. Alkenes therefore play a central role in synthetic pathways leading to the synthesis of new materials.

Ideas for context

Synthetic pathways in organic chemistry produce target molecules from starter molecules by changing:

- the functional groups
- the length of the carbon chain.

These pathways are used in the synthesis of many materials, an example being pharmaceuticals. Green chemistry principles are of key importance in these applications.

Nature of science (NOS)

The rationale for NOS

Students develop a thorough and lasting understanding of the natural sciences, which has value on several levels.

1. It develops scientific literacy—being able to engage with local and global scientific issues is central to many of the qualities in the IB learner profile.
2. It provides a framework in which students can more easily access science subjects, as in the following examples.
   - Knowing that models have limitations can prevent confusion when students are asked to apply different atomic models to explain different phenomena.
   - Knowing that established rules often have exceptions may allow for more flexible thinking, e.g. when determining electron configurations using the octet rule.
   - Appreciating that technological developments can open up new possibilities for computational modelling allows for the understanding of complex systems.
3. It supports student learning in theory of knowledge (TOK)—NOS understandings are the starting point for being able to think critically about the natural sciences and knowledge more broadly.

Engaging with NOS

Teachers are not expected to address NOS as a stand-alone topic, but instead to integrate it within the teaching of the subject. As always, it is best to vary the style of teaching rather than resort to a formulaic strategy for NOS. Several approaches are outlined here.

- It is often helpful when introducing new scientific concepts to frame them in terms of the progression of science and the use of scientific methodologies. This might mean briefly revisiting a preceding model or theory, or reviewing the evidence or technology that led to new understandings.
  - The Bohr model of the atom was formed due to new evidence (from atomic emission spectra) that could not be explained by Rutherford's model.
- The experimental programme allows for the exploration of many aspects of NOS. Additional activities can help to strengthen students' understandings.
  - Students could be presented with an experimental procedure that has clear methodological problems (e.g. it does not indicate when to stop a stopwatch during a rates-of-reaction experiment). They are asked to critique it to ensure valid data are produced. The critique can be done before, during or after the practical work.
  - Students could be provided with a data set that may or may not be as expected. Students carry out the experiment and share data to compare with the teacher's data set. This can highlight the importance of reproducibility and reliability.
  - Students could be asked to find data in the literature for further comparison.
  - The activities above could be connected so that features of the peer-review process are discussed.
- NOS might be used to set the scene and form the introduction to a topic. A teacher may choose to begin a lesson by presenting a current news article, past event or topic of debate. Alternatively, a retrospective approach could be taken, with the final minutes of a lesson or a homework task being used to look at the NOS aspects exemplified by the topic.

- A short “circus activity” (e.g. after reviewing a topic or subtopic) can be used to discuss the impact of science on society. Students rotate around five stations and are given two minutes to brainstorm possible impacts on the environmental, political, social, cultural and economic domains. A short discussion could follow to identify which area of society might be most impacted.

Real-life example	What issue is highlighted in the example?	Which aspect of NOS does the example demonstrate?
An article comparing predictions of the spread of COVID-19 based on mathematical modelling to data on virus transmission	Differences between predicted and actual transmission data suggest there are limitations to mathematical modelling in science.	Scientific models always have strengths and limitations.
Retraction by Professor Frances Arnold, a Nobel laureate in Chemistry, of a research paper she and co-researchers wrote in 2019	She explained that the results in the paper were not found to be reproducible in other studies.	Data must be reproducible before it can be considered scientifically reliable.
Nuclear power as a carbon-neutral but controversial energy source	Environmental and economic advantages to using nuclear energy must be weighed against ethical issues and environmental problems.	Ethical, environmental, political, social, cultural and economic consequences must be considered during (governmental) decision-making.

Examples of integrating NOS

The format that follows might be used to integrate relevant NOS aspects and other concepts that are related to experimental work, for example **hypothesis**, **reproducibility**, **reliability**, **validity**, **prediction** and **uncertainty**.

Outline	Example content (focusing on reproducibility and reliability)
Introducing NOS aspects —10 minutes	Show students an article about or tweet from Professor Frances Arnold, a Nobel laureate in Chemistry, relating to her announcement in early 2020. She retracted her 2019 paper on enzymatic synthesis of beta-lactams because the results were not reproducible. Now discuss the following questions. • What is meant by “reproducible”? • Why is reproducibility important? • How might reproducibility affect reliability? • How might the scientific community have responded?
Group experimental work —40 minutes	Any data collection can be used here to fit a topic. Ideally, small groups each collect one set of data for a range of independent variable values. Examples are: • concentration of reactant vs time in a rates-of-reaction experiment • number of carbons in a primary alcohol vs enthalpy change of combustion in a calorimetry experiment.
Review of NOS concepts —10 minutes	A class discussion around NOS concepts could include the following questions. • How do individual data points from different groups compare? They would be expected to be similar but not necessarily identical. Standard deviation could be used to quantify this.

Outline	Example content (focusing on reproducibility and reliability)
	• How are anomalies identified? Some educated judgement would be required to find them. If anomalies are not obvious, further repeats or checks of other secondary data may be used. • How do different groups' trendlines compare? If data are reproducible, general trends will be the same. • Would students consider the collected data to be reproducible? • How might the above points link to the reliability of the data?

NOS and the external assessment

There will be some assessment of NOS, reflecting its role as an overarching theme of the DP sciences course. The assessment questions will test general understanding of NOS, not memorization of detailed facts relating to individual NOS statements. For this reason, there is merit in teachers using contexts other than those specified in the syllabus to help to develop students' NOS understanding.

Thorough understanding of NOS will help students to perform well in data analysis questions. Skills in understanding, interpreting and analysing data presented in a variety of forms is another transferable outcome from an effectively taught course.

Students could be given a copy of the NOS table in the subject guide, either at the start of the two-year course or at the start of the revision period as the end of the course approaches. The table includes all NOS aspects and their descriptions. If a copy is provided, teachers should emphasize that this is not something to be memorized, but instead should be used for reference and for helping to develop understanding.

NOS and TOK

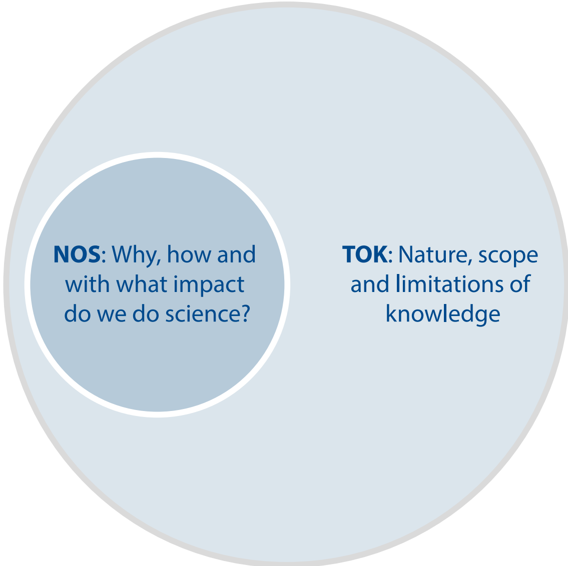
In TOK, students are encouraged to consider how knowledge claims are generated, evaluated, used and justified. This should promote an understanding of the differences between the natural sciences and disciplines such as mathematics, economics and languages.

The NOS component of the course has been designed to give students an excellent understanding of a natural science as an academic discipline. It should be a source of pride to teachers that their students can speak confidently and reflectively about natural sciences in TOK lessons. This will happen if the NOS component is integrated effectively into the teaching of the course.

Ideas relating to TOK can be addressed throughout the course. When and how frequently this is done is left up to teachers, and no specific TOK items have been included in the syllabus. There is no specific assessment of TOK in DP science examinations, although understanding of the aspects of NOS is assessed.

A Venn diagram can be used to illustrate the relationship between NOS and TOK.

The relationship between NOS and TOK



NOS focuses on understanding science through concepts such as **evidence**, **patterns and trends**, **falsification**, **theories** and **global impact of science**. These are central to scientific literacy and are considered only in the context of science.

In TOK, students are expected to think critically about their NOS understandings by exploring broad, underlying and often overlapping concepts such as **evidence**, **certainty**, **justification**, **objectivity** and **responsibility**. Considering the tensions, limitations and challenges related to these concepts in contrast with other areas of knowledge production should lead to student understandings that are nuanced and contestable. Some examples of the types of questions teachers might ask in TOK—"knowledge questions" —and possible responses to these, are provided in the following table.

Knowledge question*	Possible ideas to explore
What kinds of explanations do natural scientists offer?	• The role of scientific theories • The need for and limitations of using imagination in explanations • The extent to which we can claim certainty in a theory
How do we ensure the validity of evidence in the natural sciences?	• Problems with using inductive reasoning • The role of reproducibility • The limitations of peer review
How should we decide on appropriate ethical constraints on scientific research?	• The role of the scientific community in society • Possible tensions, e.g. for-profit companies funding healthcare research • Difficulties defining moral values

* Although these questions are focused on the natural sciences, they could equally be applied to and explored in other disciplines, such as history or the arts.

Building from NOS to TOK

NOS aspects can be extended to ask broad TOK questions (knowledge questions) that might lead to a range of possible perspectives and arguments. The *Theory of knowledge guide* highlights concepts that could be used in this exploration: **evidence**, **certainty**, **truth**, **interpretation**, **power**, **justification**, **explanation**, **objectivity**, **perspective**, **culture**, **values** and **responsibility**.

Asking a broad question containing a TOK concept*	Example perspectives in response to the knowledge question	How might we consider the question in other areas of knowledge beyond the subject?
How accurate must predictions be to justify a claim?	Perspective 1—A scientific law such as the conservation of mass must be 100% accurate within its parameters. Perspective 2—Apparent rules in chemistry often have exceptions and so cannot always be used to make accurate predictions.	Human sciences—the complexity of analysing human behaviour makes predictions inherently less accurate. Psychology—psychologists try to predict human behaviour through experience (past behaviour), experimentation and observations. Some approaches to understanding behaviour are reductionist while others take a holistic approach and take into account several factors (biological, cognitive and sociocultural). The arts—predictions are constantly tested and repurposed in the creative process. Artworks' claims are never limited to what was predicted. History—although facts, interpretations and conjectures in history may be useful to inform and have a better understanding of present and future events, they are not meant to serve as predictions. Additionally, "hindsight bias" may lead to an apparent prediction after events occur.
Does replicable data imply we are certain of our knowledge?	Perspective 1—The ability to replicate data reliably improves our confidence in the data. Perspective 2—Methodological errors may impact the validity of replicated data.	The arts—how do we consider replicas? Psychology—the field of psychology is currently experiencing a "replication crisis", resulting in concerns over the credibility of research findings. This crisis has led to the questioning of psychological research practices and findings. History—biased/partial or incorrect information in a source may be replicated in many secondary sources, which does not make the knowledge they provide more certain. A piece of information repeated in thousands of sources by mistake may lead to flawed/incomplete knowledge of historical events. In the same manner, the existence of similar accounts of a historical event (which could be considered "replicable/ confirming data") does not mean we can be absolutely certain of them.
What counts as enough evidence to corroborate a theory?	Perspective 1—The more evidence the better. Perspective 2—The type of evidence (i.e. quantitative vs anecdotal) is more important than the amount.	Mathematics—a theorem in mathematics depends on logical certainty (rigorous proof) and not "weight of evidence" (amount). Psychology—psychological theories assist in explaining and predicting human behaviour. Through research, evidence is obtained to either support or refute a theory; however, nothing is ever "proven" in psychology. Human sciences—confirmation bias (the focus or framing of a theory/hypothesis) might determine what evidence is considered and collected. Researchers may disregard evidence that contradicts a theory because they may not be looking for it.

Asking a broad question containing a TOK concept*	Example perspectives in response to the knowledge question	How might we consider the question in other areas of knowledge beyond the subject?
		Many studies in human sciences have been criticized recently because they have been conducted in relatively homogenous settings (e.g. capitalist economies, Western societies and educated populations), making the generalizations drawn from them applicable only to certain populations. This is the WEIRD ("Western, educated, industrialized, rich and democratic") critique. History—looking for sources that originated in diverse contexts (rather than just more evidence from similar sources) is necessary for getting a more complete picture. Historical arguments and narratives are constructed through available evidence, so considering the origin (and purpose) of sources, as well as their limitations, is important. Even after gathering a considerable amount of evidence, historians can make conclusions that may be valid but ultimately untrue (or only partially true). Arts (literature)—in order to present a particular interpretation (theory) of a work of art, sufficient coherent evidence needs to be presented to support it. The more evidence available to support an interpretation (in this work alone or in others by the same artist, period/ movement, etc.), the more valid it can be considered.

* This is a simple way to form a TOK question, but it is by no means the only way.

Introduction

This section aims to explore and illustrate approaches to learning and approaches to teaching in the context of Diploma Programme (DP) chemistry. This course is distinct in that it is part of the IB Diploma, where concurrency of learning in different areas of study is emphasized. Connections are therefore encouraged with your students' other IB courses, and with both your local and the global context.

The IB approaches to learning and approaches to teaching offer a framework of deliberate skills and attitudes underpinning learning and teaching. These approaches aim to support the IB mission and develop skills that enhance students' learning, both during and beyond their DP experience. Connections are therefore made to the learner profile attributes and international-mindedness, and other features at the heart of an IB education, not least a broadly constructivist and student-centred approach, where contextual relevance, concurrency of learning and a connected curriculum are paramount.

The **approaches to learning** framework comprises five skills groups.

1. Thinking skills
2. Communication skills
3. Social skills
4. Self-management skills
    - Organizational skills
    - Affective skills
5. Research skills

The approaches to teaching refer to the six pedagogical principles that underpin IB programmes.

1. Teaching based on inquiry
2. Teaching focused on conceptual understanding
3. Teaching developed in local and global contexts
4. Teaching focused on effective teamwork and collaboration
5. Teaching designed to remove barriers to learning
6. Teaching informed by assessment

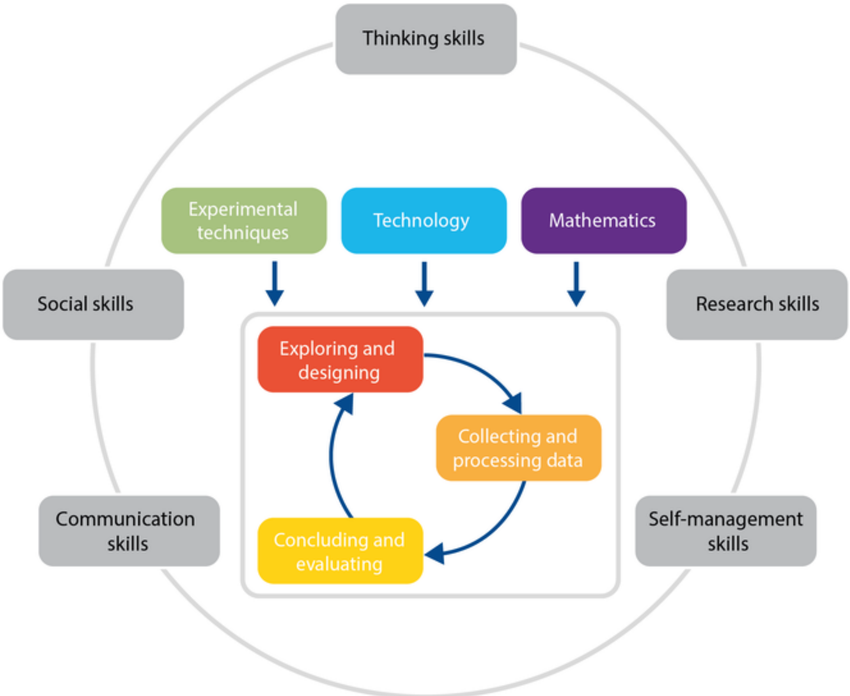
IB authorization and evaluation processes require schools to demonstrate implementation, development and review of the approaches to learning and approaches to teaching, as they relate to the *Programme standards and practices*.

This section therefore suggests how to develop different approaches to learning and approaches to teaching, for example sharing ways to help foster conceptual understanding. There are also ideas for including international-mindedness in the course, and suggestions linking topics to real-world contexts. These aim to enhance students' interest and help them see the relevance of their learning to current global challenges.

Approaches to learning

The approaches to learning framework aims to develop skills in students that support their learning throughout the DP/Careers-related Programme (CP) and beyond. They are interconnected and together support the development of the skills in the study of chemistry.

Tools and inquiry process for developing skills in chemistry



Thinking skills

Thinking skills are a broad category of approaches to learning, focusing on critical thinking, metacognition and reflection. The purpose is to develop not only discipline-specific tools in students but also curiosity, open-mindedness and creativity (International Baccalaureate, 2015). This approaches to learning skill category is connected to learner profile attributes, most significantly **thinkers**, which involves analysing and tackling problems as well as reaching reasoned, ethical decisions (International Baccalaureate, 2020a).

Nature of science (NOS) and the skills in the study of chemistry are two overarching frameworks in the chemistry curriculum. The relationship between these frameworks and approaches to learning is bidirectional: thinking skills are cultivated by and help to integrate NOS and experimental skills and techniques into the course. For example, patterns and trends are a central feature of scientific knowledge production identified as an aspect of NOS. The metacognitive awareness developed through thinking skills helps students identify and explore trends in their study of chemistry and at various stages of the inquiry process. Conversely, tools such as technology and mathematical skills can support the exploration of patterns and trends, which in turn helps to build thinking skills.

Examples

- Metacognition—students sharing their thought processes as they work through an explanation, test question or numerical exercise. Topics that are thoroughly interconnected, such as redox and enthalpy cycles, are good opportunities to support this.
- Metacognition and reflection—exploring then reflecting on different ways to remember parts of the syllabus content. For example, the required polyatomic ions can be recalled through a variety of techniques: memorization, flash card drills, mnemonics and association with conjugate pairs.
- Reflection—using visible thinking routines such as "Connect, Extend, Challenge" to reflect on learning, or "I Used to Think … Now I Think …" to explore changes in thinking (Project Zero, 2015).
- Critical thinking—discussing patterns with peers across the entire programme, and doing this collaboratively and frequently. Opportunities to support this include periodic trends, boiling point trends within a homologous series, trends in data collected through primary and secondary means, and analysis of data trends using technology and mathematical tools.
- Critical thinking—discussing ethical implications of advances in and applications of chemistry. Examples include the peer-review process and the application of green chemistry principles in classrooms and industry.
- Critical thinking—testing generalizations, assumptions, hypotheses and conclusions. Examples include exploring assumptions about heat loss or specific heat capacity in calorimetry experiments and testing the effect of the strength of intermolecular forces or their type on the applicability of the ideal gas law.
- Critical thinking—applying knowledge in familiar and unfamiliar situations.
- Visible thinking—engaging in practices that help make thought processes visible, such as "I Used to Think … Now I Think …" (Project Zero, 2015). An example activity to support this is contained in the downloadable resource "Visualizing the effect of different factors on crystal field splitting energy" (PDF).

Communication skills

Communication covers a range of applications, media and skills. Good communication allows students to convey their understanding in assessments, and facilitates learning, formative assessment, interpersonal relationships and collaboration (International Baccalaureate, 2015).

Communication skills include spoken and written communication, as well as listening and body language. In chemistry, where particle phenomena are often presented using equations, diagrams and graphs, diagrammatic and mathematical communication also play an important role. The international application of chemical symbols is another aspect of communication specific to the subject.

Successful communication also includes constructing arguments and clear lines of reasoning. These can be used in articulating and organizing written and verbal answers, in scientific investigation and in mathematical calculations.

Communication skills clearly underpin the **communicator** learner profile attribute. Effective communication is bidirectional: not only conveying personal views and understanding, but also listening to the views of others (International Baccalaureate, 2019). Actively seeking and reflecting on other perspectives is also a feature of being **open-minded**, and therefore ties in with the IB principle of international-mindedness.

Examples

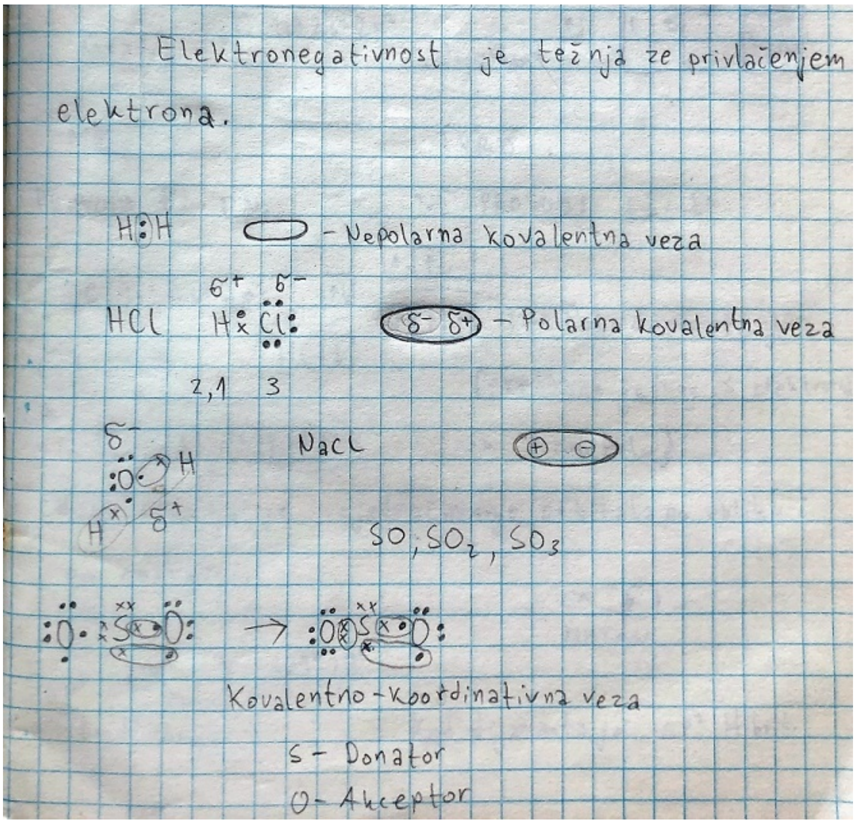
- Verbal—using visible thinking routines such as "Think, Pair, Share" (Project Zero, 2015) encourages students to engage in dialogue about the syllabus content. This gives them opportunities to practise using scientific vocabulary to articulate their understanding.
- Written—explicitly teaching methods for drafting and redrafting pieces of extended writing that are particularly suited to a scientific investigation. For example, students could practise reviewing writing at different levels.

Students use a piece of written work, e.g. an extract from an example scientific investigation.

- They assess its focus and its organization of ideas by extracting the main themes in each paragraph.
- They review how clearly each paragraph conveys its main ideas.
- They read the extract again, focusing on spelling and grammar errors, including chemistry-specific communication errors, involving (for example) significant figures, nomenclature and units.

- Written and visual—creating a scientific poster to summarize the outcome of an inquiry, instead of writing an extensive laboratory report.
- Diagrammatic—comparing and contrasting different diagrams showing a particular phenomenon. Discussing the use of labels, symbols, possible misconceptions.
- Symbolic—using chemistry texts written in a different language so that students can discuss how much they are able to infer from it, drawing on their knowledge of chemistry and chemical symbols. The image of the chemistry notes here is one example.

Set of high school chemistry notes written in Bosnian-Croatian-Montenegrin-Serbian



Social skills

Students' social skills operate at various levels: among students, between students and other members of the school community, between students and the local community, and between students and the much wider global community. Effective social skills not only support learning, but also broaden the mind and encourage responsible global citizenship. The broad relevance of social skills can be observed across several learner profile attributes (International Baccalaureate, 2020a).

- **Inquirers**: learning with others

- **Risk-takers** and **communicators**: collaboration
- **Principled**: respect for the rights of others
- **Open-minded**: seeking other points of view
- **Caring**: empathy, compassion and respect

In chemistry, social skills can be incorporated into learning processes by explicitly teaching communication and collaboration strategies, as well as locating the course content in local and global contexts. The collaborative sciences project is an excellent opportunity to focus on certain social skills, given its primary focus on collaboration. In addition, the project's emphasis on the United Nations Sustainable Development Goals fosters awareness of global issues and thus an awareness of the situations of others.

Examples

- Students completing the collaborative sciences project.
- Students completing a risk assessment for student-designed experiments that considers risks to self, to others and to the environment, and ways to minimize the risk.
- Providing a model of constructive and balanced feedback, and giving students explicit guidelines on giving each other feedback.
- Students and teachers working together to establish expectations through which learner profile attributes are applied, to:
    - support an empathetic, compassionate and respectful learning environment
    - encourage discussion and exploration in an atmosphere of attentive listening and critical thinking (e.g. Socratic seminars).
- Problem-solving in small groups. For example, groups could work together to analyse spectral data to determine the structure of an unknown substance.

Self-management skills

Self-management skills are classified into two categories.

- Organizational skills
- Affective skills

Organizational skills cover the management and organization of time, tasks and resources. Effective organization can encourage balance and help to develop independence in students. These skills are therefore connected to the **balanced** and **inquirer** learner profile attributes, respectively.

Affective skills are related to traits such as state of mind, self-motivation and resilience. This set of skills is linked to the learner profile attribute of being **risk-takers**, which seeks to equip learners with the determination and forethought needed to face uncertainty, challenges and change (International Baccalaureate, 2020a).

Examples

- Organizational skills
    - Setting interim deadlines for long tasks and projects such as the scientific investigation or extended essay.
    - Exploring revision techniques such as concept mapping, note-taking and use of flash cards.
    - Explicitly teaching effective use of practice questions and markschemes.
    - Discussing strategies for organizing files, both digital and paper-based.
- Affective skills
    - Providing opportunities for low-stakes retrieval practice to build fluency, understanding and motivation.

