CHEMISTRY
Academic Standards Statement

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

K. Barry Sharpless,
Nobel Prize in Chemistry Lecture, 2001.

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CONSULTATION DRAFT

PREPARED FOR RACI HEADS OF CHEMISTRY MEETING, OCTOBER 2013

REVISED FOR THE 2014 ROYAL AUSTRALIAN CHEMICAL INSTITUTE ACCREDITATION TRIAL

Chemistry DISCIPLINE NETWORK chemnet.edu.au

Australian Government | Office for Learning & Teaching

Nature & 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.

Context for this work

In 2011 the Australian Learning & Teaching Council published the Learning & 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 & 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 practical 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 & Teaching, the Royal Australian Chemical Institute and Heads of Chemistry (in sending delegates to the collaborative workshops) is gratefully acknowledged.

Threshold Learning Outcome Working Party membership

Associate Professor Simon Pyke	The University of Adelaide (Chair)
Professor Brian Yates	University of Tasmania (Former Chair)
Dr Glennys O'Brien (Co-Director, ChemNet)	University of Wollongong
Associate Professor Kieran Lim	Deakin University
Dr Ian Jamie	Macquarie University
Dr Siegbert Schmid	The University of Sydney
Dr Chris Thompson	Monash University
Dr Richard Thwaites	Chair, RACI Qualifications Committee

[1]S. Jones, B. Yates & J. Kelder (2011), Science Learning & Teaching Academic Standards Statement, ALTC [ISBN 978-1-921856-29-7] http://www.olt.gov.au/system/files/resources/altc_standards_SCIENCE_240811_v3.pdf

Threshold Learning Outcomes for Chemistry

	Upon completion of a bachelor degree with a major in chemistry, graduates will be able to:
Understanding the culture of chemistry	*1. Understand ways of scientific thinking 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 understanding and being able to articulate aspects of the place and importance of chemistry in the local and global community
Scientific knowledge	*2. Exhibit depth and breadth of chemistry knowledge by*: 2.1 demonstrating a knowledge of, 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
Inquiry, problem solving and critical thinking	*3. Investigate and solve qualitative and quantitative problems in the chemical sciences by*: 3.1 synthesising and evaluating information from a range of sources, including traditional and emerging information technologies and methods 3.2 formulating hypotheses, proposals and predictions and designing and undertaking experiments 3.3 applying recognised methods and appropriate practical 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 3.5 demonstrating the cooperativity and effectiveness of working in a team environment
Communication	*4. Communicate chemical knowledge 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 undertaken, key observations, results and conclusions
Personal and social responsibility	*5. 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

Threshold Learning Outcome 2.1 (Expanded)

2. Understand ways of scientific thinking by:

2.1 demonstrating a knowledge of, and applying the principles and concepts of chemistry

2.1.1 Stoichiometry, structure and characteristic properties of chemical substances

i. The mole concept is a unifying concept for describing/measuring quantities of substances. It relates the macroscale (mass) to the microscale (atoms, molecules etc.).
ii. Stoichiometry is the unique numerical relationship by which atoms, ions and molecules combine together.
iii. Electrons, protons and neutrons are the fundamental atomic particles. Distribution of electron density is rationalised using the concept of orbitals.
iv. 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.
v. 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 microscopic properties of that species.

2.1.2 Methods of structure determination

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

2.1.3 Properties of matter in relation to structure

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

2.1.4 Chemical thermodynamics, equilibrium and kinetics

i. Different chemical species have different energies. Most chemical changes are accompanied by a net change of energy of the system.
ii. Energy is conserved in chemical changes: breaking chemical bonds requires energy; formation of chemical bonds releases energy.
iii. Spontaneity of a chemical change is determined by a balance between energy change, available energy and entropy change.
iv. Starting and finishing states are independent of path, and may be predicted.
v. All chemical changes are, in principle, reversible; chemical processes often reach a state of dynamic equilibrium.
vi. Thermodynamics provides a detailed capacity to understand energy change at the macroscopic level and to understand equilibrium systems quantitatively.
vii. Chemical change occurs as a function of time over a wide range of time scales.
viii. Most chemical reactions take place by a series of more elementary reactions, called the reaction mechanism.
ix. 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.

2.1.5 Reaction processes can transform substances into very different products

i. 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.
ii. The outcome of a chemical reaction process is governed by thermodynamic and kinetic factors.
iii. Chemical reaction processes can be classified systematically into general types – this allows prediction of outcomes.
iv. Reaction processes can be selective depending on reagents and conditions and can be controlled.
v. Reaction processes may be found in a variety of contexts (e.g. industrial, biological etc.).

