ROYAL AUSTRALIAN CHEMICAL INSTITUTE

Chemistry Academic Standards Statement

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"The goal is always finding something new, hopefully unimagined and, better still, hitherto unimaginable."

K. Barry Sharpless
Nobel Prize in Chemistry Lecture
2001

The Royal Australian Chemical Institute acknowledges First Nations peoples' continuous and enduring connection to land, sky and sea as the Traditional Owners and Custodians of country. We pay our respects to elders — past and present — and through them to all Australian Aboriginal and Torres Strait Islander people.

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Executive summary

The most common program of study to qualify as a chemist is a science degree, which in Australia is often a three year Bachelor of Science. The Learning and Teaching Academic Standards for a Bachelor of Science are established and maintained by the Australian Council of Deans of Science.[1] These standards define five broad Threshold Learning Outcomes (TLOs) that summarise the knowledge and skills of all graduate scientists. These include: having deep knowledge in at least one discipline of science, and breadth of knowledge in at least one other; being able to frame problems, pose solutions and communicate their outcomes; and, to take accountability for this work.

The Chemistry community, including the Royal Australian Chemical Institute (RACI) and the Chemistry Network of Educators – ChemNet, adapted the Science-LTAS and its TLOs, to form the *Chemistry Academic Standards Statement*. This *Statement* is a succinct way to describe to all stakeholders the nature and extent of science and chemistry, and the characteristics of all graduate scientists and chemists. These include a series of Chemistry Threshold Learning Outcomes (CTLOs) that highlight important distinctions between what any degree in science will achieve compared to those with a chemistry major. The CTLOs keep the same intent as those for science, but define unique elements of chemistry practice such as: demonstrating a capacity for working effectively and safely in the laboratory to solve problems; and, knowing the relationships between chemistry, other scientific disciplines, and broader society.

RACI Accreditation is designed to ensure that graduates of accredited degrees have the skills and knowledge necessary to be a practicing chemist, and that these were gained through a purposefully designed program of study. Graduation from an accredited degree is a first step on the normal pathway to membership of the RACI. We benchmark these curricula using the CTLOs to assure that these outcomes are demonstrated through assessment well-aligned to the learner's experience. Therefore, the *Statement* is an important signal to higher education institutions about the broad intentions of a degree in chemistry in Australia. Each higher education institution seeking accreditation should design and deliver curriculum to extend and enrich these outcomes. If implemented appropriately, the *Statement* will support each institution's autonomy, diversity and reputation.

[1] Jones SM, Yates BF & Kelder J-A. (2011). *Science Learning and Teaching Academic Standards Statement.* Australian Learning and Teaching Council.

Glossary

Accreditation Accreditation is a process whereby an authority assesses for quality against an agreed set of standards. In this instance, the RACI is assessing the quality of a degree program and that the likelihood that graduates will meet the requirements for membership of the Institute (MRACI).

Curriculum At its most fundamental level, a curriculum is a plan for learning. It comprises more than just a list of topics, and includes all of a learner's experiences. Unlike in primary or secondary schools, in the higher education sector the curriculum is often defined by the institution — most often a University. Chemistry curricula can and does vary from institution-to-institution in response to priorities and capabilities of the institution.

Degree A program of study that leads to a tertiary qualification which prepares students for professional work. The entry qualification in Australia is more often a Bachelor's degree, and in this instance is most likely a Bachelor of Science.

Institution A higher education provider who is seeking accreditation for their degree program from the RACI. In Australia, higher education providers are enabled by the *Higher Education Support Act 2003*, and for our purposes are mostly Universities found in Table A.

Learning outcomes A clear statement about what a learner is expected to know, do, and/or value at the completion of learning. It should define the extent and mechanism of learning, and be linked to how it will be displayed and/or assessed.

Threshold Minimum standard of achievement or attainment.

Contents

Nature and extent of chemistry

Chemistry is concerned with the study of the interactions of matter and energy. One of the main functions of the chemist is to produce new substances or to understand how substances are formed and removed in the environment. Chemistry is the science of analysing, transforming or manipulating substances and the molecular interpretation of the world around us. It is at the molecular level that major advances are made in many diverse areas such as medicine, agriculture, biology, materials, energy and the environment. Chemistry is considered to be the 'central science' because of its role in connecting the sciences, e.g. physics, biology, earth sciences. Chemistry has an important effect on our economy by playing a vital role in developing new technologies and influencing all human activity.

The conceptual understanding of chemistry involves three related levels: macroscopic or observable properties and changes; the explanation of those properties and changes in terms of a microscopic or molecular-level description; and the use of chemical language and symbols to represent both the macroscopic and microscopic phenomena.

Matter is everything that can be touched, seen, smelt, tasted or felt; hence, the extent of chemistry is limitless. Traditionally, chemistry has been classified into three main branches: inorganic chemistry, organic chemistry and physical chemistry. Analytical chemistry has become accepted as a fourth branch. However, the nature of chemistry is such that there are no distinct boundaries between the branches of the discipline, or indeed with other disciplines. While the aforementioned categories remain relevant, modern chemistry is increasingly described thematically; encompassing topics that overlap the traditional branches and address the interfaces of chemistry with other disciplines, such as chemical biology and chemical physics, and with applied fields, such as environmental chemistry and materials chemistry.

Chemistry Threshold Learning Outcomes

The Chemistry Threshold Learning Outcomes (CTLOs) are derived from and aligned to[1] the *Science Learning and Teaching Academic Standards Statement* and its Science TLOs as the national benchmark for the agricultural, biological, chemical, earth, environmental, mathematical, and physical sciences. The CTLOs highlight important distinctions between what any degree in science will achieve compared to those with a major in chemistry or a related discipline.

Each outcome statement, as detailed in Table 1 comprises three distinct parts. They must be read together, as illustrated in Figure 1, to form a coherent outcome statement. Additionally, we have expanded two key outcomes on the principles and concepts of chemistry (CTLO2.1) and methods, and practical techniques and tools (CTLO3.3) as important knowledge and skills required of graduate chemists which requires greater definition. These third tier CTLOs define depth and breadth.