- Using strategies to identify and fill knowledge gaps, such as thorough test corrections or question and answer sessions.
- Encouraging self-reflection to acknowledge progress and identify areas of opportunity.

Research skills

Research skills encompass competence with a range of skills that need to be deliberately taught and practised. These include finding out background information, conducting preliminary experiments, composing research questions, and collecting and analysing data. Implicit in much of this is evaluation, for example of data, hypotheses, sources, arguments, methodologies, uncertainties. This set of skills is deeply connected to the inquiry process and thus the inquirer learner profile attribute (International Baccalaureate, 2020a).

Research skills figure heavily in the skills in the study of chemistry, the collaborative sciences project, the scientific investigation and the extended essay.

Examples

- Developing strategies to organize references.
- Providing opportunities for presenting results of extended research projects in condensed formats, e.g. scientific posters.
- Discussing the common features of good research questions, using examples of both good and poor quality.
- Organizing class activities involving collecting data from databases, e.g. molecular geometry data, spectral data and thermodynamic data.
- Comparing the reliability of different information sources, e.g. the portrayal of a scientific news item in various media sources.
- Designing and using activities involving processing, analysing and evaluating experimental results. These could be heavily scaffolded in the beginning, then gradually less so as students build up the required skills.
- Practising past paper and examination-style questions related to research questions, investigation design, data collection, analysis and evaluation.

Approaches to teaching

The approaches to teaching refer to six pedagogical principles that underpin IB programmes. They aim to empower teachers to create meaningful learning experiences.

Inquiry

Inquiry-based approaches to learning and approaches to teaching involve a high degree of student engagement and interaction to develop natural curiosity in students. The approaches can take a variety of forms that differ in their degree of teacher guidance. Banchi and Bell (2008) propose four levels of inquiry.

1. As part of **confirmation inquiry**, the question, process and outcome of the inquiry are provided by the teacher.
2. During **structured inquiry**, teacher guidance begins to be withdrawn.
3. During **guided inquiry**, teacher guidance continues to be withdrawn.
4. In **open inquiry**, students determine the question, procedure and outcome.

Other forms of inquiry-based learning and teaching include experiential learning (Kolb, 1984) and problem-based learning (Boud, Feletti, 1997).

Scientific inquiry can be experienced by everyone. Subjects such as chemistry offer students opportunities not only to conceptualize scientific inquiry—a central feature of NOS—but also understand it is a process that they too can undertake.

The inquiry process comprises three stages: inquiry, action and reflection. In chemistry, this process is evident in the skills in the study of chemistry, the scientific investigation and the collaborative sciences project. The inquiry process lies at the heart of the skills in the study of chemistry. The *Chemistry guide* identifies the specific inquiry skills that students must experience in their study of the course. These inquiry skills must be integrated into the course, providing students with several opportunities to master them. The collaborative sciences project also provides an opportunity to develop these inquiry skills within an interdisciplinary context and in collaboration with peers.

Effective teaching of the inquiry skills will equip students to demonstrate them in external and internal assessment. One example is when they undertake the scientific investigation, where they plan, carry out, analyse and evaluate an investigation to address a research question of their own.

Examples

Confirmation inquiry

Students perform a teacher-directed inquiry to confirm an outcome.

- Learning to use a pH sensor and using the generated data to plot a pH curve
- Determining molecular geometry using molecular model kits and valence shell electron-pair repulsion (VSEPR) databases

Structured inquiry

Students determine the outcome themselves; the aim and procedure are provided by the teacher.

- Comparing combustion data obtained from calorimetry, from a simulation and from published values in a database
- Researching the mechanism of action of different antacids, using teacher-provided websites and books

Guided inquiry

Students conduct an inquiry that addresses a question provided by the teacher, using a procedure of their choice.

- Determining enzyme-catalysed reaction rates through experimentation
- Investigating the factors affecting the rate of a chemical reaction
- Predicting the effect of the identity of the leaving group on the rate of nucleophilic substitution reactions
- Answering the guiding question using their knowledge of the subtopic

Open inquiry

Students determine the question, process and analysis.

- Writing their own factual, conceptual and debatable questions in relation to a topic or subtopic
- Undertaking the collaborative sciences project
- Undertaking the scientific investigation

Experiential learning

Students engage in inquiry opportunities outside the classroom.

- Taking a field trip to a local recycling plant
- Determining water quality or soil quality along a transect (fieldwork)
- Interviewing members of the school community who work in chemistry-related fields

Problem-based learning

Students are presented with a question or problem to solve.

- Evaluating the environmental impact of school science experiments and proposal of suitable waste minimization processes
- Identifying and justifying the "best" camping fuel. To solve the problem, students would need to define fuel quality parameters, identify and carry out analyses, and draw justified conclusions. Instead of camping fuel, teachers could vary the context to look at a different application of fuels, e.g. vehicle fuel. The prompt could be further expanded to create an interdisciplinary task involving chemistry with biology or physics

Conceptual understanding

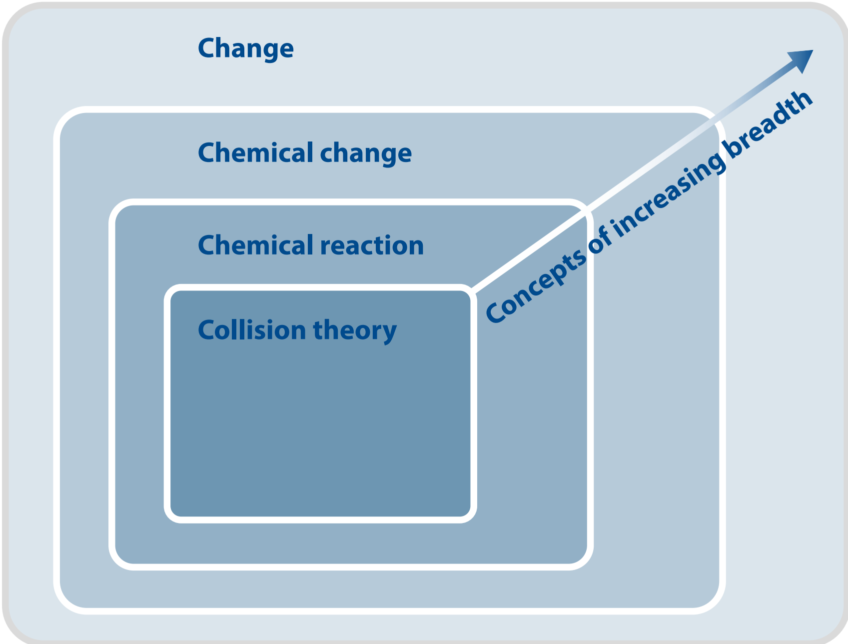
In IB programmes, conceptual understanding is defined as understanding that connects factual, procedural and metacognitive knowledge. It results from a process in which students consciously organize connections between prior and new knowledge into networks, then further develop or reconfigure those networks. This is a non-linear, ongoing process throughout which understandings evolve and misconceptions are identified and dispelled. In DP chemistry, these interconnections are explored through the linking questions. The linking questions in the *Chemistry guide* are not exhaustive, and students and teachers are invited to write their own.

Teaching for conceptual understanding is important because conceptual understanding enables students to be aware and critical of their own knowledge and understandings. They can then transfer and apply skills, knowledge and understandings to new or different contexts in creative, generative, autonomous, dynamic ways. Conceptual understanding supports the IB mission because it enables students to conceive multiple solutions to a problem, imagine different perspectives on issues, and understand more deeply how ideas change in different contexts.

Teaching approaches that promote conceptual understanding include classification, generalization, representation, internalization, concepts-in-use and near and far transfer.

A conceptual approach fosters the organization of knowledge into networks, which can evolve as students acquire new understandings. Thus, a conceptual understanding is supported by mental categories of varying breadth. These concepts or mental categories can be broad concepts that help to integrate knowledge across disciplines, or narrower, subject-specific concepts that help to organize and link disciplinary understandings. An example of a sequence of concepts of increasing breadth is shown in the figure.

Example sequence of increasing conceptual breadth



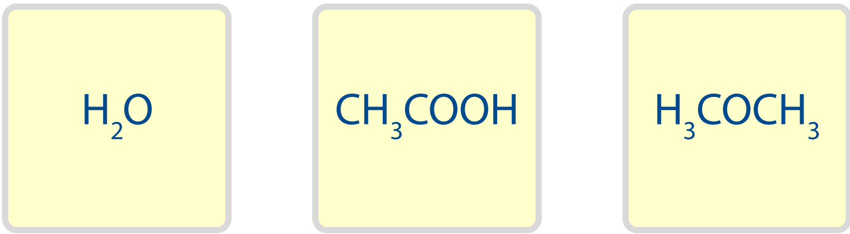
Concept-based teaching and learning does not preclude the teaching of content. In fact, a sound knowledge base is the foundation for conceptual understanding (Mills, Gay, 2018). By engaging with a conceptual approach, however, it should be remembered that ideas and knowledge—both declarative and procedural—do not exist in isolation. Concepts are connected to other concepts; they are mental abstractions constructed through experience (Taber, 2019).

Examples

- When revising several units, students write their own linking questions, share them and attempt to answer each other's questions.
- Concept mapping can be used to summarize the content of a unit. The visible thinking routine "Generate–Sort–Connect–Elaborate" can be used to structure the activity (Project Zero, 2015).
- Students participate in activities to identify correct and incorrect examples of a concept, e.g. Kelly's triads (Taber, 2002). Students are presented with three cards, each with a different diagram or substance. Students then identify the odd one out and explain their reasoning—see figures that follow.

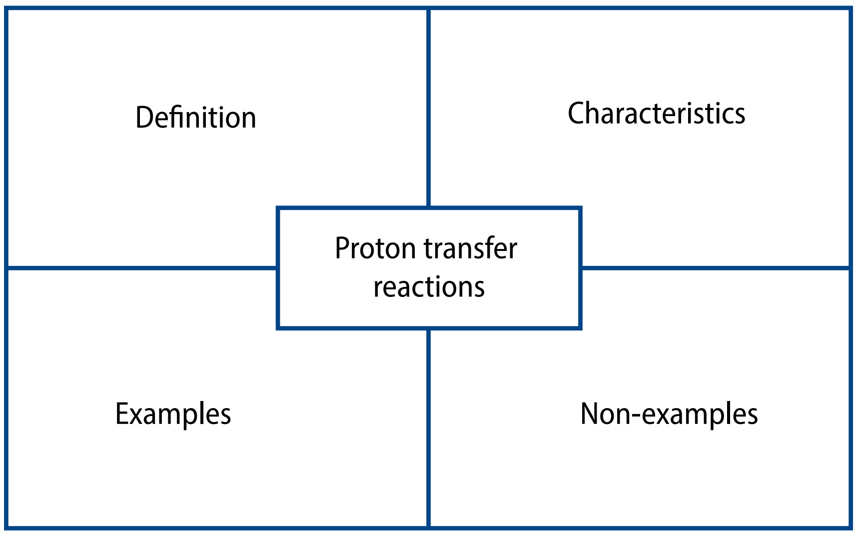
Triad that can be used to distinguish between ionic and covalent substances

Triad that can be used to conceptualize which substances can form hydrogen bonds, which substances are unsaturated, and which substances contain sp^2 hybridized atoms



- Frayer model graphic organizers help to clarify the meaning of a concept, and to identify correct and incorrect examples of the concept.

Frayer model template in which students can summarize their understanding of proton transfer reactions (Reactivity 3.1)



- Visible thinking routines such as those used in "The Explanation Game" or "The Ways Things Can Be Complex" (Project Zero, 2015) can be used, for example, to discuss the concept of energy and the perspectives on it.

Local and global contexts

Setting learning in context gives relevance to the curriculum and allows students to connect their learning to their own experiences and the world around them. Observing their surroundings through a different lens may help students understand these from a different perspective, an important component of international-mindedness and various learner profile attributes.

Chemistry is often concerned with understanding submicroscopic particle behaviour to explain macroscopic observations. Context helps to illustrate concepts that are often abstract and invisible, making them more relatable. It also helps to develop in students an appreciation for the impact of chemistry, in line with the course aims.

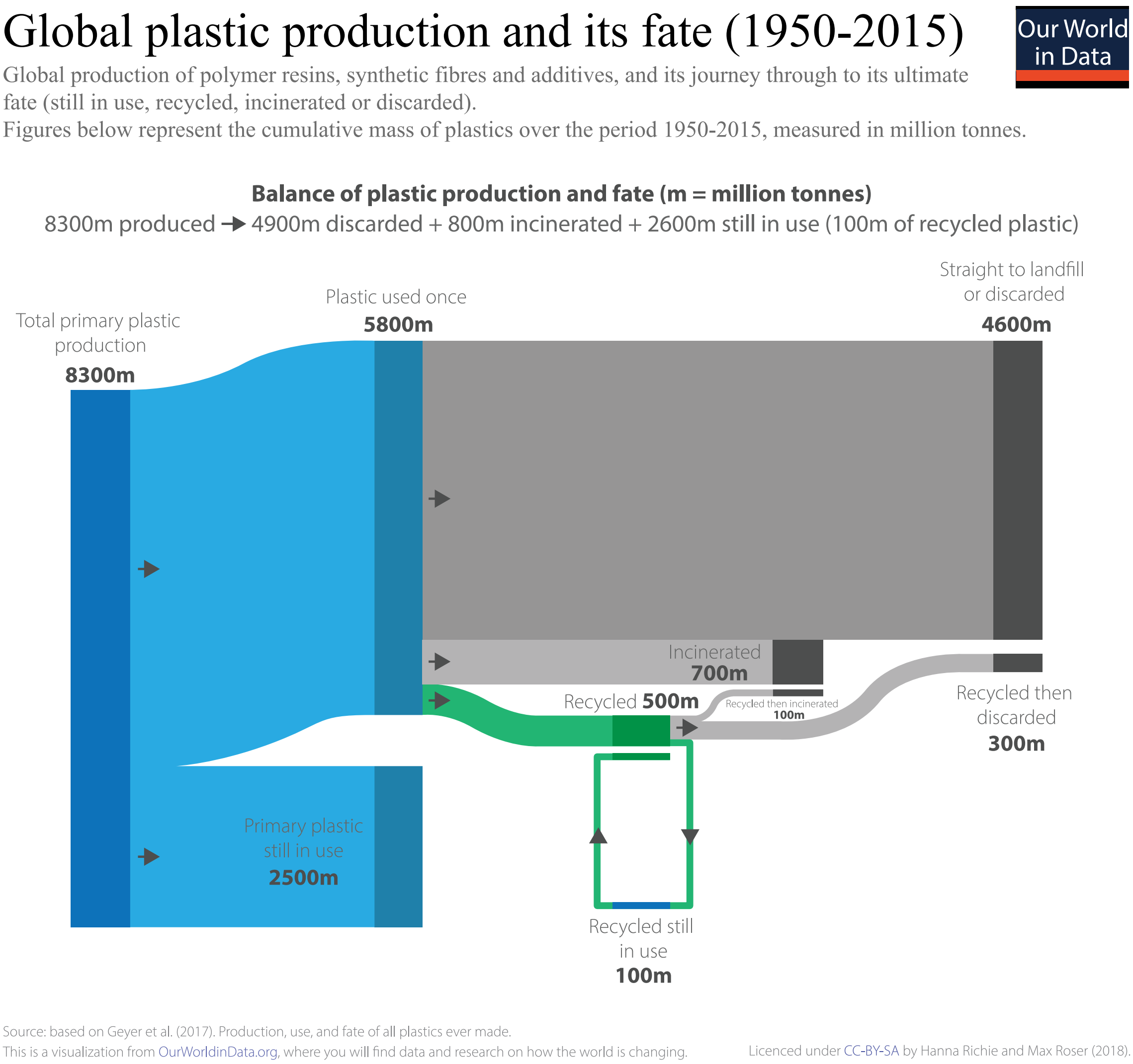
The scientific investigation, the collaborative sciences project and the extended essay are all excellent opportunities for students to delve into an application of chemistry. Applications should be emphasized by weaving many examples of local and global contexts into the course. New examples of local and global contexts may arise throughout the course. In some cases, they can be planned into teaching well ahead of time (e.g. the Haber–Bosch process when discussing equilibrium). In others, local or global news items related to chemistry may spark interesting conversations spontaneously.

Context can be introduced at different points in a learning sequence; it can lead into the teaching of a concept, or be used after concepts are taught (Turner, 2019). After a concept has been explained, students can be asked to apply it to a particular context or case study to reinforce the concept and transfer it to a less familiar setting.

Examples

- Discussing chemistry-related news items, considering:
  - relevant theoretical concepts
  - the quality of scientific communication
  - examples of ethical, environmental, economic, cultural and social impacts.
- Asking students to prepare a five-minute presentation on an application of chemistry of their choice.
- Contributing to chemistry-related data collection projects at the global level (citizen science).
- Sharing examples from teachers' own university and employment experiences.
- Inviting students' relatives with chemistry-related careers (e.g. agriculture, medical fields, materials science) to present to the class.
- Featuring prominent chemists in class when relevant, connecting their actions to the IB learner profile.
- Setting the introduction of new concepts in contexts where they are particularly relevant.
- Using authentic stimuli to generate class discussions or as assessment instruments. For example, the following tasks could be set as part of a class discussion about the figure "Authentic stimulus to generate class discussion or for use as an assessment instrument".
  - Using information from the diagram, calculate the percentage of primary plastics produced that are still in use.
  - Identify two pieces of information from the diagram that suggest plastics are largely non-biodegradable.
  - With reference to your understanding of bonding models, suggest why plastics are largely non-biodegradable.
  - Extension: Carry out research online to find some of the problems associated with incinerating plastic waste.

Authentic stimulus to generate class discussion or for use as an assessment instrument [Source: Ritchie, Roser, 2018]



Effective teamwork and collaboration

This pedagogical principle aims to encourage collaborative relationships to create a positive and dynamic learning environment. It covers collaboration between students, and between students and their teacher. In science, it also echoes the aspects of NOS that acknowledge science as a collective endeavour.

In chemistry, the collaborative sciences project stands out as one of the course requirements that specifically aims to develop collaboration skills in students. Collaborative tasks can vary significantly in terms of time and configuration. Their duration can range from short pace-changers in a lesson to extended teamwork such as the collaborative sciences project. The size of collaborative groupings also varies, from pairs of students to whole-class endeavours.

Students benefit from opportunities to articulate their thinking, which can help to clarify lines of reasoning and even reveal knowledge gaps. It is also advantageous to practise using appropriate scientific vocabulary, irrespective of whether students are fluent in the language of instruction or not. Academic language is cognitively demanding, and collaborative tasks provide spaces for students to practise using correct vocabulary, building their academic fluency.

Teamwork and collaboration also encourage a learning environment in which students share their perspectives, but also consider and integrate the views of others. For example, peer feedback is valuable for both parties. The student receiving the feedback gains from acting on the suggestions for improvement given by their peer. For the student giving the feedback, it is an opportunity to practise commenting constructively.

For students to benefit fully from collaborative tasks, behavioural expectations and the nature of effective group work need to be made explicit. For example, collaboration is permitted in the early stages of the scientific investigation. Teachers must therefore be vigilant, clarifying where necessary the difference between acceptable collaboration and collusion.

Examples

Teamwork and collaboration are possible in a variety of ways.

- The collaborative sciences project
- Solving a numerical problem individually and then explaining reasoning to a partner
- Preparing a debate on alternative energy sources (e.g. biofuels and fuel cells) covered in the *Chemistry guide*
- Collaboratively collecting experimental data that can then be compared, e.g. the enthalpy change associated with the combustion of different foods
- Constructing graphs for various trends in the periodic table using digital technology, and explaining these trends to the class
- Using visible thinking routines that encourage students to explain their reasoning, e.g. “Think, Pair, Share”, and connecting learning to prior knowledge, e.g. “Connect, Extend, Challenge” (Project Zero, 2015)
- Short collaborative research leading to a presentation with a competitive element. For example:
    - Student pairs compete for funding for carbon allotrope research by persuading an “investor” to choose their project. The investor can only support one project, so each pair must demonstrate their allotrope’s superiority over all other carbon allotropes. Students should spend 20 minutes researching the properties of the allotrope of carbon. After their research, they should take 10 minutes to prepare a three-minute persuasive pitch to explain why their allotrope is the most worthy of investment.

Removing barriers to learning

IB approaches to teaching aim to help students set challenging and appropriate personal learning goals. Differentiation to remove barriers to learning is understood to relate to four interconnected principles. The central principle is to affirm students’ identities and build self-esteem. Surrounding this are the principles of valuing prior knowledge, scaffolding learning and extending learning.

In IB programmes, language is recognized as having a vital role in learning and teaching, permeating almost all aspects of a learning environment. All IB teachers are therefore regarded as language teachers.

Chemistry has a curious relationship with language. On the one hand, it has a shared code for representing chemical processes using specialized symbols, and chemists have developed systematic ways to organize and name substances. On the other hand, chemistry sometimes uses words that have different meanings in non-chemical contexts. Teachers need to be especially mindful of these. Consider how the following words are used in everyday language and in other subject areas: *nucleus*, *error*, *acidic*, *salty*, *solution*, *volatile* … even *chemistry*.

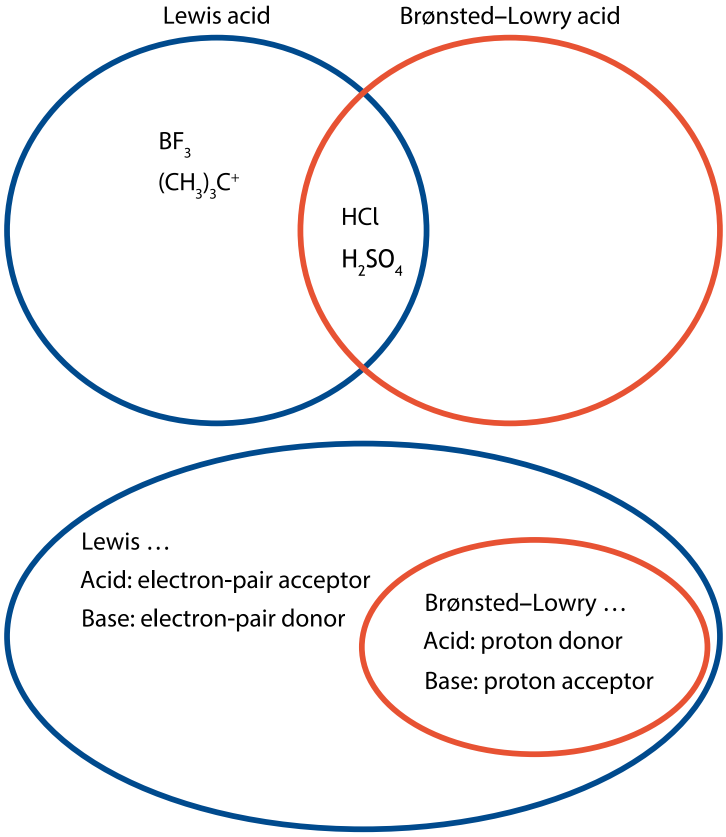
Examples

There are numerous ways to remove barriers to learning.

- Affirming identity and building self-esteem

    - Asking students to construct glossaries containing definitions in their preferred language, as well as the language of instruction (if this is different)
    - Reducing cognitive load in practical instructions by minimizing textual elements and maximizing diagrammatic elements
- Valuing prior knowledge
    - Identifying prior knowledge through diagnostic quizzes or mind mapping
    - Activating prior knowledge through linking questions
- Scaffolding learning
    - Using molecular models to represent 3D structures
    - Using graphic organizers to represent processes or relationships
        - Flow charts for processes
        - Venn diagrams for similarities and differences

Venn diagrams comparing and contrasting different definitions of acids and bases

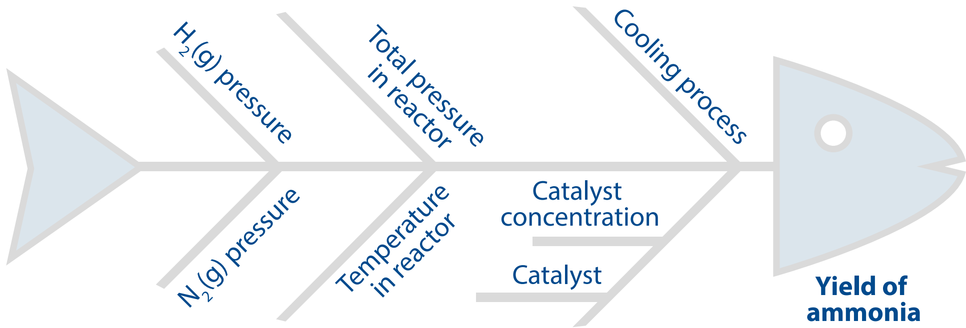


        - Fishbone diagrams examining the causes leading to an effect

          Downloadable resource

          Blank fishbone template (PDF)

Fishbone diagram analysing the changes to an equilibrium system and their effect on ammonia yield



- Extending learning
  - Applying concepts learned in a new, unfamiliar context or use of case studies
  - Exploring interdisciplinary links

Assessment

Assessment provides valuable information that supports learning and teaching and therefore should take place continually throughout the course. Assessment feeds back into the teaching process, providing information that facilitates the synchronization of learning and teaching. It is a key two-way process that can be used to improve learning, teaching and assessment. Teachers and students' own peers provide students with feedback on how to consolidate their understanding and move forward. Meanwhile, students provide teachers with feedback on their misconceptions, knowledge gaps, levels of understanding and levels of engagement, all of which inform the teacher's subsequent decisions.

Throughout the DP and CP, students work towards demonstrating the course assessment objectives through formative assessments. Some assessment tasks will be dedicated to measuring student learning and will inform predicted grades as well as internal reporting of student progress. Assessment of learning should be aligned with the course assessment objectives and grade descriptors. In chemistry, this involves providing opportunities for the students to develop the skills and techniques required to undertake the scientific investigation and exposing them to questions of the style and type they will encounter in external examinations.