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

i. 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.
ii. 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.
iii. Reaction processes can be understood in terms of mechanism – this provides a means of understanding and predicting outcomes.
iv. Chemical reactions may be used in a rational, purposeful way to synthesise desired products using a sequence of well-defined processes.

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

i. Chemical species can be separated on the basis of their chemical and/or physical properties in order to isolate the species for quantification.
ii. 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.
iii. The amount of analyte present can be quantified based on measurable chemical and/or physical parameters.
iv. 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.).
v. Quantitative results are reported in appropriate units and are subjected to a critical evaluation in order to determine their validity and reliability.

Threshold Learning Outcome 3.3 (Expanded)

3. Investigate and solve qualitative and quantitative problems in the chemical sciences, both individually and in teams, by:

3.3 applying recognised methods and appropriate practical techniques and tools, and being able to adapt these techniques when necessary

3.3.1 Generic laboratory skills
- i. Weighing and measuring
- ii. Use of appropriate glassware
- iii. Preparation and handling of solutions
- iv. Handling of gases

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

3.3.3 Qualitative & quantitative analysis skills
- i. Consideration of the sample & and an understanding of the process of sampling
- ii. Understanding of the analyte/sample/matrix under investigation
- iii. Understanding and application of separation methods (e.g. chromatography, electrophoresis)
- iv. Understanding and application of instrumental methods (e.g spectroscopic, spectrometric & diffraction methods; electrochemical & 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)
- v. Understanding and application of appropriate chemical methods

3.3.4 Modeling and/or simulation skills – knowledge that there is a range of computer/mathematical-based modeling and simulation tools that can provide additional understanding of a material or physical reality.

Explanatory Notes on the Threshold Learning Outcomes for Chemistry

These notes are intended to offer guidance on how to interpret the Threshold Learning Outcome (TLO) statements. The notes and the TLOs should be considered in the context of the statement of the 'nature and extent of chemistry'.

These TLOs have been developed to describe a pass level graduate from a bachelor degree program. A 'bachelor degree' is defined according to the Australian Qualifications Framework (AQF), within which it represents a level 7 qualification.

The TLOs 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 TLO.

Some general definitions

Learning outcomes: The set of knowledge, skills and/or competencies a person has acquired and is able to demonstrate after completion of a learning process. In the AQF these are expressed in terms of knowledge, skills and application.

Threshold: Minimum standard of achievement or attainment.

Understanding the culture of chemistry

1. Understand ways of scientific thinking by:

1.1 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.

1.2 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.

1.3 understanding and being able to articulate aspects of the place and importance of chemistry in the local and global community

- Understand 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.

Scientific knowledge

2. Understand ways of scientific thinking by:

2.1 demonstrating a knowledge of, and applying the principles and concepts of chemistry

This is the currently accepted body of facts and theories that has arisen from a systematic study of the natural world. These can be defined as areas which include but are not limited to those identified.

2.2 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.

Inquiry, problem solving and critical thinking

3. Investigate and solve qualitative and quantitative problems in the chemical sciences by:

Investigate: This term is used to describe the qualitative and quantitative 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 plan and execute an investigation.

3.1 synthesising and evaluating information from a range of sources, including traditional and emerging information technologies and methods

- Synthesising and 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).
- Range of 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 storing that information.

3.2 formulating hypotheses, proposals and predictions and designing and undertaking experiments

- Formulating hypotheses, proposals and predictions and designing and undertaking experiments: 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.

3.3 applying recognised methods and appropriate practical 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 all cases, regardless of technique or process used, graduates will be able to:
  i. Physically undertake an experiment
  ii. Explain the theoretical basis of each technique or process used
  iii. Evaluate the results of the experiment, refine the technique or process if necessary, and repeat if necessary
  iv. Report the results of an experiment effectively

  In addition, graduates should be able to:
  i. Adapt a given technique or process to new situations
  ii. Integrate a series of techniques or processes into a complex task

3.4 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 computational/theoretical) and subsequently analyse and evaluate these data 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.
- 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.

Communication

4. Communicate chemical knowledge by:

4.1 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. 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 audiences: 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.

4.2 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.

Personal and social responsibility

5. *Take personal, professional and social responsibility by*:

5.1 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.

5.2 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 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; chemistry graduates should be able to work independently with limited supervision and have an awareness of the need to function effectively as members of teams. Graduates should have the appreciation of how to interpret chemical hazard information, e.g. via Materials Safety Data Sheets or online databases, to minimise risks to themselves and others.

5.3 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.