Stem	**Upon completion of a bachelor degree with a major in chemistry, graduates will...**	*The use of 'will' is deliberate — all graduates must meet these thresholds.*
First Tier	**...Exhibit depth and breadth of scientific knowledge by...**	*The stem for all TLOs relating to 'scientific knowledge' dictate this must include both depth and breadth. Many of the first and second tier outcomes have a verb to describe a mechanism for assessment (i.e. demonstrate, analyse, exhibit) and an adjective or noun to imply the level of attainment (i.e. coherent, depth and breadth, critically, effective).*
Second Tier	**...demonstrating and applying the principles and concepts of chemistry.**	*The true definition of what it means for 'scientific knowledge' is found in the final statement. The outcomes grouped together under in CTLO 2 offer different perspectives on how a student will demonstrate depth and breadth. You will see for each of the five broad CTLOs there are between two and four statements to give fifteen in total.*

Figure 1: How to read a TLO by combining the stem with each tier to form a coherent outcome statement

[1]See Table 2 on page 16.

Table 1: Chemistry Threshold Learning Outcomes

Upon completion of a bachelor degree with a major in chemistry, graduates will…		
CTLO 1. Understanding chemistry *Demonstrate a coherent understanding of science by:*	1.1	recognising the creative endeavour involved in acquiring knowledge, and the testable and contestable nature of the principles of chemistry
	1.2	recognising that chemistry plays an essential role in society and underpins many industrial, technological and medical advances
	1.3	knowing and being able to articulate aspects of the place and importance of chemistry in the local and global community
CTLO 2. Scientific knowledge *Exhibit depth and breadth of scientific knowledge by:*	2.1	demonstrating and applying the principles and concepts of chemistry
	2.2	recognising that chemistry is a broad discipline that impacts on, and is influenced by, other scientific fields
CTLO 3. Inquiry, problem solving and critical thinking *Investigate and solve problems in the chemical sciences by:*	3.1	synthesising and critically evaluating information from a range of sources using traditional and emerging technologies and methods
	3.2	formulating hypotheses, proposals and predictions and designing and undertaking experiments
	3.3	applying recognised methods and appropriate techniques and tools, and being able to adapt these techniques when necessary
	3.4	collecting, recording and interpreting data and incorporating qualitative and quantitative evidence into scientifically defensible arguments
CTLO 4. Communication *Be effective communicators of chemistry by:*	4.1	presenting information, articulating arguments and conclusions, in a variety of modes, to diverse audiences, and for a range of purposes
	4.2	appropriately documenting the essential details of procedures taken, key observations, results and conclusions
CTLO 5. Personal and social responsibility *Take personal, professional and social responsibility by:*	5.1	demonstrating a capacity for self–directed learning
	5.2	demonstrating a capacity for working responsibly and safely
	5.3	recognising the relevant and required ethical conduct and behaviour within which chemistry is practised
	5.4	demonstrating a capacity for working effectively in a cooperative environment

The CTLOs are not intended to be equally weighted across the degree program, nor does the numbering imply a hierarchical order of importance. However, the numbering may be used to provide easy reference to a specific CTLO. Each CTLO has explanatory notes following, which are intended to offer guidance on how to interpret each outcome statement. The notes and the CTLOs should be considered in the context of the statement of the 'nature and extent of chemistry' on page 1.

CTLO1 Understanding chemistry

Chemistry graduates must appreciate chemistry is a creative endeavour which underpins human advances and has great importance to human society.

CTLO1.1

Demonstrate a coherent understanding of science by recognising the **creative endeavour involved in acquiring knowledge**, and the **testable** and **contestable** nature of the principles of chemistry.

Creative endeavour and acquiring knowledge Although chemistry is a systematic and logical study of phenomena, it is also about creating new knowledge and designing new frameworks in which to understand the molecular world. Chemistry graduates should understand the innovative aspects of chemistry and the need to think beyond the confines of current knowledge.

Testable All chemical knowledge is, in principle, testable. A chemistry graduate will understand that many chemical 'facts' have already been tested (and can be reproduced), while other chemistry knowledge has been developed by a logical process of scientific thought and awaits testing by experiments which have yet to be designed.

Contestable A chemistry graduate should have some appreciation and understanding of the historical evolution of scientific thought. A chemistry graduate will understand the need to re-evaluate existing conclusions when subsequent findings become available.

CTLO1.2

Demonstrate a coherent understanding of science by recognising that chemistry plays an **essential role** in society and **underpins** many industrial, technological and medical advances.

Essential role Applications of chemical science have contributed significantly to the advancement of human civilization and have played a pivotal role in the development of modern industrialised economies.

Underpin Chemistry is often referred to as the 'central science' because it provides a general framework for the physical, life, earth, environmental and applied sciences (including medicine and engineering). Chemistry plays a fundamental role in multi- disciplinary fields of endeavour including nanotechnology and the forensic, biomedical and materials sciences.

CTLO1.3

Demonstrate a coherent understanding of science by **knowing and being able to articulate** aspects of the **place and importance of chemistry** in the **local and global community**.

Knowing and be able to articulate A chemistry graduate should be able to contribute to society by using their scientific literacy to understand and explain chemistry-related issues. Graduates should be able to articulate the inter-relatedness of various chemistry sub-disciplines. For some graduates this might involve being an advocate for chemistry; however, all chemistry graduates should have some appreciation of, and be able to speak about, chemistry in the larger context of society.

Place and importance This phrase encompasses the impact, significance, and relevance of chemistry to the community. Chemistry graduates should have some understanding of the role of chemistry, appreciate the fundamental role of chemistry in connecting the sciences and understand that chemistry creates both challenges and opportunities for the community.

Local and global community The impact of chemistry is very broad and a chemistry graduate should understand that the community includes not only one's fellow students and academic colleagues, but may also include the local community in which they live, the social, environmental, technological, and industrial sectors and others.

CTLO2 Scientific knowledge

Chemistry graduates must have **depth** and **breadth** of knowledge from the currently accepted body of facts and theories that has arisen from a systematic study of the natural world.

Depth Chemistry graduates will have depth of knowledge in our disciplinary area. The expanded outcomes under CTLO2.1 serve as a minimum set of fundamental concepts necessary to demonstrate this outcome.

Breadth Chemistry graduates will be able to understand how chemistry relates to other disciplines of science and integrate their knowledge across the various disciplinary areas in which they have studied.

CTLO2.1

Exhibit depth and breadth of scientific knowledge by demonstrating and applying the **principles and concepts of chemistry**.

Principles and concepts of chemistry The well-developed knowledge required for a practicing chemist. A series of collaborative consensus-driven workshops established each of the third tier CTLOs to help 'unpack' this important outcome. These threshold standards for the principles and concepts of chemistry are listed below, and were deliberately structured to avoid established sub-disciplines of chemistry.

