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Good Practice Guide

(Science)

THRESHOLD LEARNING OUTCOME 3
Inquiry and problem-solving

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Please note: The examples of good practice included in this Guide and their attributions were correct at the time of writing.

Further information about these Good Practice Guides for Science can be obtained from Professors Susan Jones and Brian Yates, ALTC Discipline Scholars for Science.
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Background

This Good Practice Guide was commissioned by Professor Susan Jones and Professor Brian Yates, ALTC Discipline Scholars in Science, as part of the ALTC Learning and Teaching Academic Standards (LTAS) Project in Science. Through consultation with science academics, science students, employment groups and professional societies, the LTAS Project in Science resulted in the development of a set of five Threshold Learning Outcomes (TLOs) for undergraduate science students. These TLOs describe the minimum that a science graduate should know and be able to do by the time they graduate. The TLOs for science describe learning in the following domains:

TLO 1: Understanding science

TLO 2: Scientific knowledge

TLO 3: Inquiry and problem-solving

TLO 4: Communication

TLO 5: Personal and professional responsibility.

This Good Practice Guide (GPG) supports the implementation of Science TLO 3: Inquiry and Problem-solving, which states that:

Upon completion of a bachelor degree in science, graduates will:

Critically analyse and solve scientific problems by:

3.1 gathering, synthesising and critically evaluating information from a range of sources
3.2 designing and planning an investigation
3.3 selecting and applying practical and/or theoretical techniques or tools in order to conduct an investigation
3.4 collecting, accurately recording, interpreting and drawing conclusions from scientific data.

(Jones, Yates & Kelder, 2011).

This Good Practice Guide (GPG) includes:

1. a review of the current research and good national and international practice which support development of student capacity to critically analyse and solve scientific problems
2. an annotated bibliography and brief commentary of selected resources supporting inquiry and problem-solving
3. a selection of good practice across science sub-disciplines illustrating the range of teaching and assessment of inquiry and problem-solving skills currently used in Australian undergraduate science degrees
4. the identification of emerging areas of focus on inquiry and problem-solving in the science curriculum.

TLO 3: Inquiry and problem-solving

Inquiry and problem-solving are fundamental to progress in science and core to the activities of scientists. In a recent study of what science means for Australian society (Harris 2012) science graduates responded to the question 'What do you value most from your background in science?' by placing high on their lists skills of research, learning and inquiry; technical skills including observation; and experimentation and quantitative skills.

The value of enhancing students' capacity to carry out inquiry and problem-solving irrespective of their career intentions or employment destinations is recognised as vital by Australia's Chief Scientist, Professor Ian Chubb, who explained:

> Instead of teaching the components of an atom as a nucleus filled with protons and neutrons, with electrons encircling as 'this is what's right', we need to be able to give students insight into how scientists discovered that. It is an approach that is valuable to both future researchers, and to those who go on to work as journalists, teachers, human resource managers, wherever their career path will lead them.
>
> We need to be able to push the agenda that a science education is valuable beyond (a) career as a scientist, that the science degree is a mechanism to train students' minds in vigorous evidence-based thinking and analysis.
> Scientific thinking promotes innovative inquiry, crucial to the development of new and more efficient industries and business models.'
>
> (*The Australian* 20 July 2012, 'Time to think about the forgotten 60 per cent')

Science inquiry skills are a major strand in the Australian Science Curriculum from K–12 (National Curriculum Board, 2009), which not only emphasises the importance of such skills, but also foreshadows that many future students entering university directly from school are likely to be better prepared to enhance their capacities in this area than is currently the case.

Inquiry and problem-solving in science

For the purposes of this Guide, inquiry and problem-solving are *defined* by the descriptions given in the Science Learning and Teaching Academic Standard Statement published in 2011 (Jones et al., 2011); namely, inquiry and problem-solving encompass gathering, synthesising and critically evaluating information from a range of sources; designing and planning an investigation; selecting and applying practical and/or theoretical techniques or tools in order to conduct an investigation; and collecting, accurately recording, interpreting and drawing conclusions from scientific data. Scientific inquiry is characterised by a focus on testable questions, on independently verifiable data and on interpretation with reference to, and comparison with, publically available material. Scientific inquiry activities include theoretical thought experiments as well as experimental and observational studies.
Although four distinct areas of knowledge and skill are identified within TLO 3, in practice these areas are closely inter-related. A scientific inquiry would normally include most, if not

all of those aspects of inquiry. Likewise, the teaching and learning of inquiry often addresses multiple aspects of inquiry in the same task.