- Multiple-choice questions
- Short-answer questions
- Extended-response questions
- Data-based questions

These types of questions assess connections between concepts-, NOS- and skills-related knowledge and will be set in a context such as experimental work and day-to-day applications of chemistry.

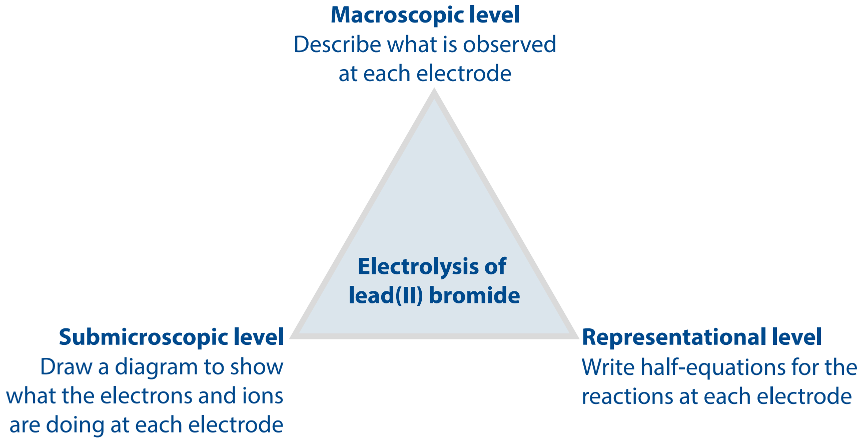
Examples

Assessment in chemistry can take many forms.

- Students practising data-based questions and experimental questions on assessments
- Using multiple-choice questions to uncover student misconceptions
- Students assigning a level of confidence to their responses to multiple-choice questions (5 for "absolutely certain", 3 for "I think this is correct", 1 for "guess"), and applying positive and negative marking. Students can also be encouraged to justify their reasoning for each response

- Students exploring and researching an application of chemistry, then presenting this in a variety of formats. Examples include a formal research paper, a scientific poster, an article for the school newspaper, a video or podcast, a presentation or assembly and an infographic
- Sharing the internal assessment criteria with students and asking them to analyse an example of student work against the criteria
- Students doing self-assessment using rubrics and markschemes
- Delving into students' understanding of a concept by asking them to consider it on several levels, as suggested by Johnstone (1991): macroscopic observations, submicroscopic particle behaviour and symbolic representations

Graphic organizer using Johnstone's triangle (1991) to delve into students' understanding



International-mindedness

The IB aims to develop "inquiring, knowledgeable and caring young people who help to create a better and more peaceful world through education that builds intercultural understanding and respect". International-mindedness recognizes similarities and affirms differences between communities, peoples and nations. Knowledge and understanding of similarity allow for the construction of common foundations, while recognition and affirmation of difference encourage a celebration and valuing of diversity.

With this in mind, teachers of DP chemistry should provide opportunities for students to foster international-mindedness within the context of the course, underpinned by a focus on global engagement. Global engagement represents a commitment to address humanity's greatest challenges in the classroom and beyond. Such challenges may relate to the environment; development; conflict, rights and cooperation. One of the aims of the course is to model solutions to local and global problems in a scientific context. DP chemistry students and teachers are therefore expected to explore local and global issues relating to the content of the syllabus. There is a close connection between international-mindedness and the IB learner profile attributes, which underpin, and are central to, understanding what it means to be internationally minded.

Along with their exposure to international-mindedness elsewhere in the DP, students should be prepared to be successful global citizens of the future.

Engaging with international-mindedness

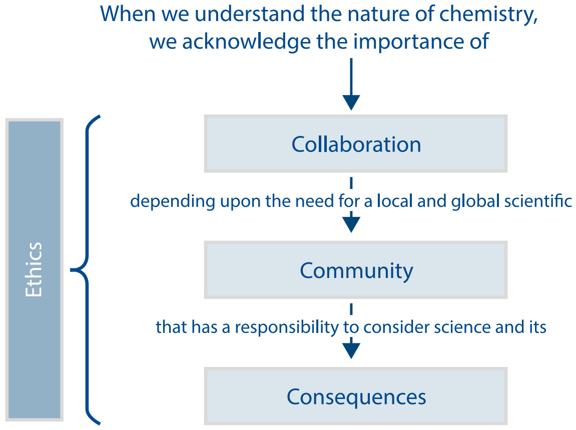
Teachers are not expected to address international-mindedness as a stand-alone topic, but instead to integrate it within the teaching of the subject.

This teacher support material (TSM) supports the teaching and learning of chemistry and includes a number of ideas and suggestions. The aim is to aid all IB teachers in addressing the need to include international-mindedness in their delivery of the course. These ideas and suggestions are by no means mandatory nor exhaustive and teachers are encouraged to generate alternative approaches and share ideas as they plan and deliver the content.

The "Chemistry and international-mindedness" section of the *Chemistry guide* highlights the international nature of science and might be a good starting point to consider the role of a scientist in a global community.

For practical purposes, it might be useful here to break down the term *international-mindedness* into specific concepts that are particularly relevant in the context of science: *collaboration*, *community*, *consequences* and *ethics*. Please note that a consideration of ethics can provide valuable overlap with the IB theory of knowledge (TOK) course.

International-mindedness through the lens of collaboration, community, consequences and ethics



A focus on these concepts throughout the course can help design learning engagements that develop international-mindedness. The table below provides scaffolding questions that might be used to unpack these concepts.

Scaffolding questions to help develop international-mindedness

This table contains a list of possible scaffolding questions that can be used to develop international-mindedness. They can also be applied to specific real-life contexts.

Concept	Scaffolding questions for developing international-mindedness
Collaboration	• Why is collaboration necessary? • What scale of collaboration is required in science? • What does scientific collaboration look like?
Community	• Who is involved in the scientific community? • What structures and organizations might be found in the scientific community?
Consequences	• How might new scientific knowledge impact future scientific research? • Which areas of society might be impacted by scientific knowledge? • How significant are the consequences of science on other areas of society? • Does every society respond similarly to scientific research?
Ethics (note overlap with the TOK course)	• What responsibilities do individual scientists possess in carrying out their own research? • What responsibilities do journals, research facilities and scientific organizations possess? • Who is responsible for the communication of science within the public domain? • Should scientific research be subject to ethical constraints?

Exploring international-mindedness

Real-life context	International-mindedness connections
Russian and US scientists collaborate at the Joint Institute for Nuclear Research near Moscow to synthesize and prove the existence of element 118, oganesson.	High cost of and need for advanced technology limits progress without collaboration. Collaboration can occur on an international level.
2019 Nobel Prize in Chemistry to J. Goodenough, M. Stanley Whittingham and A. Yoshino. The independent work of each has led to a significant leap forward in the effectiveness of lithium-ion batteries.	Scientific progress is rarely dependent on the work of a single scientist. To some extent, it might also be an example of contributions from different nationalities (American, British-American and Japanese) although the question of why certain nations are better represented than others may be more valuable.
Role of World Health Organization during the COVID-19 pandemic.	A good example of a scientific organization responsible for supporting and advising national health policies across the globe.
The Surgisphere COVID-19 scandal involved the publishing of two papers in well-respected scientific journals that were later found to be based on highly suspicious and possibly false data.	An example of a major failing in the peer-review process with global implications in how governments dealt with the COVID-19 pandemic.
The influence of big data companies in scientific progress during the COVID-19 pandemic.	Commercial companies can impact the scope of scientific progress. Ethical questions can be raised regarding the access and use of personal medical data.
Research on vaping and its interplay with politics. US and UK policy have significant differences.	This is an example of how scientific information can be interpreted and used differently when it enters the political domain.

Examples

The following tables have some general structures that could be used to integrate international-mindedness development in lessons or sections of lessons.

Research and discussion

Suggested timing (25 minutes)	Example content (for a focus on collaboration and consequences)
5 minutes	Presentation of a real-life context, e.g. the synthesis and proof for the existence of element 118, oganesson.
10 minutes	In groups, students are asked to research the real-life context using the following prompts. • Who collaborated? • Was the collaboration on a local or global level? • Why was the collaboration necessary? • What are the consequences of this new knowledge?

Suggested timing (25 minutes)	Example content (for a focus on collaboration and consequences)
	(It may also raise interesting questions about the independence of scientific collaboration beyond political tensions between Russia and the US.)
10 minutes	Groups share their findings.

Mini-presentations

Suggested timing (40 minutes)	Example content (for a focus on community and consequences)
5 minutes	Present students with a number of national and international scientific organizations. • International Union of Pure and Applied Chemistry (IUPAC) • World Health Organization (WHO) • Intergovernmental Panel on Climate Change (IPCC) • Royal Society of Chemistry (RSC) • National chemistry-related organization in your school context
15 minutes	Individually or in small groups, students are asked to research one of the organizations using the following prompts. • What does it do? • Where does it work? • Who funds it? • What are the consequences of its work? • How might it be relevant to you?
20 minutes	Individuals or groups make presentations (2–3 minutes) on their findings.

Debate

Suggested timing (45 minutes)	Example content (for a focus on ethics)
5 minutes	Brief outline of an ethical issue. Haber developed the process for ammonia synthesis (particularly important for fertilizer) but was also responsible for developing chemical weapons during the First World War. Students place anonymous initial votes on whether they support, oppose or are unsure of the motion: *Fritz Haber deserved the Nobel Prize for Chemistry in 1918.* The class is split into two teams and assigned to support or oppose the motion. It can be interesting to manipulate the groups so that they are arguing against their initial thinking.
20 minutes	Students are given time to research and build their lines of argument. The level of scaffolding prompts can be adapted to meet the needs of the class. Example prompts • What is the ethical issue?

Suggested timing (45 minutes)	Example content (for a focus on ethics)
	• What are the consequences of this issue? • What evidence might support your argument? • What might the opposite team try to argue? • How can you dismantle opposition arguments?
20 minutes	Debate • Each group selects one or two speakers to briefly (1–2 minutes) summarize their argument. • The debate is opened to the floor—a “speaking stick” can be used to prevent students talking over each other. This can be controlled by the teacher or students. • One or two different speakers briefly (1–2 minutes) summarize their arguments. • Second vote: students place final individual anonymous votes on whether they support or oppose the motion. These results can be compared to the initial votes to identify the winning team.

Introduction

The Diploma Programme (DP) chemistry course has no prescriptive sequence for coverage of the concepts and topics. Teachers are completely free to plan their own route through the course according to their circumstances. This section gives ideas for some contexts and possible routes, which may help teachers to develop their own course outlines. As it is expected that experimental work and teaching of the skills are included regularly throughout the course, extensive ideas are included for laboratory-based experimentation and applications of technology to help teachers to plan their experimental programme.

Pathways through the course

Teaching in context

The study of chemistry enables us to engage constructively with topical scientific issues. By applying chemical concepts, we are able to evaluate knowledge claims more effectively, and make informed choices for human and environmental health. Chemical research has brought innovation and benefit in many fields and continues to be at the heart of seeking effective solutions to many global challenges.

The following table presents questions about the application of chemistry in our world. Ideally, these should be visited throughout the course. They may provide context for nature of science (NOS) and some topics, as indicated by the subtopic references in the column on the right. This is not intended as additional assessable content, but rather to help stimulate application of ideas and problem-solving skills. This supports the pedagogical principle of "Teaching in local and global contexts" as part of the approaches to teaching framework. Consideration of these and related questions may help provide ideas for the scientific investigation; the collaborative sciences project; the theory of knowledge (TOK) exhibit; creativity, activity, service (CAS); the extended essay in chemistry; or in world studies.

How can chemistry address the global demand for energy?	
Burning fossil fuels—crude oil refining, carbon footprint, shale gas extraction, fracking, incomplete combustion, enhanced greenhouse effect (climate change)	Structure 1.1 Reactivity 1.2 Reactivity 1.3 Tool 1
Renewable or sustainable energy sources—biofuels, solar photovoltaics, solar fuels	Reactivity 1.3 HL Structure 3.2
Energy mobility and storage—rechargeable batteries, fuel cells, battery disposal	Reactivity 1.3 Reactivity 3.2
Hydrogen as energy carrier	Reactivity 1.3
Green chemistry—maximizing energy efficiency, use of catalysts effective at lower temperatures	Reactivity 2.1 Reactivity 2.2

How can chemists show innovative and responsible environmental stewardship?	
Ozone depletion—reactions of CFCs in stratosphere, alternative chemicals for refrigerants and propellants	HL Structure 2.2 Reactivity 3.3
Air and water pollution—sources, acid deposition, smog, catalytic converters, cleaner fuels	Reactivity 1.3 Reactivity 2.2 Reactivity 3.1
Climate change—infrared absorption by greenhouse gases, carbon dioxide levels and consequences, ocean warming and acidification, carbon capture technologies	HL Structure 3.2 Reactivity 2.3
Plastic production and waste—problems of overuse, disposal, recyclable and biodegradable plastics	Structure 2.4

How can chemists show innovative and responsible environmental stewardship?	
Toxic wastes from industry—chemical and thermal pollution	Reactivity 2.1
Green chemistry—replacement of toxic solvents with water and supercritical CO_2, maximizing energy efficiency	Structure 2.2 Reactivity 1.2

What are the factors to consider in the design of new materials and chemical agents?	
Metals and alloys—resource extraction, rare earth metals in touch screens, superconductors, alloying and galvanizing for corrosion prevention	Structure 2.2 Structure 2.4 HL Reactivity 3.4
Composites—concrete, fibreglass	Structure 2.4
Polymers—petrochemical industry, innovative properties of plastics	Structure 2.4
Synthetic pathways—chemical modification of natural substances, drug purity and analysis	Structure 3.2 Reactivity 3.1
Side effects and unpredicted consequences—toxic by-products, ozone depletion from CFCs, side effects of drugs	Structure 2.4 HL Structure 3.1 Structure 3.2 Reactivity 3.3
Green chemistry—high atom economy to minimize waste, use of renewable resources, design for degradation, use of selective catalysts	Reactivity 2.1 Reactivity 2.2

What is the role of chemistry in health, food security and clean water supply?	
Agriculture—goal and challenges of local production vs globalized supply, leaching nutrients from soil	Structure 2.1 Structure 3.1 Reactivity 2.3
Balanced nutrition—characteristics of the main food groups	HL Structure 2.4 Structure 3.2 Reactivity 1.1 Tool 1
Increasing food supply—fertilizers (organic and inorganic), eutrophication, biomagnification of pesticides and heavy metals, "organic" food production	HL Structure 2.2
Water purification—roles of chlorine and ozone	Structure 2.2 Structure 3.1 Reactivity 3.1 Reactivity 3.2 Tool 1
Green chemistry—use of enzymes in bioremediation	Reactivity 2.2

In what ways must chemists work with other disciplines to bring about effective, positive change?	
Political and ethical considerations of providing energy and food	Reactivity 1.3 Tool 2

In what ways must chemists work with other disciplines to bring about effective, positive change?	
	Tool 3 Inquiry
Economics, biological and computer technologies in molecular design	Structure 3.2 Tool 2 Tool 3 Inquiry
Applications of chemistry in renewable energy technologies	Reactivity 1.3 Reactivity 3.2 Tool 2 Tool 3 Inquiry
Ethical considerations in drug and vaccine development, testing and supply	Tool 2 Tool 3 Inquiry
Socio-economic aspects of changing behaviours, for example recycling and controlling spread of disease	Tool 2 Tool 3 Inquiry

Developing a scope and sequence

Inquiry-based process topic sequence

The inquiry-based process topic sequence was developed using past and current experiences from teaching the Middle Years Programme (MYP) sciences, in which unit design implies constructing inquiry-based questions around a real-life event. It encompasses the design of an entire unit of study around a "challenge lab" to engage student interest throughout the unit of learning. The topic sequence also identifies conceptual crossover or overlap between areas of several subjects.

The downloadable topic sequence illustrates a possible route to teach the DP chemistry concepts of structure and reactivity and how these relate to the MYP key concepts for chemistry, as well as potential real-life anchors, relevant concept-based questions based on these anchors, potential challenge labs and potential interdisciplinary learning activities.

Downloadable resources

Topic sequence: Sample teaching route mapping DP and MYP concepts (PDF)

Anchor labs: HL kinetics (PDF)

Additional online resources

Next Generation Science Storylines offers other possible themes to engage students in their learning.

Ambitious Science Teaching offers many resources with inquiry-based cycles for lab work based on real-life anchors while encouraging students to present evidence-based explanations.

Next Generation Science Standards discusses "cross-cutting concepts" and offers resources and visuals to guide the planning of interdisciplinary activities, particularly those related to science, technology, engineering and mathematics (STEM).

Chemistry guide topic sequence (first assessment 2016)

The following theme sequence starts with atomic structure and ends with analytical chemistry. Generally, it keeps the units from the *DP Chemistry guide (first assessment 2016)* together and therefore may be suited to teachers who want minimal change of topic sequence from the previous guide.

These tables set out the corresponding topic numbers between the *DP Chemistry guide (first assessment 2025)* and the *DP Chemistry guide (first assessment 2016)* according to topics and some subtopics.

Topic: Kinetic molecular theory and atomic theory

Subtopic	Subtopic number (first assessment 2025)	Subtopic number (first assessment 2016)	Content covered
Particulate nature of matter	Structure 1.1	1.1	All
The nuclear atom	Structure 1.2	2.1	All
Electron configuration	Structure 1.3	2.2, 12.1	All

Topic: Periodicity

Subtopic	Subtopic number (first assessment 2025)	Subtopic number (first assessment 2016)	Content covered
The periodic table	Structure 3.1	3.1, 3.2, 13.1	All
Complex ions	Reactivity 3.4	13.2	Complex ion formation

Topic: Moles and stoichiometry

Subtopic	Subtopic number (first assessment 2025)	Subtopic number (first assessment 2016)	Content covered
The mole	Structure 1.4	1.2	All
Ideal gases	Structure 1.5	1.3	All
Amount of chemical change	Reactivity 2.1	1.3	All

Topic: Bonding

Subtopic	Subtopic number (first assessment 2025)	Subtopic (first assessment 2016)	Content covered
The ionic model	Structure 2.1	4.1	All
The covalent model	Structure 2.2	4.2, 4.3, 4.4, 14.1, 14.2	All
The metallic model	Structure 2.3	4.5	All
From models to materials	Structure 2.4	4.5, parts of A.1, A.5, A.7, B.2, B.4	All

Topic: Energetics

Subtopic	Subtopic number (first assessment 2025)	Subtopic number (first assessment 2016)	Content covered
Measuring enthalpy changes	Reactivity 1.1	5.1	All
Energy cycles in reactions	Reactivity 1.2	5.2, 5.3, 15.1	All
Energy from fuels	Reactivity 1.3	Parts of C.1, C.2, C.4, C.5, C.6	All
Entropy and spontaneity	Reactivity 1.4	15.2	All

Topic: Kinetics

Subtopic	Subtopic number (first assessment 2025)	Subtopic number (first assessment 2016)	Content covered
Rate of chemical change	Reactivity 2.2	6.1, 16.1	All

Topic: Equilibrium

Subtopic	Subtopic number (first assessment 2025)	Subtopic number (first assessment 2016)	Content covered
Extent of chemical change	Reactivity 2.3	7.1, 17.1	All

Topic: Acids and bases

Subtopic	Subtopic number (first assessment 2025)	Subtopic number (first assessment 2016)	Content covered
Brønsted–Lowry theory, pH scale, reactions of acids	Reactivity 3.1	8.1, 8.2, 8.3, 8.4, 18.2	All
	Reactivity 3.2	8.2	Metal + acid
Lewis acid–base theory	Reactivity 3.4	18.1	Lewis theory

Topic: Redox

Subtopic	Subtopic number (first assessment 2025)	Subtopic number (first assessment 2016)	Content covered
Oxidation and reduction, electrochemical cells	Reactivity 3.2	9.1, 9.2, 19.1, C.6	All except oxidation and reduction of organic compounds

Topic: Organic chemistry

Subtopic	Subtopic number (first assessment 2025)	Subtopic number (first assessment 2016)	Content covered
Functional groups and nomenclature	Structure 3.2	10.1	Nomenclature
Radical reactions	Reactivity 3.3	10.2	All
Oxidation and reduction of organic compounds	Reactivity 3.2	10.2	Oxidation and reduction of organic compounds
Substitution reactions	Reactivity 3.4	10.2	Nucleophilic and electrophilic substitution
Synthetic pathways	Reactivity 3.3 Reactivity 3.4	20.2	Synthetic pathways
Isomerism	Structure 3.2	20.3	Isomerism

Topic: Analytical techniques

Subtopic	Subtopic number (first assessment 2025)	Subtopic number (first assessment 2016)	Content covered
Analytical techniques	Structure 3.2	11.3, 21	Analytical

Maximizing opportunities for early practical work

The following topic scope and sequence starts with the basics and the more hands-on units, followed by further theoretical units. This approach might be helpful if teachers want to expose students to a large amount of practical work early on in the course.

Topic: Kinetic molecular theory and atomic theory

Subtopic	Subtopic number (first assessment 2025)	Subtopic number (first assessment 2016)	Content covered
Particulate nature of matter	Structure 1.1	1.1	All
The nuclear atom	Structure 1.2	2.1	All
Electron configuration	Structure 1.3	2.2	All
Periodic table basics	Structure 3.1	2.2, 3.1	Electron configuration, groups and periods, and binary nomenclature

Topic: Bonding

Subtopic	Subtopic number (first assessment 2025)	Subtopic number (first assessment 2016)	Content covered
Electronegativity	Structure 3.1	3.2	Electronegativity
The metallic model	Structure 2.3 Structure 2.4	4.5	All Alloys
The ionic model	Structure 2.1	4.1	All
The covalent model	Structure 2.2	4.2, 4.3, 4.4, 14.1, 14.2	All
Bonding triangle	Structure 2.4	Parts of A.1	Bonding triangle

Topic: Moles and stoichiometry

Subtopic	Subtopic number (first assessment 2025)	Subtopic number (first assessment 2016)	Content covered
The mole	Structure 1.4	1.2	All
Ideal gases	Structure 1.5	1.3	All
Amount of chemical change	Reactivity 2.1	1.3	All

Topic: Energetics

Subtopic	Subtopic number (first assessment 2025)	Subtopic number (first assessment 2016)	Content covered
Measuring enthalpy changes	Reactivity 1.1	5.1	All
Energy cycles in reactions	Reactivity 1.2	5.2, 5.3, 15.1	All
Energy sources	Reactivity 1.3	Parts of C.1, C.2, C.4, C.5, C.6	All
Entropy and spontaneity	Reactivity 1.4	15.2	All

Topic: Kinetics

Subtopic	Subtopic number (first assessment 2025)	Subtopic number (first assessment 2016)	Content covered
Rate of chemical change	Reactivity 2.2	6.1, 16.1	All

Topic: Equilibrium

Subtopic	Subtopic number (first assessment 2025)	Subtopic number (first assessment 2016)	Content covered
Extent of chemical change	Reactivity 2.3	7.1, 17.1	All

Topic: Acids and bases

Subtopic	Subtopic number (first assessment 2025)	Subtopic number (first assessment 2016)	Content covered
Brønsted–Lowry theory, pH scale, reactions of acids	Reactivity 3.1	8.1, 8.2, 8.3, 8.4, 18.2	All
	Reactivity 3.2	8.2	Metal + acid
Lewis acid–base theory	Reactivity 3.4	18.1	Lewis theory

Topic: Redox

Subtopic	Subtopic number (first assessment 2025)	Subtopic number (first assessment 2016)	Content covered
Oxidation states	Structure 3.1	9.1	Oxidation states
Electron transfer reactions	Reactivity 3.2	9.1, 9.2, 19.1, C.6 (fuel cells)	All except oxidation and reduction of organic compounds

Topic: Organic chemistry

Subtopic	Subtopic number (first assessment 2025)	Subtopic number (first assessment 2016)	Content covered
Functional groups and nomenclature	Structure 3.2	10.1	Nomenclature
Radical reactions	Reactivity 3.3	10.2	All
Oxidation and reduction of organic compounds	Reactivity 3.2	10.2	Oxidation and reduction of organic compounds
Substitution reactions	Reactivity 3.4	10.2	Nucleophilic and electrophilic substitution
Polymers	Structure 2.4	Parts of A.5, A.7, B.2, B.4	Polymers
Synthetic pathways	Reactivity 3.3 Reactivity 3.4	20.2	Synthetic pathways
Isomerism	Structure 3.2	20.3	Isomerism

Topic: Analytical chemistry

Subtopic	Subtopic number (first assessment 2025)	Subtopic number (first assessment 2016)	Content covered
Analytical techniques	Structure 3.2	11.3, 21.1	Analytical techniques

Topic: Periodicity

Subtopic	Subtopic number (first assessment 2025)	Subtopic number (first assessment 2016)	Content covered
The periodic table	Structure 3.1	3.1, 3.2, 13.1	See note
Complex ions	Reactivity 3.4	13.1, 13.2	Complex ions

Note: Most of the content of this subtopic could be taught throughout the other topics, but completing the course through this lens should support conceptual understanding.

Chemical applications

The following topic scope and sequence is built around four applications of chemistry: materials, fuels, controlling reactions and medicinal chemistry. Each topic starts by covering the relevant knowledge and skills, leading into specific applications or case studies. Rather than a ready-made topic sequence, this is an invitation for teachers who are interested in exploring a unique route through the curriculum. Different teachers could construct widely varying topic sequences depending on their interests, context and experience. For example, a sequence could be based on a specific set of applications or case studies (e.g. relating to the environment or kitchen chemistry). Alternatively, a sequence structured around some of the "big ideas" or concepts in chemistry—such as charge, patterns, energy and transformation—could be developed.