CTLO2.1.1

Stoichiometry, structure and characteristic properties of chemical substances

- The mole concept is a unifying concept for describing/measuring quantities of substances. It relates the macroscale (mass) to the microscale (atoms, molecules etc.).
- Stoichiometry is the unique numerical relationship by which atoms, ions and molecules combine together.
- Electrons, protons and neutrons are the fundamental atomic particles. Distribution of electron density is rationalised using the concept of orbitals.
- The Periodic Table is a structured presentation of the elements which relates the position of an element in the table to its macroscopic properties and chemical reactivity.
- Chemical bonds form through the sharing or transfer of electrons between atoms. The nature and quantity of chemical bonds in a chemical species give rise to the shape, structure and macroscopic properties of that species.

CTLO2.1.2

Methods of structure determination

- A variety of experimental (e.g. spectroscopic, spectrometric and diffraction) and theoretical methods can be used to determine molecular structure.
- Spectroscopic methods are based on transitions between discrete energy levels and diffraction methods are based on scattering from periodic arrangements of atoms.
- Elemental composition may be determined using techniques such as high resolution mass spectrometry and elemental analysis.
- Qualitative chemical tests can be used to assist determination of structure.
- Separation methods and sample preparation may be required prior to determination of structure.

CTLO2.1.3

Properties of matter in relation to structure

- The size and location of the constituent atoms within a chemical species influences the shape and hence the chemical and physical properties of that species.
- Interactions within and between chemical species are essentially electrostatic in nature and influence chemical and physical properties, and with the available energy define the states of matter.

- The nature and strength of intra- and intermolecular forces / secondary interactions contribute to the macroscopic properties of a chemical species.
- The properties of a substance can be influenced by both physical and chemical environment
- The properties of a mixture can differ from those of the individual components of the mixture.
- Matter extends beyond the molecular to include metals, crystals, ionic solids and giant covalent complexes.

CTLO2.1.4

Chemical thermodynamics, equilibrium and kinetics

- Different chemical species have different energies. Most chemical changes are accompanied by a net change of energy of the system.
- Energy is conserved in chemical changes: breaking chemical bonds requires energy; formation of chemical bonds releases energy.
- Spontaneity of a chemical change is determined by a balance between energy change, available energy and entropy change.
- Starting and finishing states are independent of path, and may be predicted.
- All chemical changes are, in principle, reversible; chemical processes often reach a state of dynamic equilibrium.
- Thermodynamics provides a detailed capacity to understand energy change at the macroscopic level and to understand equilibrium systems quantitatively.
- Chemical change occurs as a function of time over a wide range of time scales.
- Most chemical reactions take place by a series of more elementary reactions, called the reaction mechanism.
- The products obtained from a chemical reaction can be influenced by controlling whether reaction rate or reaction energy plays the key role in the mechanism.
- There are relationships between chemical energy and electrical energy which can be harnessed or used to drive chemical processes.

CTLO2.1.5

Reaction processes can transform substances into very different products

- Reaction processes involve bond breaking and bond making – they neither create nor destroy matter but rearrange already present atoms into new species with chemical properties different to those of the reactants.
- The outcome of a chemical reaction process is governed by thermodynamic and kinetic factors.
- Chemical reaction processes can be classified systematically into general types – this allows prediction of outcomes.
- Reaction processes can be selective depending on reagents and conditions and can be controlled.
- Reaction processes may be found in a variety of contexts (e.g. industrial, biological etc.).

CTLO2.1.6

Reactions of metal and non-metal compounds including carbon compounds

- Controlling chemical reactions is a key requirement in the synthesis of new materials. Chemical change can be controlled by choice of reactants and reaction conditions.
- A range of general reaction types (including but not limited to: acid-base; redox; hydrolysis; addition; substitution; elimination; coordination) can be applied in different contexts to prepare target chemical species.
- Reaction processes can be understood in terms of mechanism – this provides a means of understanding and predicting outcomes.
- Chemical reactions may be used in a rational, purposeful way to synthesise desired products using a sequence of well-defined processes.

CTLO2.1.7

Quantifying concentrations and amounts of elements and compounds in simple and complex mixtures

- Chemical species can be separated on the basis of their chemical and/or physical properties in order to isolate the species for quantification.
- Chemical species can be quantified using a variety of methods chosen on the basis of the amount of analyte, nature of material and equipment availability/suitability.
- The amount of analyte present can be quantified based on measurable chemical and/or physical parameters.

- A range of factors must be considered when planning a quantitative analysis (e.g. precision vs. accuracy, sources of error and reproducibility, use of calibration curves and standard addition, statistical methods etc.).
- Quantitative results are reported in appropriate units and are subjected to a critical evaluation in order to determine their validity and reliability.

CTLO2.2

Exhibit depth and breadth of scientific knowledge by recognising that **chemistry is a *broad* discipline** that impacts on, and is influenced by, other scientific fields.

Discipline of chemistry Chemistry includes, but is not limited to, traditional sub-discipline areas of analytical, inorganic, organic and physical chemistry.

Impact of chemistry Chemistry is often referred to as the 'central science' because it provides a general framework for the physical, life, earth, environmental and applied sciences (including medicine and engineering). Chemistry also plays a fundamental role in multi-disciplinary fields of endeavour including nanotechnology and the forensic, biomedical and materials sciences.

Broad Chemistry graduates should demonstrate an understanding of the concepts underpinning the traditional sub-discipline areas and some appreciation of the role chemistry plays in a range of kindred scientific disciplines.

CTLO3 Inquiry, problem solving and critical thinking

Chemistry graduates must **investigate** and solve problems through inquiry and critical thinking.

Investigate This term is used to describe the processes of discovery and inquiry. A chemistry graduate will be aware of how new knowledge and ideas are acquired through a research/investigative process and will understand how to systematically plan and execute an investigation.

CTLO3.1

Investigate and solve problems in the chemical sciences by **synthesising and critically evaluating** information from a **range of sources** using traditional and emerging **technologies and methods**.

Synthesising and critically evaluating Chemistry graduates should be able to identify, access, select and integrate information and it is important that they are able to assess the validity of the information that they gather in the context of their knowledge and understanding of chemistry.

Range of sources This term is used to indicate that information can be gathered and critically evaluated from traditional sources (including books, refereed papers and journal articles, conference presentations, seminars, lectures and colleagues) as well as non-traditional sources (including non-refereed articles, reports, 'grey literature' and electronic posts).

Technologies and methods This term is used to indicate both the diversity of methods and technologies that may be used to search for information, as well as the diversity of technologies that may be used for manipulating, analysing or storing that information.

CTLO3.2

Investigate and solve problems in the chemical sciences by **formulating** hypotheses, proposals and predictions and **designing** and **undertaking** experiments.