Instructional strategies supporting TLO 3

The process of inquiry is the basis of several educational pedagogies. The underlying proposition is that the active processes that characterise inquiry engage students and reinforce skills and knowledge. Inquiry pedagogies such as problem-based learning and inquiry-oriented learning (Kirkup, 2013) have gained prominence across primary, secondary and tertiary education. An inquiry pedagogy does not necessarily reflect accepted concepts of scientific inquiry but can be an appropriate vehicle to develop inquiry skills for science and mathematics students. It is not the intention of this Guide to compare, contrast or promote any one instructional strategy over another, although the comparisons that can be found in the literature are recognised (see, for example, Eberlein et al., 2008).

There is no *a priori* reason why academics should favour one instructional strategy over another in order to assist students to attain TLO 3. For example, highly guided, verification-type experiences, experiments or activities in which students closely follow prescribed instructions in order to reach a well-defined end-point, do not necessarily prohibit students from developing the capacity to "critically analyse and solve scientific problems by accurately recording, interpreting and drawing conclusions from scientific data" (TLO 3.4).

However, evidence has emerged over several decades from studies carried out by science education researchers and science practitioners at secondary and tertiary education levels, that exposing students to authentic, inquiry-based or inquiry-oriented experiences better supports the acquisition and enhancement of inquiry and problem-solving skills. Such experiences have also been shown to accelerate improvement of students' understanding of scientific concepts (Armbruster et al., 2009). Support for inquiry-type approaches to learning is not unequivocal, with minimally guided approaches being criticised (Kirschner et al., 2006) and others providing evidence that engaging in inquiry-oriented activities is conditional on how well students' competencies and motivation match any particular inquiry or problem-solving opportunity (Hu et al. 2008).

Some of the literature on inquiry and problem-solving is considered.

Literature review

Education-focused and discipline-based academics have contributed to the literature on promoting and assuring students' scientific inquiry and problem-solving skills. That the audience for this GPG will include discipline-based practitioners seeking ideas to apply to their own circumstances is recognised. As a consequence, representative publications from specific sub-disciplines, such as biology, chemistry and physics, are included as well as the more general science education literature. The observations of the authors over many years are that practitioners are keen to hear of the work of others, who, like themselves, work directly with undergraduates in classrooms, laboratories, remote locations and other settings such as cooperative learning spaces and who have wrestled, or are wrestling, with approaches to enhancing students' scientific inquiry and problem-solving skills.

Satisfying TLO 3

> … [O]ur institutions of higher education will fail to provide a scientific education unless students come to learn something about the goals (and values) of trained scientists, the methods and procedures they use, and the ways in which they communicate their results.
>
> (Boud, Dunn & Hegarty-Hazel, 1989)

In satisfying TLO 3, with its focus on developing and demonstrating the capacity to critically analyse and solve scientific problems, students will experience what is special about a scientific education and "learn something about the goals (and values) of trained scientists, [and] the methods and procedures they use …". This capacity will be of lifelong value to graduates of science, whether their career trajectory takes them further into science, or towards a quite different destination (Harris, 2012). The development of self-directed and independent learners (which is a theme of TLO 5) is facilitated through inquiry-focused approaches to learning in the curriculum.

The Learning and Teaching Academic Standards (LTAS) document (Jones et al., 2011), which inspired this GPG, describes *how* students will critically analyse and solve scientific problems; namely by gathering, synthesising and critically evaluating information; designing and planning an investigation; selectively applying techniques and tools; and collecting, interpreting and drawing conclusions from data. Science educators describe scientific inquiry as asking questions (Elliott et al., 2010) and scientists emphasise a creative dimension (Wong and Hodson, 2008). To develop scientific inquiry skills, students must move beyond a passive application of pre-learned and practised methods to an adaptive and creative exploration of the world.