Application: Materials

Theme	Subtopic	Subtopic number (first assessment 2025)	Subtopic number (first assessment 2016)	Content covered
Particles	Particulate nature of matter	Structure 1.1	1.1	All
Atoms	The nuclear atom	Structure 1.2	2.1	All
	Electron configuration	Structure 1.3	2.2	All
	Periodic table	Structure 3.1	2.2, 3.1	All except d-block elements and oxidation states
Bonding	The metallic model	Structure 2.3	4.5	All
	The ionic model	Structure 2.1	4.1	All
	The covalent model	Structure 2.2	4.2, 4.3, 4.4, 14.1, 14.2	All

Theme	Subtopic	Subtopic number (first assessment 2025)	Subtopic number (first assessment 2016)	Content covered
	From models to materials	Structure 2.4	4.5, parts of A.1, A.5, A.7, B.2, B.4	All

Application: Fuels

Theme	Subtopic	Subtopic number (first assessment 2025)	Subtopic number (first assessment 2016)	Content covered
Moles and stoichiometry	The mole	Structure 1.4	1.2	All
	Ideal gases	Structure 1.5	1.3	All
	Amount of chemical change	Reactivity 2.1	1.3	All
Energetics	Measuring enthalpy changes	Reactivity 1.1	5.1	All
	Energy cycles in reactions	Reactivity 1.2	5.2, 5.3, 15.1	All
	Entropy and spontaneity	Reactivity 1.4	15.2	All
Redox	Oxidation states	Structure 3.1	9.1	Oxidation states
	Electron transfer reactions	Reactivity 3.2	9.1, 9.2, 19.1, C.6 (fuel cells), 8.2 (metal + acid)	All except oxidation and reduction of organic compounds
Fuels	Alkanes	Structure 3.2	10.1, 10.2	Alkanes
	Energy sources	Reactivity 1.3	Parts of C.1, C.2, C.4, C.5, C.6	All

Application: Controlling reactions

Theme	Subtopic	Subtopic number (first assessment 2025)	Subtopic number (first assessment 2016)	Content covered
Kinetics	Rate of chemical reactions	Reactivity 2.2	6.1, 16.1	All
	Radical reactions	Reactivity 3.3	10.2	All
Equilibrium	Extent of chemical reactions	Reactivity 2.3	7.1, 17.1	All

Application: Medicinal chemistry

Theme	Subtopic	Subtopic number (first assessment 2025)	Subtopic number (first assessment 2016)	Content covered
Acids and bases	Antacids: Brønsted–Lowry theory, pH scale, reactions of acids	Reactivity 3.1	8.1, 8.2, 8.3, 8.4, 18.1, 18.2	All
	Cisplatin: Lewis acid–base theory	Structure 3.1	13.1, 13.2	d-block elements
		Reactivity 3.4	13.2, 18.1	Lewis theory and complex ions
Organic chemistry	Functional groups and nomenclature	Structure 3.2	10.1, 10.2	Nomenclature
	Aspirin: substitution reactions	Reactivity 3.4	10.2, 20.1, D.2	Nucleophilic and electrophilic substitution
	Oxidation and reduction of organic compounds	Reactivity 3.2	10.2	Oxidation and reduction of organic compounds
	Making new medicines and drugs: synthetic pathways	Reactivity 3.3 and Reactivity 3.4	20.2	Synthetic pathways
	Thalidomide or taxol: isomerism	Structure 3.2	20.3	Isomerism
Analytical chemistry	Analytical techniques	Structure 3.2	11.3, 21.1	Analytical chemistry

Unit planners

All DP teachers are required to engage in explicit planning. However, the IB does not prescribe a particular format of unit planner that teachers should use. Nonetheless, the process of planning may be supported by using one of the template DP unit planners developed for DP teachers. These DP unit planners are not intended to mandate or restrict what DP teachers can or cannot do. Rather, they are intended to inspire and support teachers to think more about not only what they are teaching, but also how they are teaching.

Examples of DP unit planners are provided in the resource *Approaches to teaching and learning in the Diploma Programme*. This section of this support material also includes examples of completed unit plans for the DP sciences. These examples are intended to help teachers to reflect on their own planning and are not intended to be model plans or to prescribe how unit planning should be undertaken.

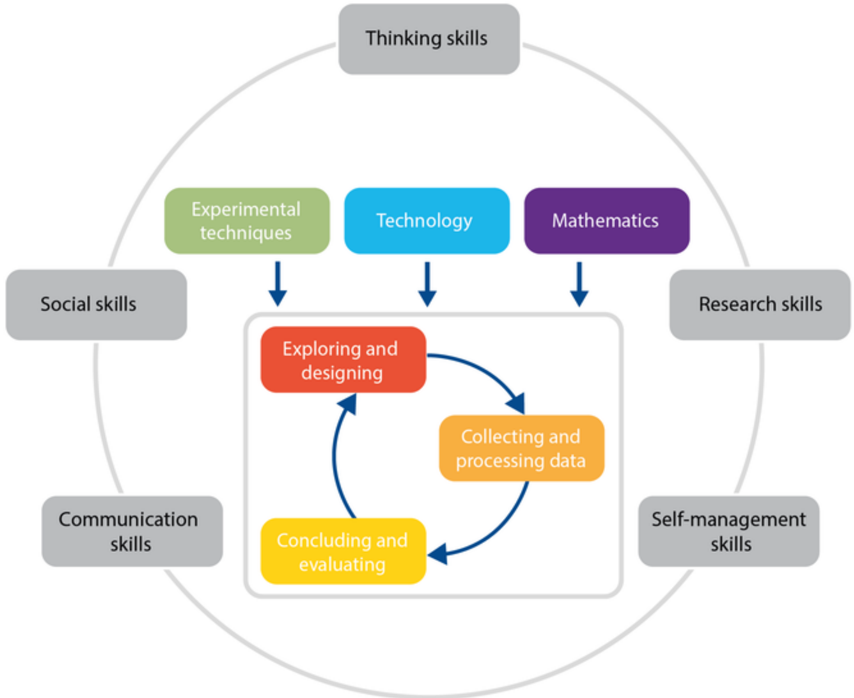
Downloadable resources

DP chemistry sample unit planner 1: Bonding (PDF)

DP chemistry sample unit planner 2: The mole (PDF)

Skills-based activities

Overview of skills in the study of chemistry



Tools

Tool 1: Experimental techniques

Skill: Addressing safety of self, others and the environment

Description
Recognize and address relevant safety, ethical or environmental issues in an investigation.
Guidance
• Safety, ethical and environmental issues should be addressed throughout the experimental programme. • Students should be given the opportunity to research the hazards associated with specific reagents and techniques, as well as proposing safety measures to minimize the risk to self, others and the environment. A consideration of safety measures should include the use of relevant protective equipment, safe manipulation of substances and equipment, waste disposal, as well as minimizing the amounts of materials and substances used. Prior to conducting any experimental work, teachers should ensure that the students' risk assessments are appropriate and aligned with local standards.
Example opportunities for integration into the chemistry programme

- Structure 3.2—Functional groups: Classification of organic compounds
  - Safety precautions needed when working with flammable substances, such as organic compounds
- Reactivity 3.1—Proton transfer reactions
  - Appropriate handling and disposal of a given acid, depending on its identity and concentration

Skill: Measuring variables

Description

Understand how to accurately measure the following to an appropriate level of precision.

- Mass
- Volume
- Time
- Temperature
- Length
- pH of a solution
- Electric current
- Electric potential difference

Guidance

- There will be ample opportunities throughout the practical programme for students to practise using the equipment needed to make these measurements. The use and relevance of equipment that provides different levels of precision and accuracy should be covered.
- Some of these measurements may also be explored through digital simulations. The difference between the measurements made by the students themselves and those in simulations may lead to interesting discussions of the role of and assumptions present in some simulations.

Example opportunities for integration into the chemistry programme

- Mass
  - Reactivity 2.1—How much? The amount of chemical change
  - Percentage yield determination by measuring the experimental mass of a solid product
- Mass and volume
  - Structure 1.5—Ideal gases
  - Mass and volume measurements involved in the determination of the molar mass of an ideal gas
- Volume
  - Structure 1.4—Counting particles by mass: The mole
  - Purpose and precision of different types of volume-measuring equipment in the preparation of a standard solution (e.g. volumetric flasks, graduated pipettes and burettes)
- Time
  - Reactivity 2.2—How fast? The rate of chemical change
  - Time measurements in kinetics investigations
- Temperature
  - Reactivity 1.1—Measuring enthalpy changes
  - Temperature measurements during calorimetry experiments
  - Reactivity 2.2—How fast? The rate of chemical change

- (HL) Temperature measurements when investigating the Arrhenius equation
- Distance
  - Structure 2.2—The covalent model
  - Distance in chromatography experiments to determine R_f values
- pH
  - Reactivity 3.1—Proton transfer reactions
  - Comparison of pH paper and pH sensors
  - Measurement of pH of solutions of different salts
- Voltage
  - Reactivity 3.2—Electron transfer reactions
  - Measurement of voltage in voltaic cells

Skill: Applying techniques

Description

Show awareness of the purpose and practice of:

- preparing a standard solution
- carrying out dilutions
- drying to constant mass
- distillation and reflux
- paper or thin layer chromatography
- separation of mixtures
- calorimetry
- acid–base and redox titration
- electrochemical cells
- colorimetry or spectrophotometry
- physical and digital molecular modelling
- recrystallization
- melting point determination.

Guidance

This section explores certain experimental techniques that are significant in chemistry. Many of these help chemists investigate chemical processes and structures that are not observable.

Example opportunities for integration into the chemistry programme

- Standard solution preparation
  - Reactivity 3.2—Electron transfer reactions
  - Determination of the concentration of a solution by redox titration against a standard solution
- Dilutions
  - Reactivity 3.1—Proton transfer reactions
  - pH measurement of different concentrations of acid
- Drying to a constant mass
  - Structure 1.4—Counting particles by mass: The mole
  - Determination of the empirical formula of magnesium oxide
- Distillation

- Structure 2.2—The covalent model - Fractional distillation of a mixture of two miscible liquids
• Reflux - Reactivity 3.2—Electron transfer reactions - Oxidation of primary alcohols to carboxylic acids
• Chromatography - Structure 2.2—The covalent model - Chlorophyll chromatography using different solvents
• Filtration - Structure 1.1—Introduction to the particulate nature of matter - Water filtration systems
• Calorimetry - Reactivity 1.2—Energy cycles in reactions - Hess's law practical work investigating the enthalpy change for the reaction between solid sodium hydroxide and aqueous hydrochloric acid
• Titration - Reactivity 3.1—Proton transfer reactions - (HL) Determination of the K_a of a weak acid by titration against a strong base
• Electrochemical cells - Reactivity 3.2—Electron transfer reactions - Investigation of factors affecting electroplating
• Colorimetry - Structure 2.4—From models to materials - Colorimetric determination of copper in brass
• Molecular modelling - Reactivity 3.4—Electron-pair sharing reactions - Representation of S_N1 mechanisms
• Recrystallization - Reactivity 2.1—How much? The amount of chemical change - Yield in the synthesis and purification of aspirin

Tool 2: Technology

Skill: Applying technology to collect data

Description
Use of sensors.
Guidance
A number of sensors and dataloggers are suitable for use in schools. Smartphone apps can also offer digital measurement and datalogging applications.
Example opportunities for integration into the chemistry programme
• Reactivity 3.1—Proton transfer reactions - Generation of pH curves for strong acid-strong base titrations (HL: pH curves for all four combinations of strong and weak acids and bases)

- Reactivity 2.2—How fast? The rate of chemical change
  - Light intensity sensors for monitoring the rate of chemiluminescent reactions
- Reactivity 2.3—How far? The extent of chemical change
  - Analysis of an iron(III) thiocyanate equilibrium mixture using colorimetry smartphone apps

Description
Identify and extract data from databases.
Guidance
For students to gain familiarity and confidence using databases, they need to be given opportunities to explore databases, practise extracting data from them and engaging meaningfully with the data they extract.
Example opportunities for integration into the chemistry programme
• Structure 3.2—Functional groups: Classification of organic compounds ▪ (HL) Use of spectral data to determine structure • Reactivity 1.3—Energy from fuels ▪ Investigation of relationships between local climate and air quality data

Description
Generate data from models and simulations.
Guidance
Modelling activities can include use of physical molecular models and graphical models. The data that can be generated from simulations range from simple to complex, depending on a model's level of sophistication.
Example opportunities for integration into the chemistry programme
• Structure 1.2—The nuclear atom ▪ Use of simulations to illustrate the arrangements of subatomic particles • Structure 2.2—The covalent model ▪ Use of molecular modelling kits or programs to investigate molecular shapes and bond angles • Structure 3.2—Functional groups: Classification of organic compounds ▪ Generation of graphical models of the physical properties of a homologous series

Skill: Applying technology to process data

Description
Use spreadsheets to manipulate data.
Guidance
To benefit fully from spreadsheet applications, students need frequent opportunities to use spreadsheets to organize and process data. This skill can often be used in conjunction with experimentation or databases (to collect data) and use of digital graph-drawing (to present manipulated data).
Example opportunities for integration into the chemistry programme
• Structure 3.1—The periodic table: Classification of elements ▪ Investigation of periodic trends across periods and down groups • Reactivity 1.1—Measuring enthalpy changes

▪ Propagation of uncertainties from calorimetry experiments

Description
Represent data in a graphical form.
Guidance
In addition to a good understanding of graph-drawing in general, students who apply technology to construct graphs need to practise using graph-drawing software.
Example opportunities for integration into the chemistry programme
• Structure 1.4—Counting particles by mass: The mole ▪ Generation of a calibration curve to determine an unknown concentration • Reactivity 1.4—Entropy and spontaneity (HL) ▪ (HL) Construction and generation of an Arrhenius plot

Tool 3: Mathematics

Skill: Applying general mathematics

Description
• Use basic arithmetic and algebraic calculations to solve problems. • Carry out calculations involving decimals, fractions, percentages, ratios, reciprocals and exponents. • Carry out calculations involving logarithmic functions. • Carry out calculations involving exponential functions (HL). • Determine rates of change from tabulated data. • Calculate mean and range. • Use and interpret scientific notation (e.g. 3.5×10^6). • Use approximation and estimation. • Appreciate when some effects can be ignored and why this is useful. • Compare and quote values to the nearest order of magnitude. • Understand direct and inverse proportionality, as well as positive and negative correlations between variables. • Calculate and interpret percentage change and percentage difference. • Calculate and interpret percentage error and percentage uncertainty. • Distinguish between continuous and discrete variables.
Guidance
Many of the quantitative areas in the chemistry programme require the ability to solve basic mathematical calculations.
Example opportunities for integration into the chemistry programme
• Addition, subtraction, multiplication and division ▪ Structure 1.5—Ideal gases ▪ Solution of problems relating to the ideal gas equation • Percentages ▪ Structure 1.2—The nuclear atom ▪ Calculations involving non-integer relative atomic masses and isotope abundance data

- Ratio
  - Structure 2.2—The covalent model
  - R_f values in chromatography
- Ratio
  - Reactivity 2.1—How much? The amount of chemical change
  - Mole ratios in stochiometric calculations
- Ignoring effects
  - Structure 1.5—Ideal gases
  - Reactivity 3.1—Proton transfer reactions (indicators are weak acids)
- Logarithms
  - Reactivity 3.1—Proton transfer reactions
  - pH calculations (HL: pOH, pK_a, pK_b)
- Mean and range
  - Reactivity 1.2—Energy cycles in reactions
  - Concept of average bond enthalpy
- Mean and range
  - Inquiry 2: Collecting and processing data
  - Repeating trials and random error
- Scientific notation
  - Reactivity 2.3—How far? The extent of chemical change
  - Determination of the position of equilibrium given the value of K
- Approximation
  - Structure 3.1—The periodic table: Classification of elements
  - Analysis of ionization energy data
- Proportionality
  - Structure 1.5—Ideal gases
  - Relationships between pressure, temperature and volume of a fixed mass of gas
- Percentage error and difference
  - Reactivity 1.1—Measuring enthalpy changes
  - Comparison of results from calorimetry experiments to theoretical values
- Continuous and discrete variables
  - Structure 1.3—Electron configurations
  - Concept of discrete energies
- Structure 3.2—Functional groups: Classification of organic compounds
  - Investigation of factors affected by number of carbons in the primary chain (number of carbons is a discrete variable)

Skill: Using units, symbols and numerical values

Description
• Apply and use International System of Units (SI) prefixes and units. • Identify and use symbols stated in the guide and the data booklet. • Express quantities and uncertainties to an appropriate number of significant figures or decimal places.

Guidance
Use of subject-specific terminology and conventions should not be taught in isolation but rather be encouraged continually throughout the programme.
Example opportunities for integration into the chemistry programme
• SI units ▪ Structure 1.5—Ideal gases ▪ Units used in the ideal gas and combined gas equations • SI prefixes ▪ Reactivity 1.1—Measuring enthalpy changes, Reactivity 1.4—Entropy and spontaneity (HL) ▪ Enthalpy calculations (HL: also entropy and Gibbs energy) • Symbols ▪ (HL) Correct use of k (rate constant), K (equilibrium constant), K_a (acid dissociation constant); also Q (heat) and Q (reaction quotient) • Symbols, significant figures and decimal places ▪ Correct use of chemical symbols, significant figures and decimal places in all written communication and calculations

Skill: Processing uncertainties

Description
• Understand the significance of uncertainties in raw and processed data. • Record uncertainties in measurements as a range (±) to an appropriate level of precision. • Propagate uncertainties in processed data, in calculations involving addition, subtraction, multiplication, division and (HL only) exponents. • Express measurement and processed uncertainties—absolute, fractional (relative), percentage—to an appropriate number of significant figures or level of precision.
Guidance
All measured values have associated uncertainties, which have an impact on calculated values. Several investigations require considerable numerical analysis of results and are excellent opportunities to consolidate uncertainty propagation skills.
Example opportunities for integration into the chemistry programme
• Sketch graphs ▪ Reactivity 2.2—How fast? The rate of chemical change ▪ Explanation, using Maxwell–Boltzmann distributions, of the effect of temperature and catalysts on reaction rate • Plotting linear and non-linear graphs and lines of best fit ▪ Structure 1.1—Introduction to the particulate nature of matter ▪ Construction of a solubility curve • Analysis of features in a graph ▪ Reactivity 2.3—How far? The extent of chemical change ▪ Analysis of graphs showing the composition of an equilibrium mixture • Extrapolation ▪ Reactivity 1.1—Measuring enthalpy changes ▪ Extrapolation of a cooling curve to determine the maximum temperature

• Interpolation ▪ Reactivity 3.1—Proton transfer reactions ▪ (HL) Interpolation of a pH curve to determine pH at half-equivalence and thus the pK_a of a weak acid

Description
• Apply the coefficient of determination (R^2) to evaluate the fit of a trend line or curve.
Guidance
The coefficient of determination, R^2, can be used to assess how well a trend line fits data. R^2 indicates to what extent a line of best fit can be used to predict changes in the dependent variable, given changes in the independent variable. While students do not need to understand how R^2 is calculated, they should be able to apply and discuss a value of R^2.
Example opportunities for integration into the chemistry programme
• Evaluating the lines of best fit. ▪ Structure 2.2—The covalent model ▪ Modelling the boiling point of a mixture of two miscible liquids

Skill: Graphing

Description
• Sketch graphs, with labelled but unscaled axes, to qualitatively describe trends. • Construct and interpret tables, charts and graphs for raw and processed data including bar charts, histograms, scatter graphs and line and curve graphs. • Plot linear and non-linear graphs showing the relationship between two variables with appropriate scales and axes. • Draw lines or curves of best fit. • Interpret features of graphs including gradient, changes in gradient, intercepts, maxima and minima, and areas. • Draw and interpret uncertainty bars. • Extrapolate and interpolate graphs.
Guidance
Graphical representations have a variety of different purposes when explaining and investigating chemical concepts. Students should be frequently encouraged to sketch, construct and analyse graphs. This will help them to develop an appreciation for graphs' explanatory and analytical power, as well as their important features and typology.
Example opportunities for integration into the chemistry programme
• Sketching graphs ▪ Reactivity 2.2—How fast? The rate of chemical change ▪ Explanation, using Maxwell–Boltzmann distributions, of the effect of temperature and catalysts on reaction rate • Plotting linear and non-linear graphs and lines of best fit ▪ Structure 1.1—Introduction to the particulate nature of matter ▪ Construction of a solubility curve • Analysis of features in a graph

▪ Reactivity 2.3—How far? The extent of chemical change ▪ Analysis of graphs showing the composition of an equilibrium mixture • Extrapolation ▪ Reactivity 1.1—Measuring enthalpy changes ▪ Extrapolation of a cooling curve to determine the maximum temperature • Interpolation ▪ Reactivity 3.1—Proton transfer reactions ▪ (HL) Interpolation of a pH curve to determine pH at half-equivalence and thus the pK_a of a weak acid

Inquiry process

Inquiry 1: Exploring and designing

Skill: Exploring

Description
• Demonstrate independent thinking, initiative, and insight. • Consult a variety of sources. • Select sufficient and relevant sources of information.
Guidance
Students will benefit from opportunities to develop research skills that allow them to consult a variety of sources, select information from them and use this to inspire lines of inquiry. Research skills such as these empower students to engage actively with scientific inquiry and explore the application of chemistry. Teachers are therefore encouraged to model research skills and help students develop the ability to identify sources available to them (possibly in collaboration with a school librarian).
Example opportunities for integration into the chemistry programme
• Reactivity 1.3—Energy from fuels ▪ Research into society's energy needs and the implications of the ways humans address these needs • Structure 2.4—From models to materials ▪ Inquiry into how structural features and properties affect the environmental impact of a material • Tool 2: Technology (databases) ▪ Extraction of physical, chemical and spectral data from databases • The collaborative science project will provide ample opportunities for developing research skills, which in turn will explicitly strengthen students' collaborative and social skills.

Description
• Formulate research questions and hypotheses. • State and explain predictions using scientific understanding.
Guidance
Chemists often relate macroscopic observations to particle behaviour. There are therefore several opportunities to formulate brief research questions, hypotheses and predictions throughout the teaching

of the programme as we wonder, for example, about the influence of a structural feature on observable properties. Research questions, hypotheses and predictions of increasing complexity and formality can be formulated as students move through the course. Exposure to the applications of chemistry through teaching in local and global contexts will help students appreciate the relevance of chemistry and how chemical principles can be applied in the world around them.
Example opportunities for integration into the chemistry programme
• Structure 1.2—The nuclear atom ▪ Prediction of the outcome of Rutherford's gold foil experiment had the "plum pudding" model of the atom been accurate • Reactivity 2.3—How far? The extent of chemical change ▪ Formulation of research questions, hypotheses and predictions on the factors affecting chemical equilibrium • Reactivity 3.4—Electron-pair sharing reactions ▪ (HL) Formulation of research questions, hypotheses and predictions on the effect of the leaving group on the rate of a nucleophilic substitution reaction • Structure 3.2—Functional groups: Classification of organic compounds ▪ Formulation of research questions, hypotheses and predictions on the effect of the identity of certain functional groups on the bioavailability of a particular medicine or drug

Skill: Designing

Description
• Demonstrate creativity in the designing, implementation and presentation of the investigation. • Develop investigations that involve hands-on laboratory experiments, databases, simulations, modelling. • Identify and justify the choice of dependent, independent and control variables. • Justify the range and quantity of measurements. • Design and explain a valid methodology. • Pilot methodologies.
Guidance
In textbook experiments such as the enthalpy of combustion of primary alcohols or the effect of surface area on the reaction between marble chips and acid, the variables are often prescribed. Since in these cases students will be familiar with the theoretical context, these may be good places to start teaching these skills. After the concepts of fair testing and safety considerations have been established, the design of more complex investigations can follow.
Example opportunities for integration into the chemistry programme
• Reactivity 1.1—Measuring enthalpy changes ▪ Enthalpy of combustion of primary alcohols • Structure 1.1—Introduction to the particulate nature of matter ▪ Factors affecting the solubility of an ionic compound • Reactivity 2.2—How fast? The rate of chemical change ▪ Factors affecting the rate of a chemical reaction • Reactivity 3.2—Electron transfer reactions, Tool 1: Experimental techniques (titration) ▪ Factors affecting the iron content in breakfast cereal

Skill: Controlling variables

Description
Appreciate when and how to: • calibrate measuring apparatus • maintain constant environmental conditions of systems • insulate against heat loss or gain.
Guidance
Variable control is relevant at all stages of the inquiry process. When planning investigations, variables need to be identified, and methods for their manipulation, measurement and control need to be established. In some cases the data collection phases throw light on the practical feasibility of controlling and monitoring variables. A good understanding of variable control is also relevant when drawing conclusions and evaluating methodologies. Students will benefit from opportunities to plan for and pilot variable control methods. In situations where environmental variables, such as temperature, cannot be controlled, students should be aware of and plan to monitor these variables.
Example opportunities for integration into the chemistry programme

• Calibration
  ▪ Reactivity 3.1—Proton transfer reactions
  ▪ Calibration and recalibration of pH sensors
• Constant environmental conditions
  ▪ Reactivity 2.2 How fast? The rate of chemical change
  ▪ Use of a water bath to maintain a constant external temperature during investigations involving enzymes
• Insulation
  ▪ Reactivity 1.1—Measuring enthalpy changes
  ▪ Comparison of methods for insulation against heat loss when determining the enthalpy of combustion of primary alcohols and the enthalpy of a single displacement reaction

Inquiry 2: Collecting and processing data

Skill: Collecting data, processing data and interpreting results

Description
Collecting data • Identify and record relevant qualitative observations. • Collect and record sufficient relevant quantitative data. • Identify and address issues that arise during data collection. Processing data • Carry out relevant and accurate data processing. Interpreting results • Interpret qualitative and quantitative data. • Interpret diagrams, graphs and charts. • Identify, describe and explain patterns, trends and relationships.