Formulating, designing and undertaking An important aspect of chemistry is the ability to form hypotheses and propose and predict outcomes in a logical manner and then design activities or experiments to test these predictions: this supports a systematic approach to problem solving. Graduates should be able to design and conduct a series of systematic investigations to justify unexpected data (e.g. in industry, a set of 'out-of- specification' results would normally require an investigation that may include a chemical assessment to explain why the results have deviated from the expected outcome). In addition, chemistry graduates should have an appreciation that many problems are not straightforward and solving them requires creativity and innovation.

CTLO3.3

Investigate and solve problems in the chemical sciences by applying **recognised methods** and appropriate techniques and tools, and being able to adapt these techniques when necessary.

Recognised methods of chemistry are those which are testable, validated, reproducible and objective; appropriate techniques and tools are those which are 'fit for purpose' in the context of the problem under investigation. These can be defined as areas which include but are not limited to those identified in the expanded third tier CTLOs below, which form a minimum set of hands-on skills necessary for a practicing chemist.

In all cases, regardless of technique or process used, graduates will be able to:

- Physically undertake an experiment
- Explain the theoretical basis of each technique or process used
- Evaluate the results of the experiment, refine the technique or process if necessary, and repeat if necessary
- Report the results of an experiment effectively

In addition, graduates should be able to:

- Adapt a given technique or process to new situations
- Integrate a series of techniques or processes into a complex task

CTLO3.3.1

General laboratory practice

- Weighing and measuring
- Use of appropriate glassware
- Preparation and handling of solutions
- Handling of gases

CTLO3.3.2

Synthesis

- Preparation — the ability to handle/manipulate chemical substances to make a desired product that is different from starting materials
- Isolation — the ability to separate and/or purify (by distillation, crystallisation, chromatography etc.) the desired product(s)
- Characterisation — the ability to use qualitative and/or quantitative instrumental and/or chemical methods to confirm product identity and/or purity

CTLO3.3.3

Qualitative and quantitative analysis

- Consideration of the sample and and an understanding of the process of sampling
- Understanding of the analyte/sample/matrix under investigation
- Understanding and application of separation methods (e.g. chromatography, electrophoresis)
- Understanding and application of instrumental methods (e.g spectroscopic, spectrometric and diffraction methods; electrochemical and potentiometric methods) including: instrument setup (operation and calibration; including preparation and use of standards); data collection, handling and analysis (including statistical analysis, estimation of uncertainty/error)
- Understanding and application of appropriate chemical methods

CTLO3.3.4

Modeling and/or simulation

- Fundamental knowledge of the main theoretical concepts, computational paradigms and mathematical-based modelling used in the various fields of chemistry.
- Fundamental knowledge of structure and data visualisation software relevant to the chemistry discipline.
- General understanding of the role of theoretical and computational tools in characterisation and prediction of chemical reactions and substances involved, as well as in designing, interpreting and quantifying aspects of chemical synthesis and reactivity.

CTLO3.4

Investigate and solve problems in the chemical sciences by **collecting, recording and interpreting data** and incorporating **qualitative and quantitative evidence** into **scientifically defensible arguments**.

Collecting, recording and interpreting data Chemistry graduates should be competent at collecting and recording data from their investigations (including modeling and/or simulation), analysing these data with the use of statistical and/or data analysis concepts, and evaluating them in the context of their understanding of chemistry to describe chemical phenomena. Chemistry graduates should be able to synthesise chemical explanations from the data generated, as well as from existing sets of data.

Qualitative and quantitative evidence Chemistry graduates will use evidence which is able to be verified. They will be able to evaluate evidence and make judgements regarding the validity, reliability, accuracy and precision of information. This will often incorporate aspects of reproducibility, error analysis, numerical uncertainty or statistical analysis.

Scientifically defensible arguments Chemistry graduates should have the capacity to pose and evaluate arguments based on scientific evidence. They should understand how their data support justifiable solutions, proofs or conclusions.

CTLO4 Communication

Chemistry graduates must be able to effectively communicate their understandings generated from their knowledge and skills.

CTLO4.1

Be effective communicators of chemistry by **presenting** information, articulating arguments and conclusions, in **a variety of modes, to diverse audiences**, and for **a range of purposes**

Presenting Chemistry graduates should engage with their audience and be able to convey their message in a clear and understandable manner appropriate to them using specific and scientifically accurate language. In particular, chemistry graduates will be able to present quantitative and qualitative data in a variety of ways, including tables, charts, graphs and symbols, which show clearly the evidence from which conclusions are drawn. Graduates should demonstrate an ability to conceptualise and visualise three-dimensional structures at the molecular and macroscopic levels and present these concepts in a variety of ways, e.g. using structures, spectra and diagrams.

A variety of modes, to diverse audience Chemistry graduates should be able to communicate to their peers, to chemistry and scientific non-experts, and to the general community. They will communicate using a range of media, including written, oral and visual media, and a variety of other techniques. Such communication could include a range of formats (such as laboratory notebooks and reports, technical reports, newspapers, journal articles, online forums, posters and oral presentations).

A range of purposes Chemistry graduates will be able to present their findings in both a technical and non-technical manner. They should use scientific language correctly and appropriately, and follow the conventions of chemical nomenclature. This might include the use of standard symbols, units, names or key terms. Chemistry graduates will be aware of the need to communicate the details of their investigations according to conventions of the discipline, and those which may be defined by publishers, editors or professional associations.

CTLO4.2

Be effective communicators of chemistry by appropriately documenting the essential details of procedures undertaken, key observations, results and conclusions

Chemistry graduates should be able to keep clear, accurate records of their work, including all relevant data and observations; using appropriate notebooks, journals and databases; and using media ranging from traditional to emerging information technologies. Documentation should be of sufficient detail that the procedure can be replicated.

CTLO5 Personal and social responsibility

Chemistry graduates must take personal, professional and social responsibility for their learning, for their safey and safety of others, and for their conduct.

CTLO5.1

Take personal, professional and social responsibility by demonstrating **a capacity** for **self-directed learning**

A capacity for While many chemistry graduates will be competent self-motivated learners, others will be just beginning to develop this capability at the time of graduation. Thus ‘a capacity for’ encompasses this range of abilities.

Self-directed learning Chemistry graduates should be able to take responsibility for their own learning. This involves an ability to work autonomously and evaluate their own performance. In order for chemistry graduates to make an ongoing contribution to a society in which scientific knowledge is continually evolving, it is important that they are motivated to continue to learn after graduation. This is also referred to as life-long learning.