Many scientists would recognise the laboratory or the field as natural settings where students develop, over the duration of a science degree program, the abilities mandated by TLO 3. Inquiry is also core to theoretical disciplines, which use similar skills in abstract thinking. Inquiry skills can be developed with the assistance of technology and in a range of settings including classrooms or cooperative learning spaces.

Developing TLO 3 abilities

Hazel and Baillie (1998) describe goals for the science laboratory that align directly with TLO 3 and which are applicable to other settings:

1. Understanding the processes of scientific inquiry … and emulating the role of scientist [through]:
   a) observing and measuring (TLO 3.1/3.4)
   b) seeing a problem and seeking ways to solve it (TLO 3.2)
   c) interpreting data and formulating generalisations (TLO 3.1/3.4)
   d) building, testing and revising a theoretical model (TLO 3.3)
2. Learning manipulative and technical skills and the use of equipment (TLO 3.3).

Hazel and Baillie describe other roles that the laboratory-based inquiry can play, for example, in supporting and enhancing students' understanding and application of discipline-specific knowledge (the focus of TLO 2); communication skills (the focus of TLO 4); and imagination and creativity.

Hazel and Baillie argue the extent to which students achieve the goals above depends greatly on the nature and design of the student activities. Table 1 (adapted from Hazel and Baillie, 1998) relates the level of inquiry inherent within an activity to the extent of student autonomy. (Similar tables can be found elsewhere in the literature: see, for example, Buck, Bretz & Towns, 2008).

Table 1: Level of openness in scientific inquiry

Type of investigation	**Level** (arbitrary number)	**Aim** (Is the aim of investigation given or is it open?)	**Materials** (Do students select their own materials or are they given materials?)	**Method** (Is the method given or can student develop their own?)	**Outcome** (Is the outcome of the experiment given to the student, or is it open?)
Demonstration	0	Given	Given	Given	Given
Controlled exercise	1	Given	Given	Given	Open
Structured investigation	2A	Given	Given in whole or in part	Open or part given	Open
Unstructured investigation	2B	Given	Open	Open	Open
Project	3	Open	Open	Open	Open

The scale of student independence correlates with increasing complexity of the task and in the depth of learning outcomes sought. Increasing level of student independence in Table 1 aligns with the higher level learning outcomes in learning hierarchies such as those described by Bloom's taxonomy (Anderson et al., 2002) and the SOLO taxonomy (Biggs & Collis, 1982). Higher level outcomes also correlate with the standards for Australian education qualifications that state graduates are expected to be able to "analyse, generate and transmit solutions to unpredictable and sometimes complex problems" (Australian Qualifications Framework Council (AQFC), 2013). This description of a bachelor-level graduate describes the essence of open inquiry tasks.

The route to students achieving the outcomes described in TLO 3 may include all or any of the types of investigations described in Table 1. While it may appear that the ability to "gather information from a range of sources" or to "collect and accurately record scientific data" (TLO 3.1 and TLO 3.4) may be adequately developed through demonstrations or controlled exercises (i.e. levels 0 and 1 in Table 1 above), there is evidence to suggest that these abilities, as well as those which might be considered to be of higher order, such as "designing and planning an investigation" (TLO 3.2) are more effectively acquired through more open and self-directed experiences irrespective of the stage (from first to final year of a science degree) the student has reached (Cobern et al., 2010; Casotti et al., 2008; Planinsic, 2007; Allen et al., 1986). Studies on the development of science inquiry skills involving secondary school students such as interpreting data, formulating a hypothesis and designing an experiment, support the proposition that open-ended experiences are effective at developing higher-order scientific process skills (Roth & Roychoudhury. 1993).

Adams (2009) reviews published work in the biosciences focusing on the use of open-ended investigations to develop students' scientific inquiry skills and problem-solving capabilities (aligning with TLO 3.1 to TLO 3.4) and includes consideration of the value of undergraduates carrying out cutting-edge research. Adams also reviews several e-learning and computer-assisted learning papers whose focus includes the promotion of students' critical thinking skills (TLO 3.1) and the enhancement of students' fluency with experimental techniques (TLO 3.3). In Adams' words, "undergraduate students appear to benefit from not only research projects ... but also from more limited project experiences that provide the opportunity for novel research".