- Identify and justify the removal or inclusion of outliers in data (no mathematical processing is required).
- Assess accuracy, precision, reliability and validity.

Guidance

Students should build an understanding of the application of the tools and techniques in Tool 1, Tool 2 and Tool 3 in the collection and processing of experimental data.

Students who are exposed to a variety of types of data as well as a range of data-processing opportunities will develop an understanding of how to collect sufficient relevant data for an investigation.

Example opportunities for integration into the chemistry programme

- Reactivity 3.2—Electron transfer reactions
  - Investigation into the effect of electrode identity on voltage in voltaic cells
- Reactivity 3.2—Electron transfer reactions
  - (HL) Qualitative observation of the products of electrolysis of various molten and aqueous solutions
- Reactivity 3.1—Proton transfer reactions, Tool 1: Experimental techniques (titration)
  - Factors affecting the vitamin C content in orange juice
- Structure 2.2—The covalent model
  - Chromatography of different pigments
- Reactivity 1.1—Measuring enthalpy changes, Reactivity 3.2—Electron transfer reactions
  - Determining the enthalpy change of a displacement reaction
- Reactivity 1.1—Measuring enthalpy changes and Structure 2.1—The ionic model
  - Investigation into the effect of salt identity on the enthalpy of solution of an ionic compound

Inquiry 3: Concluding and evaluating

Skill: Concluding

Description

- Interpret processed data and analysis to draw and justify conclusions.
- Compare the outcome of an investigation to the accepted scientific context.
- Relate the outcomes of an investigation to the stated research question or hypothesis.
- Discuss the impact of uncertainties on the conclusions.

Guidance

Some classic investigations in chemistry such as factors affecting the rate of a chemical reaction and factors affecting solubility can be good opportunities for students to complete a full scientific inquiry starting with the formulation of research questions, hypothesis, methodology all the way through to the conclusion and evaluation stages. This will allow them to practise responding to and evaluating research questions, hypotheses and methodologies of their own.

Example opportunities for integration into the chemistry programme

- Structure 1.1—Introduction to the particulate nature of matter
  - Factors affecting the solubility of an ionic compound
- Reactivity 2.2—How fast? The rate of chemical change
  - Factors affecting the rate of a chemical reaction
- Reactivity 1.1—Measuring enthalpy changes

▪ Factors affecting the enthalpy of reaction

Skill: Evaluating

Description
• Evaluate hypotheses. • Identify and discuss sources and impacts of random and systematic errors. • Evaluate the implications of methodological weaknesses, limitations and assumptions on conclusions. • Explain realistic and relevant improvements to an investigation.
Guidance
Investigations leading to calculated values that can be compared to accepted values are also worthwhile in the development of quantitative conclusion and evaluation skills. They provide practice with quantitative analyses such as the comparison of percentage error and the random error estimate obtained through propagating uncertainties.
Example opportunities for integration into the chemistry programme
• Reactivity 3.2—Electron transfer reactions ▪ Experimental determination of the charge of an electron through electrolytic deposition • Structure 1.4—Counting particles by mass: The mole ▪ Experimental determination of Avogadro’s number through the formation of an oleic acid monolayer • Reactivity 1.1—Measuring enthalpy changes ▪ Experimental determination of an enthalpy of reaction • Reactivity 2.2—How fast? The rate of chemical change ▪ (HL) Experimental determination of the activation energy of a reaction

Learning activity

This activity is designed for students to develop some of the skills in the study of chemistry. Students will generate a calibration curve of absorbance versus [$CuSO_4$], then interpolate the curve to find the concentration of a $CuSO_4$ solution.

Downloadable resource

Learning activity: Finding the concentration of a solution through colorimetry (PDF)

Ideas for experimental work in the programme by topic

The downloadable resource lists suggestions for experiments and contains links to many resources for laboratory work that teachers can integrate into their teaching. Some of the ideas will be useful for hands-on student work; others may be more suitable as demonstrations for use in class. There are suggestions here for every topic and nearly all the subtopics of the course, although none of these is prescribed content. The goal of the extensive list is to help teachers choose examples of laboratory work suitable for their circumstances.

Downloadable resource

Ideas for demonstrations and practicals (PDF)

Safe and ethical practice in experimental work

Managing safety in science laboratories sets out guidance for schools on operating laboratories and workshops safely in DP and Career-related Programme (CP) science group courses. The IB recognizes that resources and equipment available to schools for the provision of science laboratories and workshops will differ according to setting. However, some principles, such as safety, should underpin all endeavours. All schools must ensure that the requirements and guidelines in this publication have been taken into account.

IB sciences experimentation guidelines highlights safety and ethical considerations that must be followed by schools. It gives guidance for all staff involved in organizing, supervising or delivering science experiments in areas such as animal dissection, fieldwork and risk assessments.

Green chemistry is worth exploring in class, and its 12 principles should be discussed with students whenever possible.

Further guidelines are available worldwide to help schools maintain a safe environment. Some guidelines are available at the websites of the Laboratory Safety Institute and the International Council of Associations for Science Education.

Errors and uncertainties

The examples that follow are only illustrations of the depth required to address uncertainties and errors. They do not represent all the ways and means to deal with uncertainties and errors.

The significance of errors and uncertainties

Data collection and data analysis are central to the scientific process. All data are limited in the information they convey; this means that there is uncertainty in every measurement. This uncertainty is expressed as a range of possible values within which the true value lies.

Moreover, experimental design always involves some weaknesses and assumptions that may give rise to errors. These uncertainties and errors have an impact on the validity of scientific findings, and so they must be carefully communicated and considered in the evaluation of the results.

Students should, therefore, be encouraged to record uncertainties and errors, and to consider their impact on the results of **all** their experimental work during the course. The criteria for the internal assessment component of the course also include these skills.

The resources here explain the steps involved in handling errors and uncertainties, so that these processes can be integrated into students' learning. Experimental data continually expand the boundaries of science, but an awareness of the limits of that knowledge is crucial to its application.

Types and sources of error

There are two types of errors: systematic and random.

Systematic errors

The first category of errors concerns systematic errors, which:

- are errors due to identifiable causes in the experimental design
- give results that are consistently higher or lower than the true value
- are not reduced by repetition of the experiment
- can, in principle, be reduced by modifications to the experiment.

Examples of causes of systematic error include:

- error caused by poor insulation during thermochemical experiments
- error caused when measuring gas volume by collection over water, assuming the gas is insoluble.

Random errors

The second category of errors involves random errors, which:

- arise from the limit of the precision of the experimental apparatus
- lead to measurements that are equally likely to be higher or lower than the true value
- can be minimized by measurement repetition and averaging the measurements, leading to cancelling out of the variation
- can be reduced with the use of more precise measuring equipment
- can be quantified in all measurements and are expressed as a ± range of values

The following are examples of measurements showing a decrease in random error and thus an increase in precision (the term "precision" is explained in the following section).

Examples of measurements showing a decrease in random error thus an increase in precision

5.2 g ± 0.1 g

5.13 g ± 0.01 g

5.312 g ± 0.001 g

decreasing random error

increasing precision

Accuracy and precision

Accuracy is how close a measured value is to the correct value. Experiments with smaller systematic errors are more accurate.

Precision indicates how many significant figures there are in a measurement. Data with smaller random errors are more precise.

For example, the normal boiling point of water is 100°C. Measurements from two experiments are provided in the table on boiling point versus uncertainty.

Measurements from two experiments on boiling point of water vs uncertainty

	Boiling point (°C)	Uncertainty
Experiment 1	99.5°C	± 0.5°C
Experiment 2	98.15°C	± 0.05°C

Experiment 1 is more accurate but less precise. Experiment 2 is less accurate but more precise. (Note the consistency in the number of decimal places between each measurement and its uncertainty. The term "uncertainty" is explained in the next section.)

Estimating and recording uncertainty in raw data

All raw data should be given with an associated uncertainty (random error). As it is the last digit that is uncertain, the uncertainty must be expressed to the same number of decimal places as those in the measurement.

Example 1

34.0 cm^3 ± 0.5 cm^3

34.10 cm^3 ± 0.05 cm^3

It can sometimes be difficult to determine the uncertainty associated with a measurement as several factors may influence the reading. Examples include the reaction time of the experimenter when measuring time, or judging the colour change at the end point of an indicator during a titration. These may not be quantifiable but should be noted as additional sources of error.

In general, random error can be estimated as follows.

- The uncertainty for a specified temperature is often stated by the manufacturer of the instrument or glassware.
- Where not stated, for digital equipment, the uncertainty is the smallest scale division (sometimes known as "the least count").
- Where not stated, for analogue equipment, the uncertainty is half the smallest division.

Example 2

For example, consider the following data obtained from experiments to measure the mass of two samples using a digital balance. According to the table on data from the two-decimal point balance, the uncertainty is ± 0.01 g.

Uncertainty in measurements when using a two-decimal point balance

	Mass (g ± 0.01 g)
Sample 1	1.23
Sample 2	0.95

However, as the table on data from the three-decimal point balance shows, the uncertainty is ±0.001 g.

Uncertainty in measurements when using a three-decimal point balance

	Mass (g ± 0.001 g)
Sample 1	1.233
Sample 2	0.954

Note that when the same apparatus is used for a set of data, the uncertainty can be recorded in the column header, as it is the same for each reading.

Example 3

As the figure of the glassware shows, the smallest division (or least count) is 0.1 cm^3. In this case, the uncertainty is taken as ± 0.05 cm^3.

Therefore, the volume poured is expressed as 48.80 cm^3 ± 0.05 cm^3.

Example of uncertainty in measurement of volume when using analogue glassware

Consideration of uncertainties in processed data

The uncertainties associated with each measurement are known as "absolute uncertainties". When data values are processed, the impact of these uncertainties must be considered through the calculations. This process, which is sometimes referred to as "error propagation", generates a final or overall uncertainty for the experimental results. The general principle is that the overall uncertainty is the sum of the absolute uncertainties. The process used in error propagation depends on the nature of the steps in the data analysis.

Error propagation for addition or subtraction of measurements

When data values are added or subtracted, the uncertainties associated with each value must be added together. This is because the total error must include the range from the possible maximum to the possible minimum of each reading.

For example, consider the table showing data from an experiment to determine change in temperature.

Experiment to determine change in temperature

	Temperature (°C ± 0.1°C)
Final temperature	29.9°C
Initial temperature	27.9°C

According to the data,

Temperature change = (29.9°C ± 0.1°C) – (27.9 ± 0.1°C) = 2.0°C ± 0.2°C

Rationale:

Final temperature is in the range 29.8°C to 30.0°C

Initial temperature is in the range 27.8°C to 28.0°C

Therefore, the temperature difference could be as high as 2.2°C (30.0°C – 27.8°C) or as low as 1.8°C (29.8°C – 28.0°C), namely 2.0°C ± 0.2°C.

Error propagation for multiplication or division of measurements

When data values are multiplied or divided, or when measurements with different uncertainties are made, we must first standardize these absolute uncertainties before they can be combined. The following steps apply.

- Convert each absolute uncertainty into a percentage uncertainty:

  $$\text{Percentage uncertainty} = \frac{\text{absolute uncertainty}}{\text{data value}} \times 100$$

- Add the percentage uncertainties for each data value.
- Express overall uncertainty as percentage uncertainty, or convert it back into a final absolute uncertainty.

For example, see the table on an experiment to determine *n*, the number of moles in a solution.

Calculating the absolute and percentage uncertainties when determining the number of moles in a solution

	Data value	Absolute uncertainty	Percentage uncertainty
Concentration	1.00 mol dm^{-3}	± 0.05 mol dm^{-3}	$\frac{0.05}{1.00} \times 100 = 5\%$
Volume	10.0 cm^3	± 0.1 cm^3	$\frac{0.1}{10.00} \times 100 = 1\%$

$$n(\text{mol}) = \text{concentration (mol dm}^{-3}) \times \text{volume (dm}^3)$$

$$= 1.00 \text{ mol dm}^{-3} \times \frac{10.0}{1{,}000} \text{ dm}^3$$

$$= 0.0100 \text{ mol}$$

$$\text{Total uncertainties} = 5\% + 1\%$$

$$= 6\%$$

$$\text{Converting back to absolute value} = \frac{6}{100} \times\ 0.0100 \text{ mol}$$
$$= 0.000600 \text{ mol}$$

The answer can be given with total uncertainty expressed either as a percentage or as absolute value.

$$\text{n(mol)} = 0.0100 \text{ mol} \pm 6\%$$
$$= 0.0100 \pm (6\times10^{-4}) \text{ mol}$$

In calculations involving multiplication and division, the precision of the result is limited by the precision of the least precise measurement. So, the result should be given to the same number of significant figures as those in the least precise data value.

While considering the significant figures in the uncertainty, the common protocol is as follows.

- When the final percentage uncertainty is greater than or equal to 2%, it should be given to one significant figure.
- When the final percentage uncertainty is less than 2%, it should be given to not more than two significant figures.

For example, consider the table on an experiment to determine concentration.

Calculating the absolute and percentage uncertainties when determining concentration

	Data value	Absolute uncertainty	Percentage uncertainty
Mass of solute	6.5 g	± 0.1 g	$\frac{0.1}{6.5} \times 100 = 1.5\%$
Volume of solution	63.10 cm^3	± 0.05 cm^3	$\frac{0.05}{63.10} \times 100 = 0.0792\%$

$$\text{Concentration (g cm}^{-3}) = \frac{\text{mass (g)}}{\text{volume (cm}^3)}$$
$$= \frac{6.5 \text{ g}}{63.10 \text{ cm}^3}$$
$$= 0.103 \text{ g cm}^{-3}$$

$$\text{Total uncertainties} = 1.5\% + 0.0792\%$$
$$= 1.5792\%$$

As the least precise data (mass) have two significant figures, the result is given to two significant figures. As the uncertainty is <2%, the uncertainty is given to two significant figures.

Therefore,

Concentration = 0.10 g cm^{-3} ± 1.6%

Error propagation for exponents *(HL only)*

Consider calculations where a data value is raised to the power of a whole number. If this whole number is *n*, a typical calculation might be represented as follows.

Result = (data value)^n

Note that the units associated with the data value are also raised to the power *n*.

To propagate the uncertainty in this type of calculation, it is best to first convert the absolute uncertainty into a fractional (relative) uncertainty.

$$\text{Fractional uncertainty} = \frac{\text{absolute uncertainty}}{\text{data value}}$$

This fractional uncertainty is then multiplied by the exponent *n* to give the total uncertainty.

(Rationale: This is really a form of multiplication and so, again, the process involves adding the relative uncertainties—in these cases, by the same number of times as the exponent.)

For example, consider the table on a rate experiment to investigate the order of the reaction with respect to reactant A.

Absolute and fractional uncertainties of a rate experiment to determine the order of the reaction with respect to reactant A

[A] (mol dm^{-3})	Absolute uncertainty (mol dm^{-3})	Fractional uncertainty
0.30	± 0.02	$\frac{0.02}{0.30} = 0.0667$

The calculation involves raising the concentration of reactant A to the power 3 (i.e. cubing it). The fractional uncertainty in the concentration of A must then be multiplied by 3 to arrive at the total uncertainty.

$$\begin{aligned}[A]^3 &= (0.30)^3(\text{mol dm}^{-3})^3 \\ &= 0.027 \text{ mol}^3 \text{ dm}^{-9}\end{aligned}$$

$$\begin{aligned}\text{Total uncertainty} &= 0.0667 \times 3 \\ &= 0.20\end{aligned}$$

Note that 0.20 is a fractional quantity, and so it has no units.

Result = 0.027 mol^3 dm^{-9} ± 0.2

The total uncertainty can be converted back to an absolute uncertainty, as shown below.

0.20 × 0.027 mol^3 dm^{-9} = 0.0054 mol^3 dm^{-9}

Alternatively, it can be converted to a percentage uncertainty.

0.20 × 100 = 20%

Final result = 0.027 ± 0.005 mol^3 dm^{-9} or 0.027 mol^3 dm^{-9} ± (2 × 10^1)%

If a calculation involves extracting the *n*-th root of a value, the process is similar, but the fractional uncertainty is now divided by *n*.

Error consideration when taking averages of data values

Repeated measurements can be used to determine an average value for a result. In this case, the final uncertainty is the same as the uncertainty in the component values.

For example, consider the table on calculation of Δ*H* in an experiment. In this case, three data values are generated, all with the same uncertainty.

Error consideration when using average ΔH

Observation 1 Δ*H* (kJ mol^{-1})	+100 kJ mol^{-1} ± 10%
Observation 2 Δ*H* (kJ mol^{-1})	+110 kJ mol^{-1} ± 10%
Observation 3 Δ*H* (kJ mol^{-1})	+108 kJ mol^{-1} ± 10%
Average Δ*H*	**+ 106 kJ mol^{-1} ± 10%**

The final uncertainty is the same as the uncertainty of each data value.

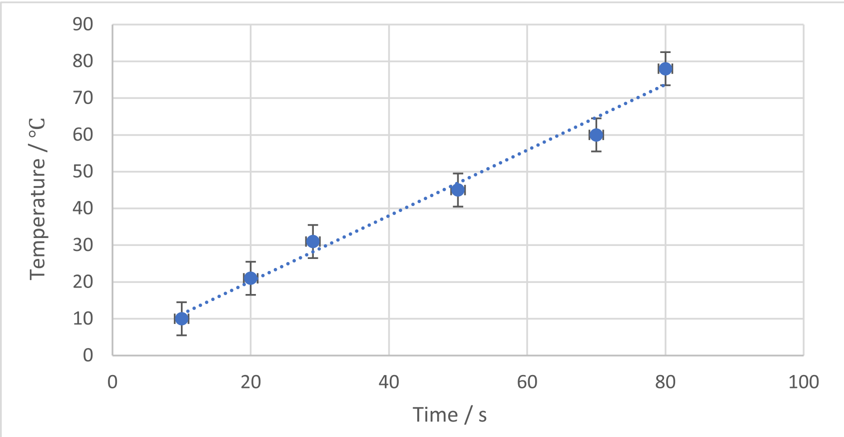
(Rationale: The uncertainty is not increased by taking repeat measurements; in fact, the experiment is repeated to reduce the random error.)

Graphical representation of uncertainties

Uncertainty bars

An effective way to communicate the uncertainties associated with data values is to use uncertainty bars (also called "error bars") in graphs. These bars join together points for the maximum and minimum of the range covered by the uncertainty, above and below the data value. They can be used on the axes of either or both the dependent (*y*) variable and the independent (*x*) variable. Uncertainty bars can be plotted manually from the data values and uncertainties. They are generally plotted using graphing software. For example, consider an experiment on change in temperature over time during a reaction. As the figure on the uncertainty bars for this experiment shows, the uncertainty of each temperature data point (displayed by the uncertainty bars) is ± 5°C.

Uncertainty bars showing uncertainty of each temperature data point

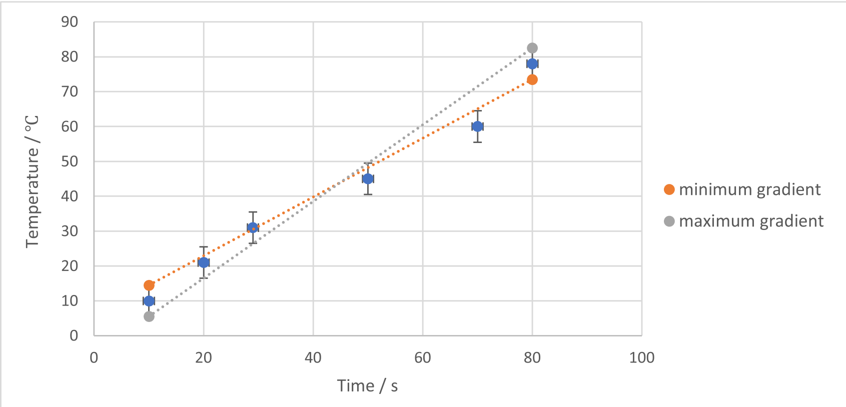


This example also shows uncertainty bars for the data values of time on the *x*-axis, but these are obviously very small compared to the uncertainties in temperature.

It is often the case that the uncertainty in one measurement is much greater than that in the other. In such cases, the total uncertainty can be taken as being due to the larger uncertainty alone, as the smaller value will have negligible impact.

Uncertainty bars can be used to calculate the gradient of the best-fit line for the given data points. As the figure on gradient of the best-fit line shows, this is done by drawing two lines: one with the minimum gradient and the other with the maximum gradient. Both lines go through the uncertainty bars. (For obvious reasons, these are sometimes called "lines of worst fit".) Graphing software can be effective here too, or the lines can be drawn by hand.

Finding the gradient of the best-fit line; the grey and red lines represent the maximum and minimum gradients, respectively.



The value of the final gradient of the best-fit line is the average of the gradients of the maximum and minimum lines.

$$\text{Final gradient} = \frac{\text{gradient of maximum line} + \text{gradient of minimum line}}{2}$$

$$\text{Final gradient uncertainty} = \frac{1}{2}(\text{maximum gradient} - \text{minimum gradient})$$

Coefficient of determination (R^2)

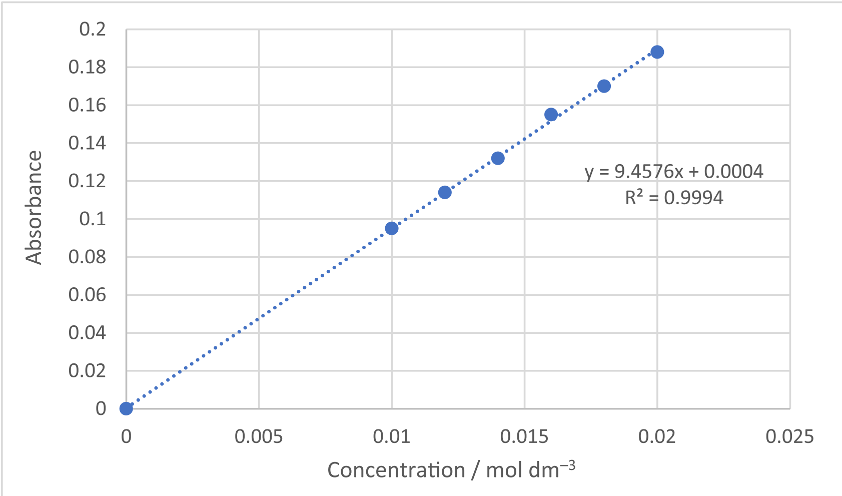
A best-fit line or best-fit curve is a trendline through a scatter plot of data points that best expresses the relationship between the points. Graphing software can often be used to generate the best-fit line by calculating its gradient and intercept in the equation $y = mx + c$. The position of the line can also be estimated manually by making a judgement of its optimum gradient and intercept, taking into account data points that may lie on either side of the line. Uncertainty bars help to make this process more accurate.

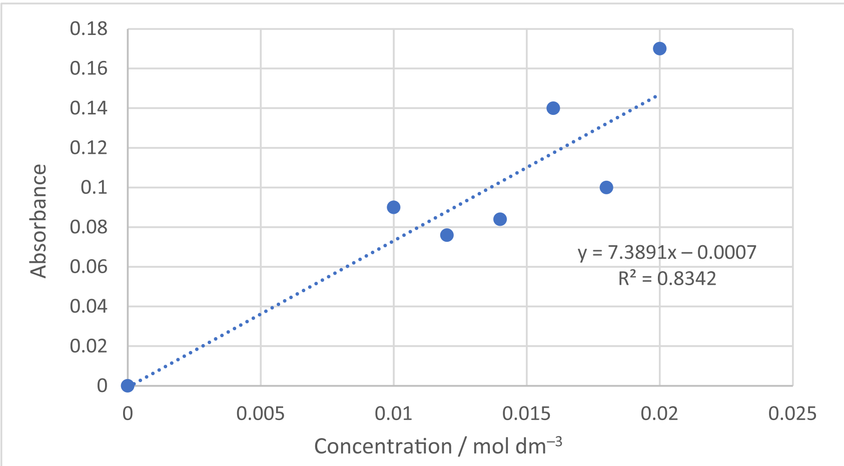
The next step is to assess how well the line or curve is a true representation of the data points. This can be done using a statistical tool known as R^2, the coefficient of determination. Students are not expected to be able to calculate R^2 values, as these are easily generated by graphing software. The important application is in interpreting their meaning.

R^2 values range from 0.0 to 1.0. An R^2 value of 1.0 indicates that the data fit the linear or curve equation perfectly. In other words, every data point lies on the best-fit line or best-fit curve. R^2 values less than 1.0 indicate that at least some variability in the data cannot be accounted for by the model. Simply put, the higher the value, the better the fit of the line with the data points.

For example, consider the figure on the best-fit lines for concentration versus absorbance data from two experiments. In the case of the first experiment, the value of R^2 is 0.9994. The best-fit line almost passes through all the data points. Note that it is likely that this best-fit line would pass through the origin if a calibration were to be carried out. Most graphing software allows users to implement this change. For the second experiment, the value of R^2 is 0.8342. Here, the best-fit line does not pass through all the data points. In fact, the data points are scattered on either side of the line.

Best-fit lines for concentration vs absorbance data from two experiments





Error analysis and evaluation

The evaluation of the conclusion of an experiment must include consideration of both systematic errors and the total uncertainty from the propagation of errors through data analysis.

Where a literature or theoretical value exists for the experimental result, the difference between the experimental and literature values can be calculated as a percentage.

$$\text{Percentage difference} = \frac{\text{experimental value} - \text{theoretical value}}{\text{theoretical value}} \times 100$$

This difference is known as the "percentage error" or "experimental error". The higher the experimental error, the less accurate the result.