CTLO5.2

Take personal, professional and social responsibility by demonstrating a capacity for working responsibly and safely

A chemistry graduate should understand how to take responsibility for themselves and others in the conduct of scientific investigations or other work situations. This term includes the occupational, environmental and mental health and safety and risk assessment requirements of the discipline. It also includes, for example, an understanding of time management, and the onus on individuals to fulfil their role as part of team projects. Graduates should have the appreciation of how to interpret chemical hazard information, e.g. via Safety Data Sheets or online databases, to minimise risks to themselves and others.

CTLO5.3

Take personal, professional and social responsibility by recognising the relevant and required ethical conduct and behaviour within which chemistry is practised

Chemistry graduates will have an awareness of the ethical requirements that are appropriate for the discipline. These may include the importance of accurate data recording and storage, proper referencing (and the need to avoid plagiarism), intellectual integrity, having an awareness of the impact on the environment of their activities, and an appreciation that chemistry can generate new knowledge with benefits and risks to society. It is important that chemistry graduates have some understanding of their social and cultural responsibilities as they investigate the natural world.

CTLO5.4

Take personal, professional and social responsibility by demonstrating a capacity for **working effectively** in a **cooperative environment**.

Working effectively Successful integration into the workplace requires graduates who can work independently and in teams to achieve shared goals. This requires understanding effective work practices at an individual and team level, and acknowledgement and attribution of each member’s contributions to the shared goals as a personal, professional and/or social responsibility.

Cooperative environment Where each member contributes near-equal and dependent actions to achieve shared goals. Like elsewhere here, many chemistry graduates will be effective in a cooperative environment, while others will be just beginning to develop this capability at the time of graduation. Thus ‘a capacity for’ encompasses this range of abilities.

Table 2: Alignment between the Science and Chemistry TLOs

STLO	Science TLO	CTLO	Chemistry TLO
1	**Demonstrate a coherent understanding of science by:**	**1**	**Demonstrate a coherent understanding of science by:**
1.1	articulating the methods of science and explaining why current scientific knowledge is both contestable and testable by further inquiry	1.1	recognising the creative endeavour involved in acquiring knowledge, and the testable and contestable nature of the principles of chemistry
1.2	explaining the role and relevance of science in society.	1.2	recognising that chemistry plays an essential role in society and underpins many industrial, technological and medical advances
		1.3	knowing and being able to articulate aspects of the place and importance of chemistry in the local and global community
2	**Exhibit depth and breadth of scientific knowledge by:**	**2**	**Exhibit depth and breadth of scientific knowledge by:**
2.1	demonstrating well-developed knowledge in at least one disciplinary area	2.1	demonstrating and applying the principles and concepts of chemistry
2.2	demonstrating knowledge in at least one other disciplinary area	2.2	recognising that chemistry is a broad discipline that impacts on, and is influenced by, other scientific fields
3	**Critically analyse and solve scientific problems by:**	**3**	**Investigate and solve problems in the chemical sciences by:**
3.1	gathering, synthesising and critically evaluating information from a range of sources	3.1	synthesising and critically evaluating information from a range of sources using traditional and emerging technologies and methods
3.2	designing and planning an investigation	3.2	formulating hypotheses, proposals and prediction sand designing and undertaking experiments
3.3	selecting and applying practical and/or theoretical techniques or tools in order to conduct an investigation	3.3	applying recognised methods and appropriate techniques and tools, and being able to adapt these techniques when necessary
3.4	collecting, accurately recording, interpreting and drawing conclusions from scientific data	3.4	collecting, recording and interpreting data and incorporating qualitative and quantitative evidence into scientifically defensible arguments
4	**Be effective communicators of science by:**	**4**	**Be effective communicators of chemistry by:**
4.1	communicating scientific results, information, or arguments, to a range of audiences, for a range of purposes, and using a variety of modes	4.1	presenting information, articulating arguments and conclusions, in a variety of modes, to diverse audiences, and for a range of purposes
		4.2	appropriately documenting the essential details of procedures taken, key observations, results and conclusions
5	**Be accountable for their own learning and scientific work by:**	**5**	**Take personal, professional and social responsibility by:**
5.1	being independent and self-directed learners	5.1	demonstrating a capacity for self–directed learning
5.2	working effectively, responsibly and safely in an individual or team context	5.2	demonstrating a capacity for working responsibly and safely
		5.4	demonstrating a capacity for working effectively in a cooperative environment
5.3	demonstrating knowledge of the regulatory frameworks relevant to their disciplinary area and personally practising ethical conduct	5.3	recognising the relevant and required ethical conduct and behaviour within which chemistry is practised

About the RACI

Founded in 1917 and granted a Royal Charter in 1932, the Royal Australian Chemical Institute (RACI) is the professional body for the chemical sciences in Australia. It acts both as the qualifying body in Australia for professional chemists, and as a learned society promoting the science and practice of chemistry.

Accreditation

RACI Accreditation is designed to ensure that graduates of accredited undergraduate degree courses have the skills and knowledge necessary to be a practicing chemist. Graduation from an accredited degree is a first step on the normal pathway to the award of the post-nominal qualification Chartered Chemist (CChem). Graduates of courses granted accreditation will be eligible for the qualification of Chartered Chemist and Corporate Membership of the RACI (MRACI CChem) once they have obtained the required professional experience.

The skills and knowledge of a graduate of a bachelor degree majoring in Chemistry are articulated in the this *Statement*, which represents the current consensus view of the Australian chemical sciences community and defines the minimum Chemistry Threshold Learning Outcomes (CTLOs) of a pass bachelor's degree in chemistry. The CTLOs are the organising principle for chemistry undergraduate curriculum, and are used by the RACI to compare and accredit undergraduate chemistry degrees. To have a degree program accredited, an institution must:

- provide evidence that degree objectives are informed by the CTLOs as the national benchmark,
- demonstrate all students enrolled have multiple opportunities to learn and practise knowledge and skills defined by the CTLOs, and
- adequately assess the CTLOs such that all graduates have demonstrated their attainment of the requisite knowledge and skills to be a practicing chemist and Member of the Institute.

The accreditation process has four stages of curriculum review:

1. **Intended:** the CTLOs are the intended curriculum.
2. **Implemented:** each institution interprets each of the CTLOs, and reports their self-assessment of student attainment in a curriculum map.
3. **Perceived:** an accreditation panel validates the alignment between the intended and implemented curriculum before recommending the award of accredited status for a given programme or programmes.

4. **Achieved:** this accreditation panel summarises the student achievement through the lens of the CTLOs in a report to the Board of the RACI who confer accredited status on the degree program.