Acquiring scientific problem-solving skills through open-ended activities is favoured in much of the literature. However, there is a recognition that, if students are not prepared for such an activity, or if the activity is not properly scaffolded, then the demands on students can be too great, leading to minimal learning (Kirschner et al., 2006). Wang and Coll (2005) explored the transition of students from highly structured activities in a second year physics subject to activities in a third year subject in which emphasis was placed on students designing and implementing their own experimental methods (TLO 3.2). Wang and Coll advise that subject developers should create bridging experiments that, while including some instructions, would progressively place more responsibility on students such that they are better able to "conduct experiments like a scientist".

Luckie et al. (2012) describe a 10-year longitudinal study based on a course for first year science majors entitled Introduction to Cell and Molecular Biology. The study provides convincing evidence that more open-ended experiences benefit the development of abilities aligned with TLO 3. In the words of the authors (p 333):

> One of the goals [of the inquiry activity] was to give students more freedom to develop their own ideas and troubleshoot and experience the process of improving their experimental design ... [G]reater freedom, combined with

> challenges of an ill-structured problem ... can ultimately help students make greater gains in learning and the mastery of scientific laboratory skills.

The scheme used by Luckie and co-workers to improve students' scientific inquiry and problem-solving skills was large-scale, ultimately involving many academics. However, there are examples of modest changes to the curriculum having positive impact on, for example, the development of students' experimental design skills (TLO 3.2) and their ability to analyse data (TLO 3.4). Cacciatore and Sevian (2009) chose an incremental approach to developing the curriculum in which students experienced both open-ended and conventional 'recipe' type investigations. The move to open-ended, research-based investigations benefitted students' experimental design and data analysis skills as evidenced by an examination of student skills development through an investigation involving the principles of stoichiometry.

Reif and St John (1979) describe scientific skill development and the teaching of physicists' 'thinking skills' through the use of minilabs. Minilabs are brief laboratory exercises focusing on a particular skill or topic, for example, the estimation of errors in experimental data. The flexibility of the minilabs is such that they can be combined in several ways so that students acquire the skills needed for a more intensive investigation. Each minilab session concludes with students carrying out a self-test to assess whether they have mastered the targeted skills.

Current Australian examples of curriculum design to develop inquiry skills are presented later in this report as good practice examples.

Learning environments to support TLO 3

The practice of science is not confined to a single environment. Scientists pursue investigations in the field, laboratories, industry, virtual spaces and through theoretical modelling. Similarly, development of student inquiry skills can happen effectively in a variety of settings. Conventional locations, such as lecture theatres, can be used for inquiry tasks although settings that promote active learning, discussion and dynamic interaction with information have been shown to be better for skill development (Beichner et al., 2006). Exposure to authentic practice has the advantage of exposing students to unpredictable and complex situations where they learn to adapt an investigation and are diverted into new lines of inquiry.

The capacity to link students with remote sources of information, tools and colleagues has profoundly changed the possibilities for inquiry learning. In a paper on authentic learning, Lombardi (2007) notes "the internet and a variety of emerging communication, visualisation, and simulation technologies now make it possible to offer students authentic learning experiences ranging from experimentation to real-world problem-solving". Lombardi details several technologies that support inquiry and problem-solving in science including virtual laboratories, mobile technology for retrieving and inputting data, and access to remote instrumentation.

Remote instrumentation is an important element of an innovation designed by Weaver et al. (2006) which connects students to research and inquiry. This innovation gives first year students enrolled in a learning module access to research quality instruments so that they can carry out authentic research which produces data of value to the researcher who devised the learning module. Students are able to design and plan experiments for execution remotely.

Virtual laboratories in which students work with virtual apparatus and instruments, are growing as an alternative to conventional laboratories owing to the flexibility, cost effectiveness, accessibility and safety. Chen (2010) points to several studies that have provided evidence of the “positive learning effects of virtual environments that support students to explore, test hypotheses and analyse data as scientists do”. Chen argues that simulations should be as realistic as possible in order to avoid promoting an oversimplified view of scientific inquiry. For example, in an investigation involving the motion of a body, turning off the effects of friction or air resistance should not be an option as much of the richness and challenge which stems from dealing with and explaining non-ideal situations will be lost. A compendium of virtual laboratories of varying complexity and sophistication focusing on introductory biology, but also containing examples from chemistry and physics, can be found at <www.biologyjunction.com/virtual_labs.htm>.