The experimental error should be compared with the total uncertainty value for the experiment. If the experimental error is outside the range of the total uncertainty, it suggests that random error alone cannot explain the experimental error and that systematic errors are also present.

For example, consider the table showing data from an experiment to measure the enthalpy of a reaction.

Experimental error when measuring the enthalpy of a reaction [Source: Halfman, n.d.]

Experimental value	Theoretical value	Experimental error
58.5 kJ mol^{-1} ± 2.5 kJ mol^{-1}	55.0 kJ mol^{-1}	$\frac{(59.5 - 55.0)\ \text{kJ mol}^{-1}}{55.0\ \text{kJ mol}^{-1}} \times 100 = 6.36\%$

$$\text{Percentage total uncertainty in the experimental value} = \frac{2.5}{59.5} \times 100$$
$$= 4.27\%, \text{ rounded to } 4\%$$

The experimental error is, therefore, larger than the total uncertainty. This means that the difference between the experimental and theoretical values cannot be explained in terms of the random errors in the measurements alone; systematic errors must also be present.

An important aspect of experimental evaluation is to suggest sources of systematic error, to determine in which direction each error may have influenced the result and to suggest modifications to the experiment to reduce these effects.

Teacher and student responsibilities

This section outlines the actions and responsibilities of both teachers and students during the scientific investigation. The teacher is the mentor who provides guidance and support to students during the process, so that students can demonstrate the necessary inquiry skills described in the sections "Approaches to learning", "Approaches to teaching" and "Skills in the study of chemistry".

Teachers are encouraged to accompany and guide students in this journey, allowing them to make their own decisions with confidence, replicating the processes undertaken by scientists. Topics that have some personal significance will encourage students into more innovative approaches.

Teacher responsibilities

General responsibilities

Teachers must provide "non-decision-making" guidance and support. They must develop a range of strategies to ensure ongoing authenticity of the student work, which may include:

- discussing with students their initial proposals and the investigative methods to be used
- being present and supervising students during data collection
- discussing the content of the work with students and the conclusions being drawn
- scrutinizing the draft and final versions of the work, e.g. by comparing a student's writing style with that of their other work, or using web-based applications to detect plagiarism.

Specific responsibilities

While facilitating the scientific investigation, teachers have the following responsibilities.

Prior to student development of a research question, teachers must:

- explain the aims and requirements of the scientific investigation, ensuring that the criteria are well understood by students
- ensure that students have developed the required skills for their scientific investigation and for authoring their reports
- encourage students to explore ideas and ask questions that relate to topics studied during the course
- remind students that different types of investigation could be carried out, e.g. hands-on investigations, fieldwork, use of databases and online simulations
- ensure that approximately 10 hours are allocated for the design and implementation of the scientific investigation.

During student development of a research question, teachers must:

- discuss with students the appropriateness of their research question for a report with a 3,000-word limit
- counsel students on whether the projected research is suitable for the chemistry course and feasible in terms of time, resources, and safety, ethical and environmental considerations
- ensure that each student develops their own research question
- ensure that the investigative method proposed by each student is adequate to obtain valid and sufficient data.

During initial collaborative work, teachers must:

- guide students in organizing themselves into groups

- ensure that each group consists of no more than three students.

In this phase, the school, the teacher and the students share responsibility for ensuring that each student's input is assessed only on the work they carry out for their own investigation.

During the investigation, teachers must:

- supervise the work and data collection carried out by students. If students are collecting data outside the classroom, sufficient steps should be established to ensure authenticity of student work
- monitor student progress in data collection and processing
- where necessary, show students how to operate equipment, or guide them in the steps needed to carry out tasks such as graphical analysis and navigating a database. However, the teacher should not choose equipment, the method of analysis or the database for the students.

During report writing, teachers must:

- remind students of the requirements of the written report—it should be relevant and concise, with references—and of the assessment criteria
- ensure that students understand concepts related to academic integrity, e.g. authenticity and intellectual property. In the case of collaborative work, the difference between collaboration and collusion must be made clear
- read and comment on students' draft investigative reports. The teacher's comments should aim to help students identify issues and shortfalls according to the assessment criteria, but they must not directly offer solutions
- ensure that the internally assessed work is entirely that of each student, and that any information incorporated from external sources is appropriately cited and acknowledged.

Student responsibilities

General responsibilities

- First and foremost, the work submitted must be a student's own.
- Individually, each student must:
  - formulate a research question
  - establish a research methodology
  - identify variables
  - collect and analyse the data
  - draw conclusions.
- Students must also understand and actively apply concepts related to academic integrity, such as authenticity, respect for intellectual property, and citing and referencing according to accepted systems.

Specific responsibilities

Prior to the development of a research question, students must:

- understand that the internal assessment is compulsory for both standard level (SL) and higher level (HL) students
- read and understand the assessment criteria.

During development of a research question, students must:

- choose a suitable topic in chemistry for the scientific investigation
- formulate and develop their own research question, even if working in small collaborative groups
- consult with the teacher to ensure that the proposed scientific investigation is feasible. The research question must be focused, non-trivial and testable

- design a method that is suitable to address the research question and allows collection of valid and sufficient data
- seek teacher guidance to learn how to set up and use equipment, and to be sure that their methodology is appropriate considering the time and resources available.

During the investigation, students must:

- follow experimental guidelines, and local ethics, safety and environmental regulations
- follow school and teacher recommendations and stipulations
- record all observations and measurements.

During the report writing phase, students must:

- present a concise draft version of the report to the teacher
- use subject-specific terminology and conventions
- acknowledge all sources of information, with adequate references
- consider teacher recommendations regarding the draft version of their report, before submitting the final version
- confirm that the report submitted is their authentic work, and constitutes the final version of that work.

Scheduling and planning the internal assessment

As stated in the *Chemistry guide*, "the internal assessment should, as far as possible, be woven into normal classroom teaching and not be a separate activity conducted after a course has been taught".

Each school is free to decide the stage of the course most appropriate to carrying out the scientific investigation, when students have developed sufficient skills and subject content.

Factors to consider in scheduling and planning include:

- the experimental skills and concepts to be developed during the two-year course
- the 10 hours to be allocated to the work, e.g. when these should be scheduled
- the number of students being assessed, all of whom will need guidance and supervision
- coordination with teachers of other Diploma Programme (DP) subjects, to avoid excessive student workload
- school calendars, local regulations and other DP assessment activities
- accessibility to any outdoor environment (if applicable)
- the types of investigation chosen by the students:
    - laboratory work
    - fieldwork
    - investigations using simulations, databases and modelling
- the IB submission deadline indicated in *Diploma Programme Assessment procedures* (updated annually).

Student preparedness

Over the course of their studies, student preparedness for the internal assessment is developed through multifaceted learning opportunities.

Developing approaches to learning skills in chemistry

Table 3 in the *Chemistry guide* describes the approaches to learning skills that students must experience during the course. Through these experiences, the approaches to learning skills—thinking, communication, social, research and self-management—can be practised and developed before the scientific investigation is attempted.

Formative practical experiences

The section "Skills in the study of chemistry" in the *Chemistry guide* describes the experimental techniques, technology and skills that students must attain to support the inquiry process. Students develop their scientific skills and techniques, and their understanding of scientific methodologies, using a range of active learning processes through which they experience the syllabus content. Throughout the course, this involves carrying out different formative practical activities, investigations, experiments, fieldwork and assignments. It is essential that students are given the opportunity to ask a range of research questions with differing methodologies. These experiences will be applied to the scientific investigation through the inquiry process, which includes the stages of designing the investigation, collecting and processing data, concluding and evaluating. This is also an opportunity to reinforce the *IB sciences experimentation guidelines* and academic integrity guidance, as well as giving guidance on how to cite and include references.

Presenting and explaining the internal assessment criteria

The internal assessment criteria are introduced in class activities throughout the first year of the course. Applying the criteria to smaller assignments, whether individual or collaborative, is another way to familiarize students with the criteria. Students should have sufficient opportunities to unpack the requirements for each criterion.

Student planning

An important success factor for the internal assessment is for students to organize themselves according to the time and resources available. For example, major tasks can be broken down into stages, each one with an agreed deadline. A staged process may involve the following.

Ideation sessions

Ideation sessions can be very useful for students to develop a culture of asking questions based on personal interests, observations and subject content within the syllabus. Ideation sessions can also be valuable in revising the *IB sciences experimentation guidelines*.

Students should be encouraged to choose a topic of interest for the scientific investigation.

Developing a research question

Each student should read about their topic of interest to gather background information that will lead to meaningful study. They should record details of all the websites and literature they consult.

Students can then formulate a focused research question identifying the relevant variables, including those that need to be controlled. After a question is formulated, the teacher spends time with each student to verify that the research question is testable, and that variables have been correctly identified. For example, it may be necessary to select a suitable range of values for the independent variable.

Deciding on a methodological procedure

Each student decides on the most appropriate method to ensure the collection of relevant and sufficient data that address the research question and allow for a valid conclusion to be drawn. Each student provides a list of materials and equipment required for the investigation.

The teacher evaluates the suitability of the student's proposed methodology to answer the research question. If asked, teachers may (for example) need to show how equipment is used, how a technique should be followed, or how a graphical analysis is carried out.

Collecting data

Each student agrees with the teacher when and where data are to be collected. The teacher should verify that all safety, ethics, environmental and experimental guidelines are followed. They should also monitor the progress of the investigation and supervise the work being carried out by the student as part of the ongoing authenticity check.

For large cohorts of students, a staggered process could be organized.

Writing a draft report

Each student agrees with the teacher on the handover deadline for a draft report. The teacher reads it and provides holistic feedback on the work, without editing the draft. Teacher comments should be broad and general. This is the last opportunity for the teacher to:

- emphasize the importance of a relevant and concise report
- emphasize the correct use of references
- ensure that the work is commensurate with the level of the course
- ensure that the work meets the criteria against which it will be assessed.

Delivering the final report

The student agrees with the teacher on the final handover deadline. Students should revise the contents of the work and make any necessary amendments or improvements before submitting the final version.

Each student must confirm that the scientific investigation is their own authentic work and is their final version. As stated in the *Chemistry guide*, "the requirement to confirm the authenticity of work applies to the work of all students, not just the sample work that is submitted to the IB for the purpose of moderation".

Internal assessment deadlines

Further work is necessary after the students have submitted their final report. Teachers must therefore take the following steps into consideration while scheduling the work.

Assessment of the reports

The final report from each student about their work must be read, assessed using the internal assessment criteria and authenticated by the teacher.

It is strongly recommended that comments are made on the work. This aids in awarding the correct level for each criterion. During the process of external moderation, comments help examiners understand the reasoning behind the marks given by the teacher.

Internal standardization

Internal standardization is essential to ensure that works are marked consistently within the school for a given examination session. If only one teacher is teaching chemistry, standardization across science subjects is recommended.

Submission of marks to the IB

After the marks of all the students are entered, a randomized set of works are selected for moderation. Teachers work with heads of department and DP/Career-related Programme (CP) coordinators to make sure marks are submitted prior to the deadline published in *Diploma Programme Assessment procedures* (updated annually).

Submission of works to the IB

The works of the students chosen by the IB for external moderation must be uploaded before the deadline, following the procedures indicated in *Diploma Programme Assessment procedures.*

Activities to develop skills for the inquiry process

Asking questions worth answering

The process of investigating is an opportunity for students to use time and resources to answer a research question. It is the teacher's responsibility to give students opportunities to ask meaningful questions and to steer them away from trivial ones.

Teachers must challenge students to ask questions:

- that are not easily answered using an online search engine
- that are not versions of previously written practical reports
- for which answers are not found in their textbook
- for which the answers are not self-evident from the syllabus.

Some strategies for teaching students to ask questions worth answering include the following.

Exploring unanswered questions

Try asking questions and leading the discussion. For example:

- The ability of biosorbents such as lemon, artichoke and bean shells to remove lead(II) ions from wastewater has been reported (Ergüvenerler et al., 2020). Can other biosorbents do the same?
- We know heavy metals inhibit enzymes, but what about other metal ions?

Scheduling a lesson on just research questions

Kitchen chemistry can be a good starting point for an inquiry. The chemical transformations that take place during cooking and meal preparation are often highly visible and therefore relatable for students. The transformation of food ingredients into interesting edible meals is underpinned by the principles of chemistry.

Students can explore a series of videos on kitchen chemistry, which is the topic of a free online course, "The Science of Gastronomy", developed by King L. Chow and Lam Lung Yeung at the Hong Kong University of Science and Technology.

1. Watch the video titled "1.6: How do we cook by convection?" (Chow, Yeung, n.d.b).
    a. Stop the video at 6:50. The typical boiling point of pure water is 100°C. Write a list of some of the factors that might affect the boiling point of a sample of pure water.
    b. Continue watching until 8:33, adding further ideas to your list in (a).
    c. For one of the factors you identified in (a) and (b), describe how you would test your hypothesis.
    d. Complete watching the video. What other research questions could you ask about how heat conduction in a liquid is affected by the liquid's viscosity?
2. Watch the video titled "7.3: What gives green color to plants?" (Chow, Yeung, n.d.c).
    a. Stop the video at 2:03. How could you analyse the pigments present in a green plant?
    b. Complete watching the video. What experiment could you design about factors affecting the presence of some or all of the pigments in green plants?
3. Watch the video titled "7.5: Demonstration—Manipulating the color of red cabbage" (Chow, Yeung, n.d.d).
    a. How could you quantify the colour of a red cabbage solution?
4. Watch the video titled "7.4: Why some plants are not green in color?" (Chow, Yeung, n.d.e).
    a. What experiment could you design about factors affecting the colour of anthocyanins?

b. Conduct an online search for the structures of some of the pigments you learned about (e.g. chlorophyll, beta-carotene and betanin). What functional groups can you identify? How would you expect their solubility to vary in different solvent systems? How could you test your hypothesis?

If any class time remains, watch any two or three additional videos from this Coursera course (Chow, Yeung, n.d.a) and write down further possible research questions.

The videos can be found here:

Chow, K., & Yeung, L. L. (n.d.a). *The science of gastronomy* [Online course]. Retrieved April 23, 2022 from https://www.coursera.org/learn/gastronomy

Chow, K., & Yeung, L. L. (n.d.b). *1.6 How do we cook by convection?* [Online course]. Retrieved April 23, 2022 from https://es.coursera.org/lecture/gastronomy/1-6-how-do-we-cook-by-convection-qqzHU

Chow, K., & Yeung, L. L. (n.d.c). *7.3: What gives green color to plants?* [Video]. Retrieved April 23, 2022 from https://www.coursera.org/learn/gastronomy/lecture/oeKYD/7-3-what-gives-green-color-to-plants

Chow, K., & Yeung, L. L. (n.d.d). *7.5: Demonstration—Manipulating the color of red cabbage* [Video]. Retrieved April 23, 2022 from https://www.coursera.org/learn/gastronomy/lecture/PY9rp/7-5-demonstration-manipulating-the-color-of-red-cabbage

Chow, K., & Yeung, L. L. (n.d.e). *7.4: Why some plants are not green in color?* [Video]. Retrieved April 23, 2022 from https://www.coursera.org/learn/gastronomy/lecture/gLUaf/7-4-why-some-plants-are-not-green-in-color

Reminder: What makes a good research question? The examiner notes say explorations of the relationship between variables should:

- identify the independent variable
- indicate the range of the independent variable
- identify the dependent variable (and/or derived dependent variable)
- describe the chemical reaction or system being studied
- include a methodology.

Collecting stories

Stories can help to develop students' skills for the inquiry process. They can act as real-world inspiration that helps students think of areas to explore. The following are examples from IB teachers.

Example 1

People have been using natural pigment sources (such as insects and plants) to dye materials such as textiles for millennia. Dyes sourced from plants include madder, indigo and onion. Natural dyes have largely been replaced by synthetic counterparts, which offer better resistance to fading (known as "fastness"), as well as variety and cost-effectiveness. Mordants increase the extent to which a dye binds to a particular fibre. The Quechuan words *colpa* and *alcaparosa* refer to both alum and iron(II) sulfate, which Andean people have used as mordants for centuries (Antúnez de Mayolo, 1989).

Growing concern about the environmental impacts of the textile industry has renewed popular interest in natural dye sources (Alves et al., 2014) and research into dye recycling (Adeogun, 2022).

Ask students to research the factors affecting the action of natural dyes and to suggest three research questions from their research. Each research question must:

- describe the system being studied
- describe the methodology used
- identify the independent and dependent variables (if applicable).

Example 2

Guacamole, a dip made from mashed avocado, is a popular dish originally from Mexico. After an avocado has been peeled, it is prone to enzymatic browning. This gives it an unattractive colour, although it is still safe to eat. Methods used to prevent guacamole from browning include adding lemon or lime juice, placing plastic film over the surface and placing an avocado stone in the guacamole. What else can prevent enzymatic browning of food and how might students investigate a question like this? Ask students to develop a method. Background reading material may include Bates (1968) and Brunning (2014).

Example 3

Every place I visited seemed to have their favourite vitamin C source, with parents often saying fruit X had Y times the vitamin C of oranges. For example in India, we are fans of amla; in Southeast Asia, guava is a favourite source; my Japanese students were sure it would be yuzu. Students can discuss possible methodologies that they could use to analyse food samples to investigate these claims. Students could then do some background research (e.g. Islamic Publications, n.d.; Japan National Tourism Organization, n.d.; Medindia, 2019; Royal Society of Chemistry, 2013), devise a research focus and draft the introduction, materials and method.

Running a "skills circus"

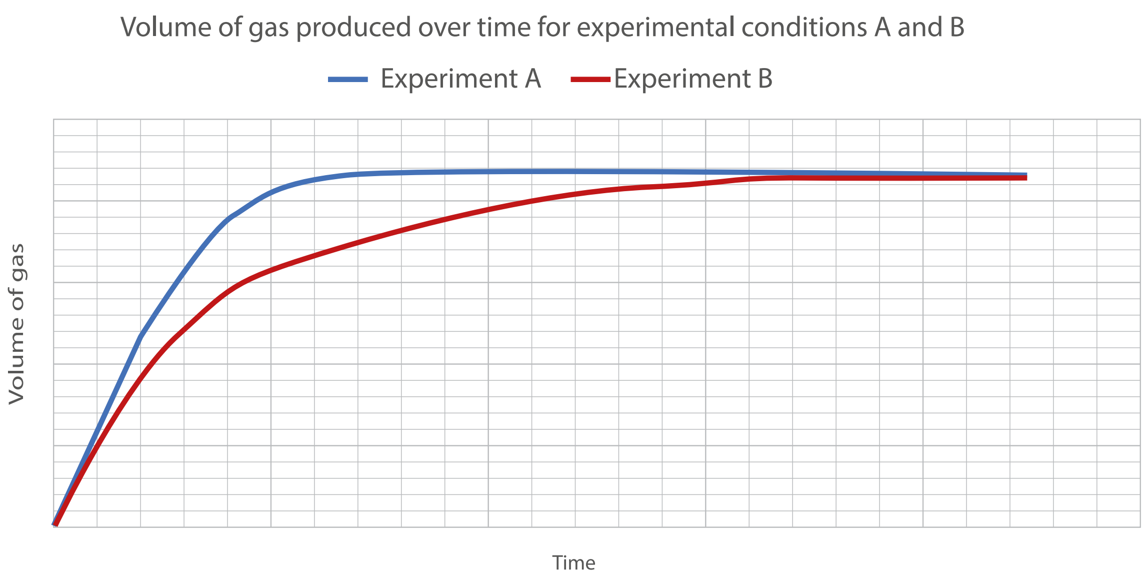
A session involving different activities can help refresh and develop students' practical inquiry skills. Here are two examples.

Activity 1—For different laboratory experiments that students have carried out over the past year, gather the apparatus and other materials they used and set it out on laboratory benches. Students then try to use the apparatus to refresh their memories of investigations they undertook. They can use any resource to refresh their memories.

For experiments, also ensure students follow the guidance given in *IB sciences experimentation guidelines* and *Managing safety in science laboratories and workshops*.

Activity 2—Each student receives a graph of experimental results. Their challenge is to set up the correct apparatus and other materials that would be needed to replicate the results shown on the graph.

For example, if given the graph below, students would set up a rate of reaction laboratory experiment involving a gas-producing reaction. They would then conduct the experiment with two different concentrations of an aqueous reactant.



Playing a variable lotto

Variable lotto is a low-stakes, high-feedback exercise. The following example involving chance choice with scientific variables aims to develop experimental design skills.

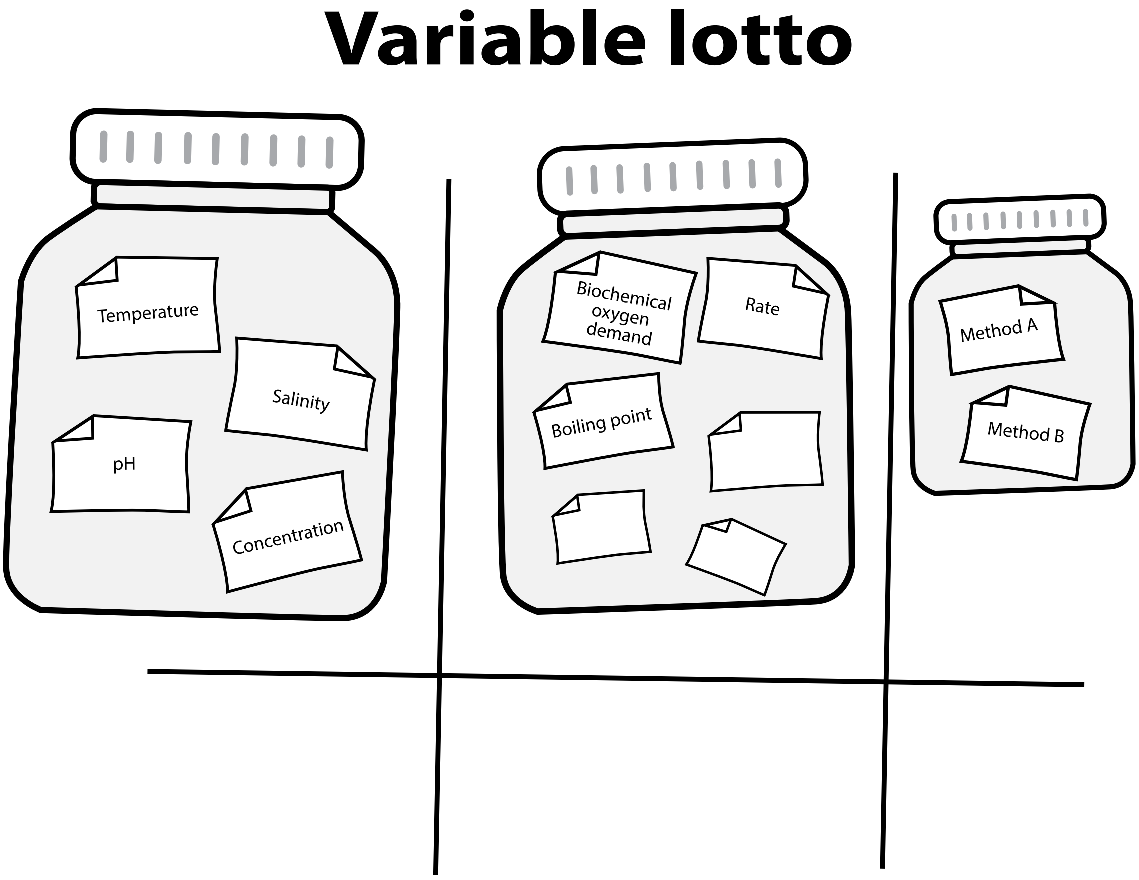
Prepare three beakers or jars containing folded pieces of paper (see the figure) marked with:

- a range of possible independent variables (jar 1)
- various dependent variables (jar 2)

- the letters A and B, referring to different methodologies (jar 3).

Students take a piece of paper from each jar. This shows them the laboratory experiment they will need to design for the next lesson.

An example of a variable lotto



Examples of lotto outcomes

- Effect of temperature on biochemical oxygen demand using method A, measurement using a dissolved oxygen probe
- Effect of salinity on biochemical oxygen demand using method B, a titration

Describe, explain, evaluate, predict

For a graph or set of graphs, students take turns describing what they observe, then explain the results. They then evaluate other factors, such as possible weaknesses in the study, or how the data are presented. Finally, they attempt to make predictions from the data given, or extrapolate to suggest how the experiment that produced the data could be extended further.

For each graph, students:

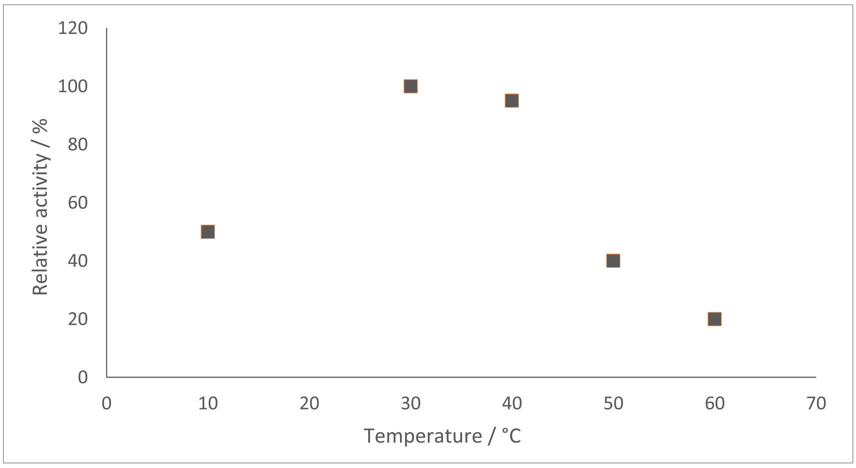
1. suggest an explanation
2. suggest an alternative explanation
3. design experiments to eliminate the alternative explanation.