We use the CTLOs to benchmark and compare undergraduate chemistry curriculum around Australia, where they serve as an intended undergraduate curriculum. Each institution can (and should) design their own curricula to accommodate their strengths and priorities to meet or exceed the CTLOs.

Context for this work

First Edition

In 2011 the Australian Learning and Teaching Council published the Learning and Teaching Academic Standards Statement for Science.[1] This work, led by Professor Sue Jones and Professor Brian Yates (both from University of Tasmania) also encompassed development of Standards Statements for Chemistry. Funding from the Office for Learning and Teaching of the Chemistry Discipline Network (ChemNet) in 2011 provided the opportunity to further develop and extend the Standards Statement for Chemistry to support implementation as part of the emerging national quality assurance environment. ChemNet established a Threshold Learning Outcomes Working Party which ran a series of collaborative workshops in 2012/2013 (attended by a total of 81 delegates from 25 institutions) aimed at developing a shared understanding of several key issues, with the foremost issue dealt with to date being the requirement to outline the core “body of knowledge” and thus identifying what are considered to be:

1. the principles and concepts of chemistry, TLO 2.1 (i.e. ‘core knowledge’); and
2. the recognised methods and appropriate techniques and tools that underpin these principles and concepts, TLO 3.3 (i.e. ‘core practical skills’).

The synthesis of ideas collected at the collaborative workshops can be found at TLO 2.1 (addressing ‘core knowledge’) and TLO 3.3 (addressing ‘core practical skills’). The remainder of the Explanatory Notes are from the 2011 Standards Statement.

In addressing the issues identified above, it should be recognized that the intention was not to create a prescribed curriculum; sufficient flexibility needs to be maintained in order for institutions to retain the individual identity of their programs of study.

Support of the Office for Learning and Teaching, the Royal Australian Chemical Institute and Heads of Chemistry (in sending delegates to the collaborative workshops) is gratefully acknowledged.

Working party membership

Simon Pyke (Chair) .... The University of Adelaide

Brian Yates (Former Chair) .... University of Tasmania

Glennys O’Brien (Co-Director, ChemNet) .... University of Wollongong

Kieran Lim .... Deakin University

[1] Jones, S., Yates, B., & Kelder, J.-A. (2011). *Science Learning and Teaching Academic Standards Statement.* Australian Learning and Teaching Council.

Ian Jamie .... Macquarie University

Siegbert Schmid .... The University of Sydney

Chris Thompson .... Monash University

Richard Thwaites .... Chair, RACI Qualifications Committee

Second Edition

The first edition of the *Chemistry Academic Standards Statement* served as the national benchmark for accreditation of courses in chemistry and related disciplines from 2015 to 2021. During this period, through the curriculum mapping process, we collected data about:

- 16 institutions
- 34 degree programs
- 319 units of study
- 992 assessments

The occurrence of each outcome is mapped at three levels. First, the institution provides self-reported evidence about whether each second tier threshold learning outcome is taught, practised and/or assessed. This provides information about **engagement** with the learning outcome. Secondly, the institution reports which **assessment** tasks have demonstrated all or part of each outcome. And in this second step, some of these outcomes will be reported to **graduate** level. These data have been aggregated to help inform any changes to the CTLOs or explanatory notes contained in the *Statement*, and are presented as a percentage in Figure 2.[2]

There was reasonable engagement with each outcome available across the self-reported curriculum, with notable prominence of key outcomes differentiating chemistry from other disciplines of science — these will be discussed for CTLO2.1 and 3.3 below. The aggregation of data in Figure 2 presents some concerns for two second tier outcomes, which are underrepresented at both the engagement and assessment level — CTLO1.3 and 3.5 discussed below.

Overall, the data demonstrates the CTLOs represent a remarkably good representation of curriculum and of outcomes relevant to chemistry across Australia, and therefore should be retained as the benchmark for accreditation beyond the present period. Minor revisions to the *Chemistry Academic Standards Statement* derived from this discussion have been collected together in the changelog in Table 4 on page 26.

[2] With the exception of CTLO3.5 which has moved to CTLO5.4 in the second edition, all other CTLOs retain the same intent.

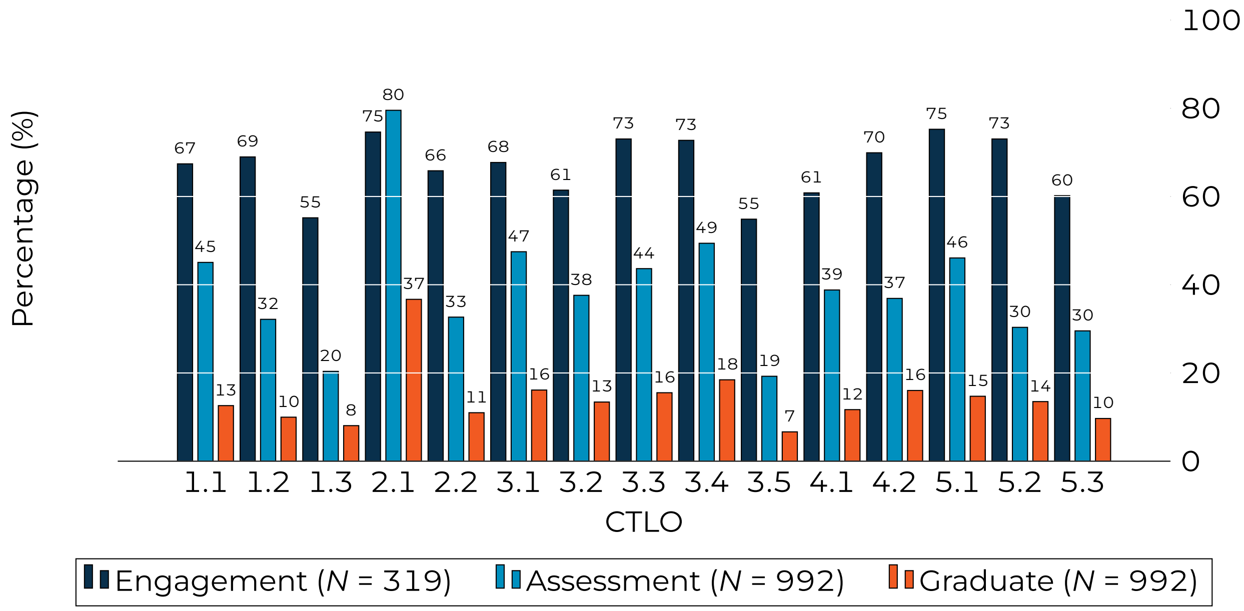

Figure 2: CTLO development in curriculum by engagement and assessment at any level or to graduate level only

CTLO1.3

> *"Understand ways of scientific thinking by understanding and being able to articulate aspects of the place and importance of chemistry in the local and global community"* First Edition

CTLO1.3 is intended to explore socioscientific issues emerging from and impacting on chemistry at both local and global levels. It was designed to differentiate the extrinsic nature of how chemistry impacts on society, as opposed to the intrinsic impacts on social development. On review of each accreditation, CTLO1.3 was adequately demonstrated in curriculum, often in very rich contextual ways. However, it was often peripherally placed in curriculum through capstone[3] projects, which makes it appear artificially fragile. Therefore, no change is recommended to the outcome at this time. Case studies demonstrating good practice in assessing CTLO1.3 will be collected throughout the second cycle of accreditation to help inform its further development, or it may be merged with CTLO1.2 (see the Science TLO 1.2 in Table 2, for example).