Assessment of learning outcomes for inquiry and problem-solving

The purposes of assessment include examining whether educational objectives have been met and supporting the grading of students (MacDonald, 2005). Objectives, and criteria by which successful achievement of the objectives can be judged, need to be clearly stated so that assessments can be devised to establish the extent to which students have satisfied those criteria (Hazel & Baillie, 1998). For example, the learning outcomes of a physics activity devised to enhance students’ scientific inquiry and problem-solving skills by exploring the performance on solar cells might be expressed as follows:

In carrying out a practical investigation on solar cells, students will:

1) master the use of instruments and techniques to determine the energy efficiency of a solar cell (TLO 3.3)
2) devise an investigation to study factors affecting the energy efficiency of a solar cell (TLO 3.2)
3) collect, interpret and draw conclusions from the energy efficiency data obtained during investigation (TLO 3.4).

Several modes of assessment may be appropriate to any of these learning outcomes. MacDonald and Savin-Baden (2004) describe several modes of assessment in the context of problem-based learning which are equally applicable for assessing scientific inquiry and problem-solving. The reported assessment modes include papers and reports; logs and laboratory notebooks; posters; practical tests; examinations (written and oral); portfolios; self- and peer-assessment; and group and individual presentations. These modes of assessment are common in higher education. For inquiry and problem-solving tasks, assessment must look beyond disciplinary content to measure skills.

Assessment of problem-solving skills can be achieved in process tests and examinations. Problem-based learning curricula have developed a range of assessment instruments including a sequenced exam format known as the triple jump (reviewed in Nendaz & Tekian, 1999). In this format, students are given information about a problem in three separate stages and asked to plan an inquiry, integrate subsequent information and draw conclusions. Student responses are collected at each stage of the exam to allow the examiner to follow the development of the student's thinking. This approach has been adapted for scientific inquiry in research disciplines (Rangachari, 2001).

A number of authors have described approaches to assessment which attempt to measure student achievement across all aspects of an inquiry. Suits (2004) devised a practical examination of the investigative skills of science and engineering majors in an introductory chemistry subject at a US university. During the examination, students devise their own protocol and write a report as part of the examination. Students are graded on the protocol (TLO 3.2), their experimental technique (TLO 3.3), their data (TLO 3.1), and discussion of the data (TLO 3.4).

Halonen et al. (2004) describe a detailed rubric promoting the authentic assessment of scientific inquiry learning outcomes in psychology adaptable to other science disciplines. The intent of the authors was to capture "qualitative aspects of meaningful and enduring learning". The rubric considers a range of scientific inquiry skills including design, synthesis and evaluation skills (TLO 3.1 and 3.2), and observation, measurement and interpretation skills (TLO 3.3 and 3.4). The rubric describes levels of achievement by students ranging from 'before training' through to the level expected by an advanced undergraduate and beyond. In moving from 'cookbook' experiments to a collaborative inquiry project, Luckie et al. (2004) revised the assessment schedule in order to assess by means of student interviews, concept mapping and peer review of students' analysis, synthesis and evaluation skills.

Zwicki et al. (2013) describe the transformation of a senior physics laboratory in which special attention is paid to the assessment of learning goals. The goals include (students) modelling physical systems (TLO 3.1, 3.4), designing experiments to answer research questions (TLO 3.2), and acquiring technical skills (TLO 3.3). Assessment of the goals was accomplished in four ways: student achievement on the laboratory-based activities; weekly survey of students' lab experiences; student self-assessment of learning gains; and a locally developed survey which considered student attitudes towards learning experimental physics.

Findings and issues from the literature

There is general agreement in the science education as well as discipline-focused literature that scientific inquiry and problem-solving skills are more effectively developed through authentic activities that mimic the practices of scientists than in passive activities where students carry out predetermined instructions in order to reach what is (often) a well-known conclusion. This perception holds true as long as the authentic open-ended activities are scaffolded such that students are not 'thrown in the deep end' and the students have sufficient knowledge to allow them to make sense of the inquiry or problem-solving activity in which they are engaged.