Some example graphs follow, including some answers that students could suggest.

Catalase decomposition of hydrogen peroxide

In this graph, the results are expressed as relative activity, a percentage of the highest reaction rate measured.

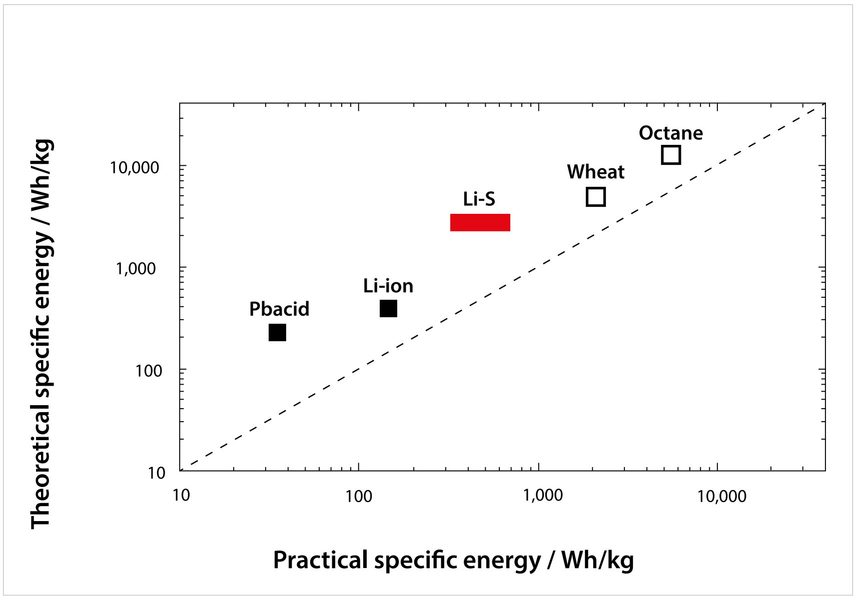
Catalase decomposition of hydrogen peroxide [Source: adapted from Al-Bar, 2012]



- **Explanation**: Most collisions between reactant molecules happen between 10°C and 30°C, and enzymes denature at temperatures higher than this.
- **Alternative explanation**: The spontaneous breakdown of hydrogen peroxide happens more quickly at higher temperatures, or the probe stops working at temperatures higher than 40°C.
- **Possible methods to eliminate alternative explanation**: If this was just the spontaneous breakdown of hydrogen peroxide at higher temperatures, the same trend would be seen even in the absence of the enzyme. The student could include a series of test tubes, one for each of the given temperatures, that contain everything but the catalase. There should be no similar increase of reaction rate between 10°C and 25°C.

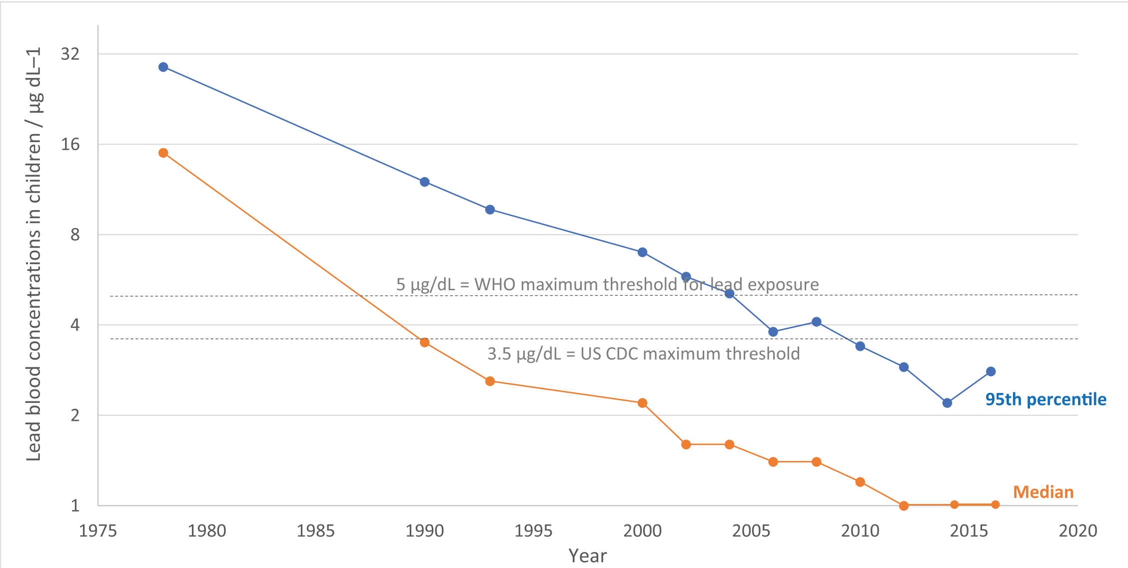
Comparing energy contents of batteries, fuels and materials

Energy contents of batteries, fuels and materials [Source: adapted with permission from Balsara, Newman, 2013]



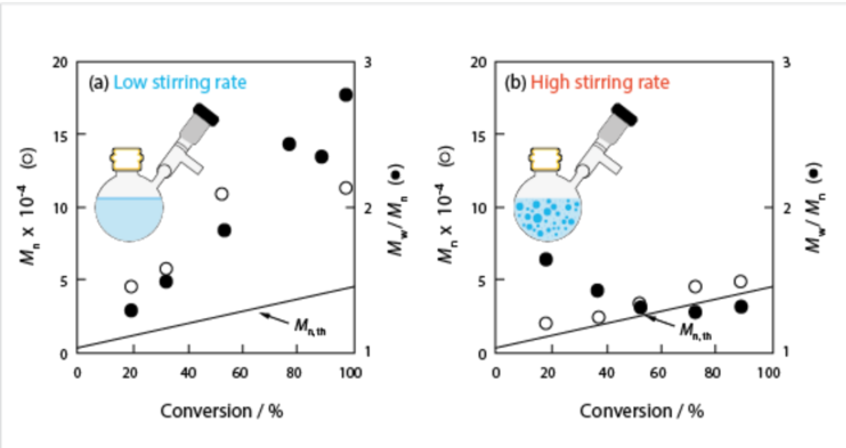
Analysing lead concentration in children's blood

Lead concentration in children's blood [Source: adapted from: Data from Centers for Disease Control and Prevention; National Center for Health Statistics, USEPA (2019) via Our World in Data. https://ourworldindata.org/grapher/lead-blood-usa-children?yScale=log&country=95th+percentile~Median, using: USEPA. (2019). ACE Biomonitoring—Lead. Retrieved April 23, 2022 from https://www.epa.gov/americaschildrenenvironment/ace-biomonitoring-lead, and Ritchie, H., & Roser, M. (2022). Lead concentrations in the blood of children in the United States. Our world in data. Retrieved April 23, 2022 from https://ourworldindata.org/grapher/lead-blood-usa-children?yScale=log&country=95th+percentile~Median]



Investigating polymerization of styrene

Polymerization of styrene [Source: adapted with permission from Moribe et al., 2010]



Using mentor texts when writing the scientific investigation

Mentor texts can be an effective tool to help students learn the specific requirements of disciplines and subject-specific tasks. Teachers know that each discipline has its own specific demands. Students will enter DP chemistry classes with some writing skills, but teachers will still need to find ways to familiarize students with the internal assessment criteria. They will also need to introduce students to specific conventions expected in science writing, and teach them some of the subject-specific vocabulary required for this task (Pytash, Morgan, 2014).

Mentor texts are often pieces of work that students can read to identify very specific sentences or phrases, and whether they were effective or ineffective. They can then "integrate what they learned from this process into their own writing" (Thompson, Reed, 2019). A mentor text will show students, not just tell them, how to write well, allowing them to envision the kind of writer they can be as they develop their skills (Dorfman, Cappelli, 2017).

One way this exercise varies from the use of mentor texts with younger students is that it does not use a "perfect" exemplary piece of work. Students are invited to find strengths and weaknesses in the mentor text based on teacher clarification of the rubric.

Sample mentor text lesson

In this lesson, taught over two days, students will read two unrelated investigations from the *Chemistry assessed student work*. While neither of these investigations is perfect, they scored highly enough that students will be able to identify strengths, as well as areas for improvement.

This lesson is best taught after students have collected some data in a laboratory experience, for example a simple rate experiment that generated data for which they can draw a conclusion.

The activity, "Assessing mentor texts" (PDF), guides teachers and students through these texts and marking rubrics specifically for the "Conclusion" and the "Evaluation" criteria, but the lesson format is fairly straightforward and can be modified to include other sections.

1. The teacher introduces each internal assessment criterion individually by going over the rubrics, the clarifications and then some more focused points.
2. Students read an assigned section of the mentor text, usually no more than two or three pages of student work. Individually, they mark up where they believe aspects of the conclusion criterion have been achieved, or where they believe there are omissions.
3. Students discuss their findings in groups and give feedback to the class about what markband they would assign this student for that criterion.
4. The teacher then uses a marked-up copy of the mentor text to go over what makes an effective conclusion.
5. Students then spend 15 minutes writing their own conclusions individually.
6. The next day, students continue reading, discussing and marking the evaluation section. The teacher then uses the marked-up copy of the mentor text to go over what makes an effective evaluation.
7. Students then spend 15 minutes writing their own evaluations individually.

General advice

Calculating the overall criterion mark

Deciding on an overall mark for a criterion can seem challenging, but it is less so when a clear methodology is used.

- When marking a student's report, read the complete report first to get a general impression of the work before deciding on the marks to be awarded.
- Evidence for a single criterion will inevitably appear in several places in a report—it is not expected that students will respond to the criteria in a linear or standard way. Read the report several times, marking the report overall against each criterion.
- A best-fit approach must be used to decide the appropriate mark for each criterion. The overall mark awarded for a criterion is *not* an arithmetic mean of the different strands. Rather, it is a holistic judgement reflecting the overall standard of work the student has demonstrated for that criterion.
- Read the level descriptors for each criterion (starting with the lowest level) until you arrive at a descriptor that most appropriately describes the level reached by the student's work.
    - If a piece of work seems to be between two descriptors, read both descriptors again. Choose the descriptor that more appropriately describes the student's work.
    - Consider how well the application of command terms has been addressed, as described in the *Chemistry guide*.
- It is not necessary that all level descriptors are met within a single markband for a mark to be awarded.
- Mark positively—give credit for what the student has done; do not penalize what they could have done or should have done. Record only whole numbers when giving marks; partial marks (fractions and decimals) are not acceptable.

Markbands, level descriptors and strands for the "Research design" criterion

Research design

This criterion assesses the extent to which the student effectively communicates the methodology (purpose and practice) used to address the research question.

Marks	Level descriptor
0	The report does not reach the standard described by the descriptors below.
1–2	• The research question is stated without context. • Methodological considerations associated with collecting data relevant to the research question are stated. • The description of the methodology for collecting or selecting data lacks the detail to allow for the investigation to be reproduced.
3–4	• The research question is outlined within a broad context. • Methodological considerations associated with collecting relevant and sufficient data to answer the research question are described. • The description of the methodology for collecting or selecting data allows for the investigation to be reproduced with few ambiguities or omissions.
5–6	• The research question is described within a specific and appropriate context. • Methodological considerations associated with collecting relevant and sufficient data to answer the research question are explained. • The description of the methodology for collecting or selecting data allows for the investigation to be reproduced.

First strand

In this "Research design" criterion there are three **strands**.

The first strand concerns the research question. The second and third strands are the next two items in the markband.

Each strand repeats in each markband, incrementally differentiated each time.

In "Research design" the three strands appear three times each, in markbands 1–2, 3–4, 5–6.

Awarding zero for a criterion

It is rare that a student's report should be awarded a zero, but there are specific circumstances in which this is appropriate.

- In the case of an incomplete report if there is no evidence at all for a criterion, a zero is awarded.
- If there is some evidence of some effort to address a criterion, the work should only be awarded zero if the response is incomprehensible or totally irrelevant to the criterion.

If one strand of a criterion scores a zero when the other strands do not—If a strand is not addressed at all, or the student's work does not reach the required standard for scoring in that strand, the appropriate score is zero. However, if the other strands are found to match the higher markbands, the overall mark for the criterion should reflect the student's achievement, that is, not over-penalizing the zero-scoring strand.

Investigations not focused entirely on chemistry

The internal assessment is not an opportunity for an interdisciplinary study—the focus should be on chemistry.

Some topics or concepts may be relevant to more than one science subject (e.g. enzymes in biology and chemistry) but the investigation should be formulated and carried out with a focus on chemistry. For example, chemistry investigations that try to establish connections with health issues will rarely find sufficient chemical data to answer the research question.

If a teacher is concerned about the focus of the investigation proposed by a student, they can visit My IB to consult other experienced teachers and examiners for clarification. It remains the teacher's responsibility to make sure each student's internal assessment report is appropriate for assessment in chemistry.

Collecting sufficient data

Designing the collection of sufficient data

Students should be creative or demonstrate initiative in the design, implementation or presentation of their investigation. It is not expected that every investigation will generate a lot of data. The data collected should be commensurate with the 10 hours' work required for the scientific investigation overall. Student guidance is necessary, especially at the outset of the scientific investigation.

There is no single standard for determining that data collected in an investigation is insufficient: some chemistry investigations will generate data more quickly than others. The amount of data collected that addresses a methodology will be determined by the nature of the investigation and the time available. The number of repeats should be selected with a clear rationale.

For example, a rate of reaction investigation will usually generate data more quickly than an investigation to determine the activation energy of a reaction.

Some limitations may only become apparent during data processing. It is strongly recommended that the student considers the appropriateness of data as they are being collected. Carrying out rough processing while collecting data may help the student identify issues. This allows them to modify the range, interval or frequencies as well as collect additional data.

The report should be an account of what happened, and the outcomes may not be those predicted. The report should include details of problems encountered when collecting data. It should also describe issues faced by the student during their trials and how the student responded to them. One possibility is that a potentially feasible investigation fails to provide sufficient data, through no fault or inexperience of the student. The data may be rough and possibly inconclusive. The student should be adaptable, and express this in their account of the method.

Sufficient data are necessary for adequate processing to be evidenced. Interpreting the results and arriving at a conclusion will require care and attention if the results are inconclusive. A hybrid investigation combining a hands-on method and rapid data collection (e.g. a simulation or database) could be considered as a more rapid alternative to an investigation that is entirely hands-on.

The impact of the amount of data collected on other criteria

Insufficient data and poor consideration of uncertainties may impact students' marks for all the criteria.

The amount of data collected will impact the type of processing that can be done.

If, through no fault of the student, insufficient data are collected, the only viable processing may be to calculate the mean and the range. If the processing carried out is commensurate with the level expected to address the research question, the work could achieve the highest marks available.

Insufficient data will impact on the conclusion and the evaluation of the investigation. It is important to look for evidence in the report that the student is aware that the amount of data is limiting the conclusion. Note too that if the data are limited the processing will also be limited, and the interpretation will be impacted too. The teacher should counsel the student to follow a process that will be productive with the time and materials available. If there is no good reason why more data could not have been collected, the mark for data analysis could be impacted.

Using databases, simulations and models

For work involving databases, simulations and models, the same design rules apply. The source of the data needs to be identified clearly, its reliability established, and its sufficiency and relevance to answering the research question considered. Students using databases and simulations should provide the necessary screenshots, including web addresses or the program name, to clearly demonstrate appropriate data collection and manipulation in support of their methodology. Databases and simulations that are free or behind paywalls are acceptable.

When using secondary data sources, more independent variables can be included, because sufficient data can be collected rapidly.

The student will need to explain how the data sampling is controlled and how it is extracted or filtered. They should explain their selection and the decisions taken for extracting data, and consider using a series of screenshots to illustrate the method. When using computational chemistry, databases and simulations, the student must include screenshots or pictures to illustrate the methodology.

Investigations based on tables found in published articles are rarely suitable, because the authors have often already made decisions that the students themselves should make.

Repetitions that result in the same value each time receive minimal credit. In this case, the student can use additional simulations or databases to gather sufficient data to answer the research question. The student must explain how and why the specific simulation was used, and the methodology for collecting data.

Investigations based on computational analysis should include tools that calculate properties accurately, rather than those limited to visual representations.

Molecular modelling that provides only visual data is rarely suitable and should not form the basis of an investigation.

Communication style and report length

The structure of the internal assessment report is the student's responsibility. The IB offers no guidelines here, except that the report should be clear, concise and focused, and demonstrate relevant scientific skills. A cover page and a table of contents are often distractions and should not be included. A clear and informative title reflecting the research question and a first paragraph should inform the reader about the investigation.

There is no fixed style for presenting the method. Both prose and recipe style are acceptable. This is a chemistry investigation, not an assessment of language skills. The use of the passive voice or a personal style should not impact the marks given. Neither should errors of expression, spelling and grammar, unless these result in ambiguity, contradictions, or amount to incomprehensible content. The structure, scientific relevance and conciseness of the report are more important than the language used. This is particularly important considering that many students are not working in their preferred language.

Assessment is always based on evidence from the student's report, and this evidence needs to be clearly communicated in scientific terms. Effective communication is not a criterion on its own; it is an essential part of all four criteria.

- Effective communication is explicit in the research design criterion. The student needs to communicate the methodology (the purpose and practice) and the context of their investigation.
- Effective communication is an aspect of the data analysis criterion, where the recording and processing of data should be clear, precise and accurate in relation to the research question.
- Effective communication is also implicit in the conclusion and evaluation criteria, where an answer to the research question must be justified and where evidence of an evaluation needs to be expressed.

The report should be a maximum of 3,000 words. The word count does not include data tables, sketches, graphs, headings, references or bibliographies. Where a large amount of data has been collected, only a sample of the data should be included. If a report is clear, concise and focused, 3,000 words (maximum) will be more than adequate. If the report exceeds this limit, examiners are not compelled to read further.

Citations, bibliographies and academic integrity

If the student is quoting broadly accepted facts or theories, citations are generally not needed. However, if a specific fact is quoted, a citation would be expected. For example, the fact that the rate of a reaction increases with temperature can be considered general knowledge in this subject, but the fact that the activation energy for the decomposition of H_2O_2 without a catalyst is 75 kJ mol^{-1} would require a citation.

Citations can be in-text, in footnotes on each page, in endnotes, or written as references in a bibliography. The citations should allow sources to be traced, for example the URL and retrieval dates for online sources. They should be limited to sources that have been used in the investigation, either for ideas, content quoted or images copied. The style of citation is up to the student, but they should follow a clear and consistent method of referencing. The bibliography can be used to record the full reference details.

Academic integrity is important to IB educational philosophy and, indeed, to any academic pursuit. Honesty is the hallmark of scientific inquiry. When writing their reports, the student must clearly distinguish between their words or ideas and those of others.

If a teacher believes some of a report's content may have been taken from a source without adequate citation, this may be a case of malpractice. The teacher must discuss this with the student, to clarify how and why the content came to be presented in the report.

If an examiner is not satisfied that the report is the student's own work, the IB will instigate an inquiry on suspected malpractice.

For further guidance, refer to the IB's *Academic integrity policy* and *Effective citing and referencing*.

Appendices

All information relevant to the investigation must be presented within the report. Appendices will not be read by the examiner. The only appendices permissible and sometimes necessary are consent forms for students participating in data collection.

The full raw data is no longer required in an appendix if there is too much to fit in the actual report. The teacher should have seen the full raw data and made a comment in the work to that effect. The sample data used in the report should be taken at regular intervals so it covers the range of the independent variable.

Research design

This criterion assesses the extent to which the student effectively communicates the methodology (purpose and practice) used to address the research question.

Research question and context

The teacher should check that the:

- research question is unique to the student
- independent variable is present
- dependent variable or derived dependent variable is present
- variables are quantifiable
- background context or theory is relevant and focused
- context of the independent and dependent variables is relevant and focused
- choice of data sources, in the case of databases, is explained and their reliability is commented on.

Deciding on the research question

The research question needs to be unique to the student. In the case of group work, the teacher should verify this. Both the research question and the background context provided need to be considered.

All students (whether standard level (SL) or higher level (HL)) can explore topics outside the syllabus. Students should avoid research questions where the answer is known to them beforehand.

The research question may not necessarily include the actual dependent variable but a derived value. For example, for the question "What is the effect of inorganic catalysts on the rate of decomposition of H_2O_2?", the rate would be derived from the measured values. The link between the dependent variable and the investigation—the context—would need to be established in the background, for example which inorganic catalysts and which methodology will be implemented. This may not be the case for simulations that may result in derived values such as rates. In these cases, the rate would be the raw data.

Teachers should discourage overambitious research questions that cannot be answered with the proposed methodology, as well as the use of vague terms (e.g. "efficient" and "suitable").

When a more general research topic is being investigated, the student needs to express it in a form that clearly states the quantities and their relationship, thus guiding an appropriate investigation method.

General accounts of the broad area of study will not achieve the highest marks (e.g. a general overview of enzyme activity). Students should focus their background reading on the exact research question. The background may provide information that will lead the student to identify variables.

The student needs to explain the relationship of the dependent variable to the system being investigated. For example, the context and background for an investigation on the decomposition of H_2O_2 by different catalysts could note that the H_2O_2 decomposes to release oxygen gas and water, while catalysts accelerate the reaction, and that the dependent variable measures the rate of reaction. The way the measurement is taken—e.g. by pressure sensor, oxygen probe—would be part of the methodology.

The context should be specific to the system used. The range chosen for the independent variable must be realistic. An example is the relationship between dissolved oxygen and temperature in global warming. Some of the world's highest ocean surface temperatures (32.2°C) occur in the Red Sea, so an experimental range beyond 50°C would imply a weak understanding of this environmental issue.

The use of correctly balanced chemical equations with their corresponding state symbols should be standard practice.

If the investigation's background is too broad and/or lacks specifics, the student's work will not reach the top markband in the first strand.

Students are permitted to present more than one independent variable, but there must be a clear link between them. They should also carefully consider if including more than one variable will allow the investigation to reach the expected depth, considering the word limit.

Students are permitted to formulate a hypothesis for the outcome of the investigation, though this is not obligatory. A hypothesis can help to set the research question in context. If a hypothesis is included, it must be addressed in the conclusion.

Methodological considerations

The teacher should check:

- that the method can generate data that may answer the research question
- the type of data collected
- the protocol for collecting relevant data
- that a preliminary or trial investigation is described and assessed
- the description of measuring the dependent variable
- the range and intervals of the independent variable
- the sampling rate
- the method of controlling or monitoring each variable
- the discussion of other factors that would need to be controlled
- the techniques used to ensure adequate control (fair testing)
- the use of control experiments
- the quantity of data collected, including sufficient repetitions given the nature of the system investigated
- that provision is made for qualitative observations.

Protocols, methods and procedures

The protocol will be a record of the method used, including an account of trialling. It should not be a proposed plan. Students will probably use standard protocols for determining the dependent variable; the protocols should be cited.

The method employed will depend on the nature of the investigation and may be limited by time or materials. The student's method needs to make reasonable provision for the collection of sufficient data to answer the research question in a 10-hour period of investigative work. This 10-hour period may include a certain amount of designing and trialling, followed by redesign, which could be time consuming. The quantity of data collected needs to be realistic. The student must consider time constraints during design. If the investigation requires more time than that allocated, the teacher should provide the necessary scaffolding.

The reader needs to understand how the methodology and procedures were implemented, and how the equipment and other materials were used. There needs to be enough information so that the reader could, in principle, repeat the investigation. The procedure should be clear and detailed enough to be reproduced.

Details of equipment, and measuring instruments and their sizes, must be included to assess their suitability and the stated uncertainties. Examples of other important information include descriptions of how solutions were prepared and how the limiting reactant was established.

Defining and explaining variables

A table can be used to list and explain the variables. It is not necessary for the variables to be identified explicitly and separately (e.g. using subheadings).

The dependent variable needs to be accurately defined and explained. If the investigation is looking for a trend, a minimum of five data points is expected for the independent variable. In some exceptional cases (e.g. using an expensive or harmful chemical), four may be accepted.

The rationale for the range and intervals used for the independent variable needs to be explained in the context of the investigation. In many experiments the sampling rate needs to be considered to ensure that meaningful but not excessive data are collected. This can often be best determined during trialling.

The report must include sufficient information on the chosen samples. For example, the amount of sulfur dioxide in different red wines may change with grape variety or country of origin. A simple statement that a sample is "red wine" lacks the required detail for adequate data assessment. Sampling is a crucial step in many investigations. For example, for an investigation determining the amount of free and combined chlorine in a swimming pool, the sampling location will affect results. Even though sampling is the first step in many scientific investigations, a research question cannot be correctly answered if the samples are not representative. Correct storage of samples also deserves careful attention, given that storage conditions can affect the results.

The method should identify which variables can be controlled and how this is achieved. It should also identify which variables cannot be controlled but need to be monitored (confounding variables).

Room temperature may not vary very much during an experiment, but in temperature-sensitive investigations it needs to be recorded. Merely setting the room's thermostat or air conditioning is not sufficient to control room temperature for an experimental set-up.

In chemistry investigations, temperature is normally controlled by a thermostatic bath. The method should also include how the most relevant variables that could affect results were controlled. For example, when the methodology used Beer's law (content beyond the syllabus), how was the specific wavelength chosen?

Repeats are a standard expectation, to ensure the validity of the results. A student whose work indicates several trials should not be penalized for not mentioning repeat measurements in their methodology.

Students should reflect on the quality of the data while carrying out the investigation, including some rough data processing to detect issues that can be addressed.

Risk assessment

The teacher should check for:

- safe handling of chemicals or equipment
- application of *IB sciences experimentation guidelines*
- judicious consumption of materials
- appropriate disposal of waste
- consideration of impact and safety on field sites
- consideration of safety and environmental concerns.