CTLO2.1

The expansion of CTLO2.1 into a third tier was offered to respondents who nominated that students were engaged in this outcome (either taught, practised or assessed). The purpose is to explore the depth of this engagement across the seven core knowledge areas of chemistry. The number of responses to each of these seven core knowledge areas of chemistry are illustrated in Figure 3, which shows reasonable engagement with each across the curriculum.

[3] See here for a definition: https://www.capstonecurriculum.com.au

2.1.1 Stoichiometry, structure and characteristic properties of chemical substances

2.1.2 Methods of structure determination

2.1.3 Properties of matter in relation to structure

2.1.4 Chemical thermodynamics, equilibrium and kinetics

2.1.5 Reaction processes can transform substances into very different products

2.1.6 Reactions of metal and non-metal compounds including carbon compounds

2.1.7 Quantifying concentrations and amounts of elements and compounds in simple and complex mixtures

- Other, please specify

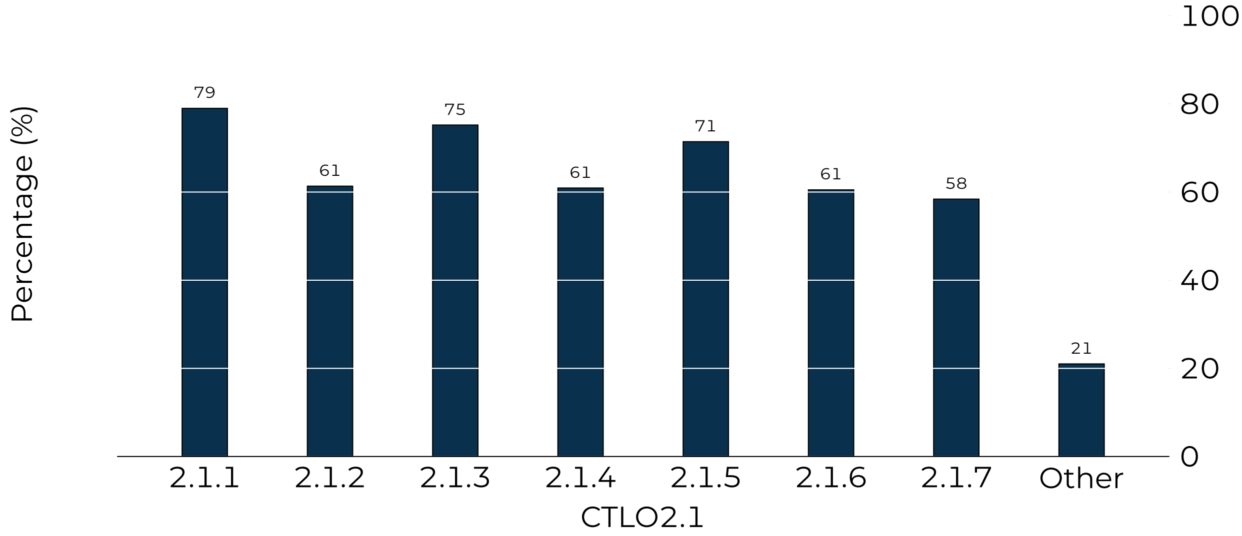

Figure 3: Third tier expansion on concepts of chemistry, CTLO2.1 (N = 238)

The respondents who chose 'other' were invited to nominate what concept of chemistry was not otherwise expressed by those previously defined. These responses were aggregated and analysed into themes, which are shown in Table 3. This table illustrates that the majority of the responses were in error, either because the concept suggested was defined elsewhere, was interdisciplinary or out-of-scope, or could be variable based on student experience.

The thematic analysis identified a series of missing concepts which did not clearly form part of the originally defined core concepts, and may otherwise stand alone as a concept or contribute to a richer description of an existing concept. Recommendations for each are given below.

Quantum mechanics may be implied as an underlying theory to explain many observed phenomena described elsewhere in CTLO2.1, but not as a concept *per se*. The mention of explicit theories were excluded from the original definitions of

Table 3: Thematic analysis of the open-text responses to 'other' for CTLO2.1 (n = 50, N = 238)

Category	**Example**	**Count**
Already defined within CTLO2.1.x	"Chemical thermodynamics, acid/base chemistry, equilibrium"	11
Interdisciplinary or out-of-scope	"Drug action and it relationship to chemical structure"	13
Misinterpreted	"See exam"	6
Missing	"Quantum mechanics"	5 out of 11
	"Electrochemistry"	4 out of 11
	"Computational or theoretical chemistry"	3 out of 11
Other CTLO	"laboratory OH&S, chemical storage, legislation"	4
Project	"It depends on the individual project topic area"	5

each core knowledge area to avoid becoming prescriptive. Therefore, it is recommended that quantum mechanics is considered out-of-scope at this point, with the intention of later inclusion if it persists as an independent concept.

Electrochemistry was defined as a method under qualitative and quantitative analysis CTLO3.3.3, but not otherwise as a phenomenon in its own right in CTLO2.1. A statement was added to CTLO2.1.4 to describe the fundamental relationship between electrical energy and chemical energy as another phenomenon within chemical thermodynamics, equilibrium and kinetics.

Computational and theoretical chemistry was defined as a method under modeling and/or simulation CTLO3.3.4, but not otherwise as a phenomenon in its own right in CTLO2.1. It was decided to more explicitly describe theoretical and computational chemistry as skills in CTLO3.3.4 rather than concepts under CTLO2.1. Many thanks to Dr Raffaella Demichelis and Associate Professor Paolo Raiteri for their assistance with these definitions.

CTLO3.3

The expansion of CTLO3.3 into a third tier was offered to respondents who nominated that students were engaged in this outcome (either taught, practised or assessed). The purpose is to explore the breadth of skills development in laboratory practice across four domains of skills. The number of responses to each of these domains are illustrated in Figure 4, which shows variable engagement across the curriculum.