The emphasis on giving undergraduates real research experiences, which promote the inquiry and problem-solving learning outcomes that graduates must demonstrate (Brew 2010), is growing and will continue to do so as ”it fits in with the research ethos of academia” (Elton, 2003).

There remains much emphasis on laboratory and field settings in promoting TLO 3 though, with increased sophistication and availability of remote and virtual laboratories, the use of the latter is likely to continue to grow. Well-conceived and established resources exist to assist with the development and assessment of activities that promote scientific inquiry skills (e.g. Hazel & Baillie, 1998).

Evaluation of inquiry and problem-solving tasks provides some indication of the relative merit of published innovations and is gradually becoming more common in publications. Evaluation may include measurement of student satisfaction through surveys, student self-assessment of skill development, and direct measurement of learning outcomes. Student satisfaction surveys can indicate student engagement but give little information about the efficacy of the inquiry task. Self-assessment promotes student self-awareness and can be used to estimate skill levels. The criteria for and learning outcomes from well-developed and validated assessment tasks provide a more rigorous measure of student achievement.

The development of the skills of scientific inquiry and problem-solving using open-ended activities is a challenge in large enrolment classes (Kirkup et al., 2010) and is likely to remain so as class sizes continue to increase. In addition, supporting students as they develop scientific inquiry skills in large classes requires academics or teaching assistants to act in the role of facilitator, rather than the more conventional role of giving students direct instructions (Hazel & Baillie, 1998). Where such a role is unfamiliar to academics, professional development opportunities need to be provided.

Resources for TLO 3

Curriculum development resources

Handbook for research skill development and assessment in the curriculum
<www.adelaide.edu.au/rsd/docs/rsd_Handbook_Dec09.pdf>

Not surprisingly, scientific inquiry and problem-solving skills have much in common with scientific research skills. This similarity is revealed in the comprehensive Research Skills Development (RSD) framework developed at Adelaide University and used by five other universities <www.adelaide.edu.au/rsd/>. The purpose of the framework is to "[help] academics conceptualise how they could facilitate research skills development".

Table 2 below shows a sub-section of the framework (the full framework contains five levels of student autonomy). The framework has been designed to inspire the development of student research skills across many disciplines including science. The prominence of the word 'research' in the document might suggest that it is not a suitable resource for assisting academics to support, and for students to attain, learning outcomes at the threshold level. This is not, in fact, the case. The word 'research' could be reasonably replaced in the table by 'inquiry' and, indeed, throughout the document with few other changes necessary.

Table 2: Adapted from the Research Skills Development Framework
http://www.adelaide.edu.au/rsd/framework/

The first column indicates facets of research; the second column contains the TLO equivalence; and remaining columns describe the levels of student autonomy.

		Level of student autonomy		
Research is when students:	**TLO**	**Level 1 (Prescribed Research)** Highly structured directions and modelling from educator prompt student research	**Level 2 (Bounded Research)** Boundaries set by and limited directions from educator channel student research	**Level 3 (Scaffolded Research)** Scaffolds placed by educator shape student independent research
Find and generate Find and generate needed information/data using appropriate methodology.	3.2/ 3.3/ 3.4	Collect and record required information or data using a prescribed methodology from a prescribed source in which the information/data is clearly evident.	Collect and record required information/data using a prescribed methodology from prescribed source/s in which the information/ data is not clearly evident.	Collect and record required information/data from self-selected sources using one of several prescribed methodologies.
Evaluate and reflect Determine and critique the degree of credibility of selected sources and of data generated, and reflect on the research processes used.	3.1/ 3.4	Evaluate information/data and reflects on inquiry process using simple prescribed criteria.	Evaluate information/data and reflect on the inquiry process using given criteria.	Evaluate information/data and inquiry process using criteria related to the aims of the inquiry. Reflect insightfully to improve own processes used.
Analyse and synthesise Analyse information/data critically and synthesise new knowledge to produce coherent individual/team understandings.	3.1	Analyse and synthesise information/data to reproduce existing knowledge in prescribed formats. **Ask emergent questions of clarification/curiosity**.	Analyse and synthesise information/data to reorganise existing knowledge in standard formats. **Ask relevant, researchable questions emerging from the research**.	Analyse and synthesise information/data to construct emergent knowledge. **Ask rigorous, researchable questions based on new understandings**.