Teachers have a responsibility to ensure that their students carry out safe, ethical investigations and that the students also consider the environmental impact of these.

Risk assessment is an important part of experimental design. However, issues concerning safety, ethics and environmental impact may not apply to the same degree for each investigation. The impact of risk assessment on the mark awarded for the criterion will depend on whether there are significant safety, ethical and environmental factors that are, or need to be, considered by the student. It should be clear that these risks have been mitigated. Stating an issue indicates the student is aware of it, but not necessarily that the issue has been addressed. If an investigation has no safety, ethics or environmental considerations, the student should include a statement to this effect.

For work with databases, simulations or modelling systems, safety and environmental concerns will not be relevant. However, ethical issues can arise for the use of databases, and it is to the student's credit if they are raised.

The student should take responsibility for the impact of laboratory waste on the environment. Even if a teacher or technician oversees disposal as part of school policy, the student must explicitly describe disposal methods for specific chemicals and organic matter. Whenever possible, the student should follow and endorse the principles of green chemistry.

Examiners who encounter experimental set-ups that constitute a severe risk to safety or the environment will refer these to the IB. The relevant school may then be contacted.

Describing the data collection method

The teacher should check for:

- a logical sequence
- the presence of essential information
- unnecessary repetition
- the sketches, diagrams, charts and photographs used to illustrate the investigation
- the use of screenshots to explain how the data were captured (in the case of investigations using databases and simulations)
- correct use of scientific terms (spelling is not penalized if there is no ambiguity)
- the selection of measuring instruments and their sizes
- chemicals and concentrations used when pertinent for the correct preparation of solutions and dilutions
- brand names of items used as variables.

Students need to present information in enough detail for the reader to understand readily how the methodology was implemented, such that they could, in principle, repeat the investigation.

Illustrations and lists

Students should consider illustrating their investigation using annotated sketches, diagrams, charts and photographs of the experimental set-up. These can help to describe the investigation, with minimal impact on the word count.

Illustrations should only be included when they add value. For example, a diagram of a burette and the conical flask for a titration is superfluous.

A list of materials is useful but not obligatory. Details of the materials can be included in the method if appropriate.

Data analysis

This criterion assesses the extent to which the student's report provides evidence that the student has recorded, processed and presented the data in ways that are relevant to the research question.

Communication of the recording and processing of data

The teacher should check for:

- collection of sufficient and relevant data to address the research question
- appropriate qualitative observations (images/drawings correctly labelled)
- concise presentation (of text, tables, calculations, graphs, other illustrations)
- use of correct scientific units and their symbols
- appropriate formatting of data: units are correct and uncertainties are identified; a consistent number of decimal places or significant figures
- clear and precise processed data that addresses the research question
- a sample calculation or the use of screenshots where appropriate
- relevance of graphs (e.g. with best-fit lines or curves).

Units and decimal places

International System of Units (SI) or other metric units (e.g. mL or cm^3, L or dm^3 for volumes) are acceptable. Non-decimal system units (e.g. °F, cups, inches) are not appropriate and should be converted.

A correct and consistent number of decimal places, based on the degree of precision, is expected. Minor errors in data tables can be accepted if, overall, the student is trying to maintain consistent decimal places between the raw data, any degrees of precision expressed and the processed data. In chemistry, students are not expected to use significant figures conventions; if they do, these should be used correctly.

Recording and processing data

The presentation of the analysis will depend upon the data-processing tools being used. Percentages, means, standard deviations or ranges at the end of the column or row of data they represent are sufficient evidence of processing. For more complex processing (e.g. using spreadsheets), screenshots including the formula used are acceptable. For other less orthodox processing, a worked example is necessary.

Providing examples of full calculations is superfluous or irrelevant when using dedicated software programs. However, the processing and reasoning must be clear so that the validity of the calculations and interpretations can be verified.

Note: Interpretation of the data as it relates to the research question is assessed in the "Conclusion" criterion.

Correctly tabulated data should have appropriate titles and numbers, or they should be set in a context that makes them unambiguous. Within the text of the report, they should be referenced using, for example, Figure 1 or Graph 1. Where relevant, there should be concise column headings and units in the column headers with their uncertainties. It is not necessary to provide separate tables for raw data and processed data. However, uncertainties should be presented with enough clarity for the reader to assess if the processing has been done correctly; for example, only showing averages does not make it clear if data were dispersed or if any outliers were included.

If large amounts of data have been collected, students are permitted to present only a representative sample of the raw data, to facilitate comprehension. Data taken directly from an electronic device are raw data and require further processing to constitute processed data. For example, a device that determines "rate" produces raw data. If software automatically constructs a graph, the graph itself is acceptable as raw data. Details about how results were obtained, and information about quantities, units and precision, should be mentioned in the text. The gradient of or area under the graph may then be used for further calculations.

Inadequate labelling of a graph (axes, legends, titles) will impact data analysis. The type, size, proportions and scaling of the graph impact not only presentation, but also the graph's usefulness in data analysis.

Descriptions of qualitative observations are expected to accompany the raw data where applicable. Their importance will depend on the nature of the investigation.

Considering uncertainties

The teacher should check for:

- degrees of precision in the instruments used
- consideration of errors and uncertainties
- consistency in the reported uncertainties
- variation in the results, as shown by propagation of uncertainty, uncertainty bars, trend lines, R^2 values
- ranges (maximum value minus minimum value)
- an appropriate response to outlier data.

Note: The processing of data to obtain an uncertainty value is assessed in the third strand (relevant processing of data) of the "Data analysis" criterion. Consideration of the impact of uncertainties is assessed in the "Conclusion" criterion because (in part) this criterion assesses the relevance of the conclusion to the analysis.

It is not expected that students will necessarily cover all of the above parameters. This is merely a guide to the ways a student may evidence that they have considered the impact of uncertainty on the analysis.

Uncertainties in measurements

Measurement uncertainties can be obtained from an instrument's graduations, manufacturer specifications (for electronic devices) or the read-out for least count. The realistic use of an instrument also needs to be considered. For example, a handheld stopwatch used to measure the time of an event will not have a precision of 0.001 seconds, even if the stopwatch can provide such a read-out—human reaction times are not this fast. Students should justify the size of uncertainty based on the nature of the experiment. Repeating a measurement for the same event often reveals an uncertainty larger than the precision of the instrument.

Uncertainties associated with single measurement must be expressed to the same degree of precision as raw data. Using the least count, the uncertainty could be expressed as 0.1 for 2.3 s, 0.01 for 2.34 s and 0.001 for 2.345 s. This is the minimum uncertainty, but often the uncertainty is greater. For example, measurement of a volume could be $(87.4 \pm 0.1)\ cm^3$. Expressions such as $(87.4 \pm 0.05)\ cm^3$ or $(87.4 \pm 1)\ cm^3$ are inappropriate.

Where relevant, measurement uncertainties should appear in the column headings along with the units, unless there is reasonable justification for data to have different values of uncertainty within a column. Uncertainties are also expressed graphically using scatter plots with trend lines. These may also include uncertainty bars and R^2 values. Uncertainties that are present but too small to be visible should be noted in the report. Uncertainty bars are not a requirement in chemistry.

Statistical tests are not recommended. However, if they are considered appropriate by a student, refer to the "Mathematics" section of the Diploma Programme (DP) *Biology teacher support material* for guidance.

When one uncertainty is negligible, it could be omitted but a brief, clear explanatory comment about its exclusion would then add value to the analysis. Students must be careful when the uncertainties involve logarithmic values (e.g. in relation to Beer's law or pH).

Outliers

Data identified as possible or probable outliers should not be systematically omitted from calculations. Outliers are actual measured results and therefore need to be considered. Removing them so that the results "fit better" with expectations or with a general model is not good practice. This is manipulation of data and it is unscientific. Instead, students could consider presenting the outcome with the outliers included and excluded, thereby revealing their impact.

Outliers may be identified statistically from the data. They are most likely to occur as a result of human error, methodological flaws, or irregularity in the equipment or environment. **A student considering excluding these should provide a justification**. This is especially important for data in chemistry as the sample size is usually very small (n<15). If observations can explain an outlier, or if a weakness in the methodology is identified and corrected, then these data can be justifiably removed. Often, the quantity in question can be re-measured. The scientific method requires rigour and integrity in gathering data, while the IB requires academic integrity from students. This is more important than the appearance of consistent data.

Processing of data

The teacher should check for:

- processing that is efficiently presented and at the DP level for the topic
- appropriate processing tools
- realistic trend lines in presented data
- appropriate graphing techniques including adequate scale, title and labelled axes
- correct calculations and graphing.

Processing is the transformation of raw data to arrive at a conclusion. Mathematical skills are important, and this is stressed in the nature of science (NOS) aspect of this course; however, this is not a mathematics course. Nevertheless, some topics require special attention to mathematics due to their significance (e.g. averages of pH values).

Graphing, even that of raw data, is part of processing, especially if it is used to derive values such as gradients for rates. Graphing often adds value; however, graphical analysis is not mandatory.

Graphing raw data when the graphing of *processed* data would be more appropriate can be considered insufficient, or even irrelevant; but it is not wrong.

The types of graphs produced by the student should be appropriate to the data being analysed.

To be confident that a trend line can be drawn on data points, sufficient data need to be obtained. A trend line may be used to show how the limited data collected fit a given model.

An appropriate best-fit line or curve is common practice and should be guided by theoretical considerations, known equations or dimensional analysis. Students should not assume a linear fit unless it is justified. Placing a trend line on the data can be a helpful step in processing and interpretation, for example for comparison with an accepted model. A trend line can be especially helpful if uncertainty bars accompany it, or a correlation coefficient (r) or the coefficient of determination (R^2 value).

A high R^2 value does not necessarily mean that the chosen trend line mirrors the correct underlying chemical or physical process. When the best-fit line is relevant to the research question, minimum and maximum gradients could be constructed. These would be used to establish an uncertainty range in the gradient and an uncertainty in the y-axis intercept.

The use of standard deviation or standard error can be helpful, assuming there are a sufficient number of replicates to calculate these. Otherwise, calculating the difference between maximum and minimum values to determine the range is acceptable.

Although statistical analysis is not encouraged in DP chemistry, some students may opt for standard deviation. Standard deviations may be calculated on sample sizes as low as 5. The standard error of the mean is influenced more by sample size, so it should be reserved for sample sizes greater than 30, which are rare at this level of study. For other statistical analysis, the minimum is 10. The report should include a sample of the values used for statistical analysis, which can be done using screenshots or images.

Conclusion

This criterion assesses the relevance of the conclusion to the research question, to the analysis presented and to the accepted scientific context.

Relevance of the conclusion

The teacher should check for:

- a valid explanation of trends in the results or correlations of the results
- a conclusion that addresses the research question in the proposed context
- evidence that sense has been made of the data and/or results, leading to a conclusion that is realistic
- references to a hypothesis (if one has been stated)
- a discussion of the impact of uncertainties
- a discussion of the reliability of the data (which may indicate an appreciation of the strengths of the data)
- whether the data supports any hypothesis that has been proposed.

The student must discuss whether the data address the research question or not. The data collected and processed may not demonstrate clear patterns or trends. The data may also be inconclusive. For some investigations, the data may partially support a conclusion, but not necessarily lead to a strong one.

Students should ensure they do not introduce bias in the interpretation to form conclusions that are not supported by their data. For example, interpreting the rate of reaction when it has not been calculated, referring instead to the shape of the graph or how steep the gradient is, provides limited evidence of critical thinking.

The student should be able to identify trend lines correctly—a negative correlation is not the same as an inverse relationship, for example.

Where relevant, terms such as “optima”, “maxima” (plateau) and “intercepts” should be used.

Considering uncertainties in the conclusion

Measures of variation, such as the range or the standard deviation, can indicate the reliability of the results.

All measurements in chemistry have a degree of uncertainty. Uncertainties need to be addressed in the conclusion. A conclusion statement needs to express not only the resulting value but also an experimentally acceptable range of values.

If the student has a reference value, having the percentage difference and considering the propagated error(s) will allow discrimination between systematic and random errors. These should be specifically identified, and the direction of the former should be stated.

While the student can determine the random error without the reference value, the systematic error may not be as easy, but an analysis can still be produced.

Considering the time allowed for the scientific investigation, the sample size will usually be small. The impact of errors will depend on the topic. For example, calorimetry typically shows high errors resulting from heat losses.

Other indicators of uncertainty may be used, such as the coefficient of determination, the R^2 value. The report should discuss if a trend line, straight or curved, fits the data well.

If the student has used databases, the consideration of experimental versus theoretical values, and the conditions for collecting data, are important.

The conclusion and the scientific context

The teacher should check for:

- a relevant scientific context, with references from the literature that help explain the investigation's outcomes
- reliable scientific sources, referenced with sufficient detail to be traced (e.g. retrieval dates for online sources)
- comparison with general models and a proposed explanation in the context of chemistry.

There may be no accepted value for comparison (e.g. the yield of a chemical reaction). In this case, the student must determine if the result is reasonable.

Evaluation

This criterion assesses the extent to which the student's report provides evidence that weaknesses and limitations in the investigative methodology have been assessed, and improvements have been suggested.

Methodological weaknesses and limitations

The teacher should check for:

- methodological and procedural weaknesses and limitations
- evaluation of the relative impact of weaknesses and limitations
- evidence supporting the identified weaknesses and limitations
- a clear understanding of the topic in the suggested context and of the methodology used.

There is no expectation that a student will address all aspects relating to methodological weakness and limitations. Nevertheless, when evaluating the results of an investigation, students should explain the relative impact of those that are significant. They can do this in a qualitative way, identifying minor and major weaknesses by explaining how the issue would affect the results.

Discussion of methodological weaknesses needs to consider both the issues in the methodology and their effect on the quality of the data. Weaknesses do not include errors due to careless manipulation skills or hypothetical events for which there is no evidence.

Discussion of limitations acknowledges that experiments will only go so far in answering the research question. Even if conditions are perfect, an experiment will still have its shortcomings. For example, a simulation may have few methodological weaknesses, but it will have some limitations.

The degree of impact of these weaknesses and limitations on the outcome of the investigation needs to be judged qualitatively.

The reliability of the results needs to be judged in the light of the uncertainties that have been established. The direction of any systematic error should be stated and related to methodological weaknesses and limitations.

Instruments that are faulty or that have not been calibrated correctly cause systematic errors. These errors, which affect accuracy, can also be caused by human error.

Random uncertainties are unpredictable in size and direction. The precision (measurement uncertainty) of instruments varies due to random errors. Judging the degree of impact of each measuring instrument on the results is an important task in science.

The student must clearly address the suitability of the range and frequency of collected data. When appropriate, the student must explicitly consider the relevance of their control experiments.

The limitations should be consistent with the analysis and interpretation of uncertainties presented in data analysis. They should be supported by evidence rather than speculation. For example, a comment such as "the temperature of the surroundings was not controlled or monitored and may have changed during the extended testing period" has limited value.

Limitations such as small sample size or procedural weaknesses (e.g. an uncalibrated pH meter) are generic limitations; often, these should have been solved during the trials. The use of apparatus and instruments should be considered during design. For example, a pH meter or colorimeter should be calibrated to ensure the output of accurate and consistent data. If the data are erratic and no other instrument is available, it is in the student's best interests to consider changing the methodology. The same might apply to issues related to incorrect sampling or storage of samples.

Students are often familiar with certain methodological limitations (e.g. heat losses in calorimetry, and difficulties determining the end point for a titration). These are valid limitations but will only add value when the student has tried to minimize impact of these during the design. For example, if the student worked with an open container without insulation, referring to heat losses in calorimetry is weak evidence of the understanding of this methodological limitation.

In investigations using databases, the student should not refer to the validity of the sources because this should have been done in research design. However, there are issues in the curation of databases, and a reflection in this regard adds value to the conclusion. Problems resulting from experimental and theoretical values present the same challenges.

Suggesting improvements to the investigation

The teacher should check for:

- realistic and relevant improvements
- a clear understanding of the topic in the suggested context and the methodology used.

Suggested improvements should be realistic and relevant to the investigation. The improvements must be related to the weaknesses or limitations that have been identified, and should be feasible in a school environment or field course. They need to be based on the identified weaknesses that are relevant to the research question and methodology.

The student should avoid generalities such as "take more measurements" or "use a more precise measuring method". Only if these generic issues are connected to specific issues can they be seen as improvements to weaknesses.

During the design phase, changing to a more precise instrument may not be an option if the choice of instruments is limited. In an enzyme investigation at home, using a number of different household items to establish the pH is a weakness. (Using buffers would be an improvement.) The range of pH used may fail to establish the optimum pH. This is a limitation, so extending the range would be an improvement.

References

Adeogun, J. (2022). *Fashion forward: How to combat climate change through clothing*. https://www.imperial.ac.uk/stories/fashion-forward/?utm_source=alumni-bulletin&utm_medium=email&utm_campaign=alumniebulletin#group-section-Scientific-solutions-w8arAWnCPQ

Al-Bar, O. A. M. (2012). Characterization of partially purified catalase from camel (Camelus dromedarius) liver. *African Journal of Biotechnology*, *11*(40), 9633–9640. DOI: 10.5897/AJB12.850. https://www.ajol.info/index.php/ajb/article/view/127156

Alves, H., Manhita, A., Barrocas Dias, C., & Ferreira, T. (2014). Traditional dyeing—an educational approach. *Chemistry Education Research and Practice*, *15*(4), 610–619. https://doi.org/10.1039/C4RP00038B

Antúnez de Mayolo, K. K. (1989). Peruvian natural dye plants. *Economic Botany*, *43*(2), 181–191. http://www.jstor.org/stable/4255151

Arunan, E., Desiraju, G. R., Klein, R. A., Sadlej, J., Scheiner, S., Alkorta, I., Clary, D. C., Crabtree, R. H., Dannenberg, J. J., Hobza, P., Kjaergaard, H. G., Legon, A. C., Mennucci, B., & Nesbitt, D. J. (2011). Defining the hydrogen bond: An account (IUPAC technical report). *Pure and Applied Chemistry*, *83*(8), 1619–1636. https://doi.org/10.1351/pac-rep-10-01-01

Balsara, N. P., & Newman, J. (2013). Comparing the energy content of batteries, fuels, and materials. *Journal of Chemical Education*, *90*(4), 446–452. https://doi.org/10.1021/ed3004066.

Banchi, H., & Bell, R. (2008). The many levels of inquiry. *Science and Children*, *46*(2), 26–29.

Bates, R. P. (1968). The retardation of enzymatic browning in avocado puree and guacamole. *Proceedings of the Florida State Horticultural Society*, *81*, 230–235. http://www.avocadosource.com/Journals/FSHSP/FSHSP_VOL_81_PG_230-235_1968.pdf

Boud, D., & Feletti, G. (1997). *The challenge of problem-based learning* (2nd ed.). Routledge.

Brunning, A. (2014). *Why do avocados turn brown?—The chemistry of avocados*. https://www.compoundchem.com/2014/08/03/why-do-avocados-turn-brown-the-chemistry-of-avocados

Chow, K., & Yeung, L. L. (n.d.a). *The science of gastronomy* [Online course]. Retrieved April 23, 2022 from https://www.coursera.org/learn/gastronomy

Chow, K., & Yeung, L. L. (n.d.b). *1.6 How do we cook by convection?* [Online course]. Retrieved April 23, 2022 from https://es.coursera.org/lecture/gastronomy/1-6-how-do-we-cook-by-convection-qqzHU

Chow, K., & Yeung, L. L. (n.d.c). *7.3: What gives green color to plants?* [Video]. Retrieved April 23, 2022 from https://www.coursera.org/learn/gastronomy/lecture/oeKYD/7-3-what-gives-green-color-to-plants

Chow, K., & Yeung, L. L. (n.d.d). *7.5: Demonstration—Manipulating the color of red cabbage* [Video]. Retrieved April 23, 2022 from https://www.coursera.org/learn/gastronomy/lecture/PY9rp/7-5-demonstration-manipulating-the-color-of-red-cabbage

Chow, K., & Yeung, L. L. (n.d.e). *7.4: Why some plants are not green in color?* [Video]. Retrieved April 23, 2022 from https://www.coursera.org/learn/gastronomy/lecture/gLUaf/7-4-why-some-plants-are-not-green-in-color

Dorfman, L. R., & Cappelli, R. (2017). *Mentor texts: Teaching writing through children's literature, K-6* (2nd ed.). Stenhouse Publishers.

Ergüvenerler, F., Targan, S., & Tirtom, V. N. (2020). Removal of lead from aqueous solutions by low cost and waste biosorbents (lemon, bean and artichoke shells). *Water Science and Technology*, *81*(1), 159–169. https://doi.org/10.2166/wst.2020.093

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. *Science Advances*, *3*(7), e1700782. http://advances.sciencemag.org/content/3/7/e1700782

Halfman, J. (n.d.). *Linear regression in Excel-2007*. Hobart and William Smith Colleges. Retrieved June 15, 2020, from http://people.hws.edu/halfman/Excel-07-demo/07-Linear-Regression.html

Harlen, W. (Ed.) (2015). *Working with big ideas of science education*. The InterAcademy Partnership. https://www.interacademies.org/publication/working-big-ideas-science-education

International Baccalaureate. (2015). *Approaches to teaching and learning*. International Baccalaureate Organization. https://resources.ibo.org/permalink/11162-43504?lang=en

International Baccalaureate. (2019). *What is an IB education?* International Baccalaureate Organization. https://resources.ibo.org/permalink/11162-58229?lang=en

International Baccalaureate. (2020a). *The IB learner profile*. International Baccalaureate Organization. https://resources.ibo.org/permalink/11162-43492?lang=en

International Baccalaureate. (2020b). *Programme standards and practices*. International Baccalaureate Organization. https://resources.ibo.org/permalink/11162-51685?lang=en

International Baccalaureate. (2022). *Our mission*. International Baccalaureate Organization. https://www.ibo.org/about-the-ib/mission/

Islamic Publications. (n.d.). *A is for … Amla (Indian gooseberry)*. Retrieved August 1, 2022 from https://the.ismaili/nutrition-centre/%E2%80%A6-amla-indian-gooseberry

Japan National Tourism Organization. (n.d.). *Japanese superfoods*. Retrieved August 1, 2022 from https://www.japan.travel/en/guide/japanese-superfoods

Johnstone, A. H. (1991). Why is science difficult to learn? Things are seldom what they seem. *Journal of Computer Assisted Learning*, *7*, 75–83. https://doi.org/10.1111/j.1365-2729.1991.tb00230.x

Kolb, D. (1984). *Experiential learning: Experience as the source of learning and development*. Prentice Hall.

Medindia. (2019). *Fruit in news—guava*. Retrieved August 1, 2022 from https://www.medindia.net/patients/lifestyleandwellness/the-fruit-in-news-guava.htm

Mills, G. E., & Gay, L. R. (2018). Education research: Competencies for analysis and applications. London, England: Pearson Education. *Journal of Applied Learning & Teaching*, *1*(2).

Moribe, H., Kitayama, Y., Suzuki, T., & Okubo, M. (2010). Emulsifier-free, organotellurium-mediated living radical emulsion polymerization of styrene: Effect of stirring rate. *Macromolecules*, *44*(2), 263–268 https://doi.org/10.1021/ma1022346

Project Zero. (2015). *Project Zero's thinking routine toolbox*. Harvard Graduate School of Education. https://pz.harvard.edu/thinking-routines

Pytash, K. E., & Morgan, D. N. (2014). Using mentor texts to teach writing in science and social studies. *The Reading Teacher*, *68*(2), 93–102.

Ritchie, H., & Roser, M. (2018). Plastic pollution. *Our World in Data*. https://ourworldindata.org/plastic-pollution

Ritchie, H., & Roser, M. (2022). Lead concentrations in the blood of children in the United States. *Our World in Data*. https://ourworldindata.org/grapher/lead-blood-usa-children?yScale=log&country=95th+percentile~Median

Royal Society of Chemistry (2013). *Measuring vitamin C in food—A global experiment*. [Video]. Retrieved April 22, 2022 from https://www.youtube.com/watch?v=1P3W9DykGBg

Statistics Solutions. (2019). *Pearson's correlation coefficient*. Statistics Solutions. https://www.statisticssolutions.com/pearsons-correlation-coefficient/

Taber, K. (2002). *Chemical misconceptions: Prevention—diagnosis and cure: Volume 1 Theoretical background*. Royal Society of Chemistry.

Taber, K. (2019). *The nature of the chemical concept: Re-constructing chemical knowledge in teaching and learning*. Royal Society of Chemistry.

Thompson, S., & Reed, D. K. (2019). *Using mentor texts to learn from the best and improve students' writing*. https://iowareadingresearch.org/blog/mentor-texts-student-writing

Turner, K. (2019, May 23). Applying context to lessons. *Education in Chemistry*. https://edu.rsc.org/ideas/put-it-in-context/3010449.article

USEPA. (2019). *ACE biomonitoring—Lead*. https://www.epa.gov/americaschildrenenvironment/ace-biomonitoring-lead

Updates to the publication

This section outlines the updates made to this publication over the past two years. The changes are ordered from the most recent to the oldest updates. Minor spelling and typographical corrections are not listed.

Corrections for July 2024

Mathematics > Errors and uncertainties

"Error analysis and evaluation"

Correction of error in the previous version.

The formula to calculate percentage difference was amended to correct the misplaced multiplication.

Unpacking the internal assessment > General advice

"Collecting sufficient data"

Introduction of revised or improved content.

In the section "Using databases, simulations and models", more guidance was added for teachers to understand the requirements of the internal assessment reports when students have used databases or simulations.

"Communication style and report length"

Amendment in response to stakeholder feedback.

In the section "Appendices", more guidance was added for teachers to understand what should (or should not) be present in an appendix of an internal assessment report.