3.3.1 Generic laboratory skills

3.3.2 Synthesis skills

3.3.3 Qualitative and quantitative analysis skills

3.3.4 Modeling and/or simulation skills

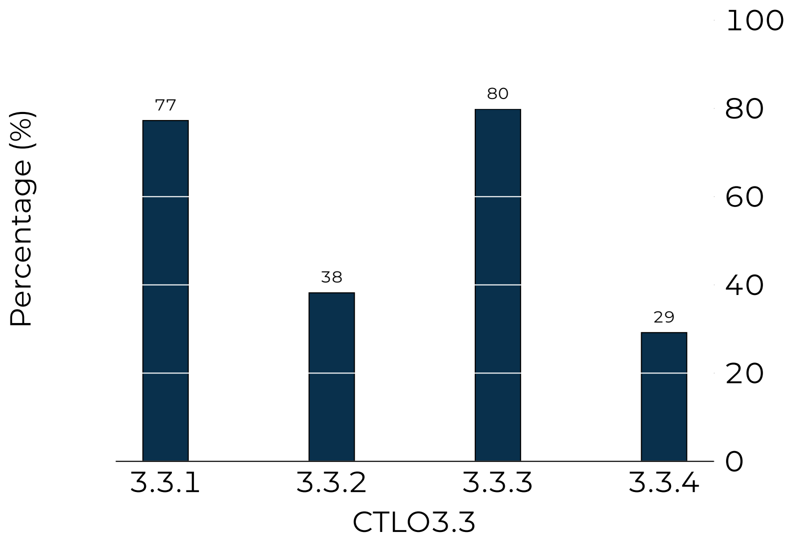

Figure 4: Third tier expansion on laboratory skills, CTLO3.3 (N = 233)

The collated data in Figure 4 demonstrates significantly more time is spent on general and analytical laboratory skill development than the other two domains of synthesis and modelling/simulation. This reflects the transferable nature of general and analytical laboratory skills to other experiments, while synthesis and modelling/simulation are only likely to be encountered in experiences concerned with these skills. Some further articulation of methods and appropriate techniques and tools beyond these domains of laboratory skills may be necessary for these data to have relevance to accreditation. The existing CTLO3.3 third tier descriptions will remain intact in the second edition of the *Statement*, with the addition of further information for CTLO3.3.4 on modelling and simulation as recommended on page 23.

CTLO3.5

> *"Investigate and solve qualitative and quantitative problems in the chemical sciences by demonstrating the cooperativity and effectiveness of working in a team environment."* First Edition

CTLO3.5 was derived from consultation on an earlier draft of the CTLOs, which specified in the first tier stem of CTLO3 that inquiry had to be conducted 'individually and in teams'. This was perceived to be burdensome on some second tier outcomes, and impractical in others, and therefore the intent for teamwork was then devolved to a second tier outcome. The term 'cooperativity' was chosen to represent a particular model of teamwork requiring interdependency.

Feedback throughout the first cycle of accreditation indicated a lack of understanding of the terms used, which was reflected in the poor level of engagement and assessment of the outcome (see Figure 2 on page 21). The first edition of the *Statement* lacked any further explanation, unlike other outcomes, which further exacerbated this unintended confusion. Subsequently, the Science TLOs placed teamwork within CTLO5 on personal, professional and social responsibility as an extension of working effectively, responsibility and safely in STLO5.2 (see Table 2 on page 16).

A new CTLO5.4 was created to align with the equivalent outcome STLO5.2. It was decided to retain a distinct outcome from the established CTLO5.2 on demonstrating a capacity for working responsibly and safely, which is highly important in chemistry practice and worthy of an independent outcome. The concept of cooperativity was retained in CTLO5.4 to describe a particular model of teamwork, with descriptions added to the *Statement* (see page 15).

Table 4: Changelog of CTLOs from first to second edition

ID	First Edition	Second Edition	Reason
CTLO1	Understanding the culture of chemistry	Understanding chemistry	The description of the first tier CTLO was altered to align with the Science TLO.
CTLO1	Understand ways of scientific thinking by	Demonstrate a coherent understanding of science by	The stem of the first tier CTLO was altered to better align with the Science TLO.
CTLO2	Exhibit breadth and depth of chemistry knowledge by…	Exhibit breadth and depth of scientific knowledge by…	To avoid repetition of 'chemistry' in the combined outcome statement, and better reflect the intent of these outcomes as derived from the Science statements.
CTLO2.1	…demonstrating a knowledge of and applying the principles and concepts of chemistry.	…demonstrating and applying the principles and concepts of chemistry.	To avoid repetition of 'knowledge' in the combined outcome statement.
CTLO2.1.4		There are relationships between chemical energy and electrical energy which can be harnessed or used to drive chemical processes.	Feedback suggested there was no concept relating to electrochemistry.
CTLO3	Investigate and solve qualitative and quantitative problems in the chemical sciences by…	Investigate and solve problems in the chemical sciences by…	Removal of the phrase 'qualitative and quantitative' as the problems themselves are not necessary either or both, but the data generated to solve them may be. Removes duplication with these terms in CTLO3.4 where its use is more appropriate.
CTLO3.1	…synthesising and evaluating information from a range of sources, including traditional and emerging information technologies and methods.	…synthesising and critically evaluating information from a range of sources using traditional and emerging technologies and methods.	Rephrased slightly to integrate the technologies and methods, to broaden scope in technology, and to better align with the STLOs.
CTLO3.3	…applying recognised methods and appropriate practical techniques and tools, and being able to adapt these techniques when necessary.	…applying recognised methods and appropriate techniques and tools, and being able to adapt these techniques when necessary.	Removal of the word practical to broaden scope, as some tools in the area of modelling and simulation are inherently theoretical.
CTLO3.3.x	…skills		Removed the phrase 'skills' when referring to the techniques and tools to avoid it becoming recessive.
CTLO3.3.4		A more explicit description of modelling and simulation skills	Addressing feedback from CTLO2.1.
CTLO4	Communicate chemical knowledge by	Be effective communicators of chemistry by	The stem of the first tier CTLO was altered to align with the Science TLO.
CTLO5.4	…demonstrating the cooperativity and effectiveness of working in a team environment.	…demonstrating a capacity for working effectively in a cooperative environment.	Moved from CTLO3.5 to CTLO5.4 and changed focus to define cooperativity as a personal and social responsibility, and more precisely defining it as 'cooperative environment' as a key element of this outcome.