The Research Skills Development (RSD) handbook describes examples of activities and assessment tasks from a range of disciplines including human biology intended to "diagnose, develop and track" research skills. A shell of a rubric that can be customised in order to assess the level of students' research/inquiry skills can be found in an appendix of the handbook along with other resources including links to organisations that promote undergraduate research.

Rubrics for inquiry and problem-solving

Rubrics, when used with context-specific exemplars, clarify for students and academics what is being assessed and the quality required to satisfy each level of attainment from pass to high distinction. They also allow students to self-assess before submission; highlight to students their strengths and weaknesses; assist students to recognise their strengths and weaknesses; and allow for better student understanding of their strengths and weaknesses.

The Association of American Colleges and Universities has published adaptable rubrics on problem-solving <www.aacu.org/value/rubrics/ProblemSolving.cfm> and inquiry and analysis <www.aacu.org/value/rubrics/InquiryAnalysis.cfm>.

Though primarily designed for school teachers, a resource for building customisable rubrics which could then be modified to suit assessment of inquiry and problem-solving in undergraduate courses can be found at <rubistar.4teachers.org/index.php?screen=CustomizeTemplate&bank_rubric_id=26&section_id=4&>.

Evaluating experiments with an inquiry focus

Advancing Science by Enhancing Learning in the Laboratory (ASELL) <www.asell.org/> is an Australian initiative promoting the development and assurance of quality undergraduate experiments in biology, chemistry and physics, including those with an inquiry focus. ASELL has created a database of accessible, peer-reviewed experiments adaptable by academics to local contexts. ASELL also "seeks to bring together diverse educational expertise and resources for universities both in Australia and throughout the Asia-Pacific region".

Resources for evaluating experiments with an inquiry focus can also be found on the OLT-sponsored Inquiry Oriented Learning in Science website <www.iolinscience.com.au/>. In particular, the website contains an Adaptable Resource Kit (ARK) <www.iolinscience.com.au/wp-content/uploads/2011/11/ARK_version1a.pdf> which is designed to assist academics as they move from the early stages of developing an inquiry-oriented experiment or activity to later stages where the activity is ready to be rolled out to its intended audience.

Web resources for inquiry and problem-solving tasks

Web resources for inquiry and problem-solving include examples of real practice (NCCSTS, MERLOT) as well as advice on design and delivery of tasks (IOL in Science, BioAssess). Extensive resources exist to assist with general aspects of curriculum design which are not canvassed here. Most universities also have internal academic development services which will assist with curriculum development.

National Center for Case Study Teaching in Science (NCCSTS)
<sciencecases.lib.buffalo.edu/cs/>
Although case studies are not necessarily inquiry tasks, this rich resource offers scenarios, teacher support materials and many ideas for active learning. The collection spans a wide range of science disciplines and includes a range of formats for teaching including problem-based learning. Interested educators can also publish their own tasks here.

Multimedia Educational Resource for Learning and Online Teaching (MERLOT)
<www.merlot.org/merlot/materials.htm?sort.property=overallRating>

The MERLOT collection includes content resources, ideas and articles for online learning. Submitted materials are available for peer review with reviews published on the site. The extensive repository can be challenging to navigate but there are hidden gems to discover.

Inquiry Oriented Learning in Science
<www.iolinscience.com.au/>
This website provides an overview of inquiry-oriented learning (IOL) and includes references, resources and links helpful to staff intent on developing new, or revising existing, IOL activities. The website also includes details of IOL activities developed by Australian academics suitable for supporting TLO 3 in the undergraduate biology, chemistry and physics undergraduate curricula.

BioAssess
<www.bioassess.edu.au/home>
This website offers an excellent orientation to assessment in the biosciences but is equally applicable to other science disciplines. Examples include formative and summative assessment tasks that could be built into a more comprehensive inquiry task.

Academic journals for inquiry learning and teaching

Inquiry learning articles and reviews are found in a wide variety of educational journals. Higher education journals which publish on the scholarship of learning and teaching often focus on aspects of pedagogy, staff development or comparisons of learning outcomes. Useful examples of inquiry tasks and strategies in science and mathematics are reported in leading discipline education journals. Notably, some leading research journals also publish in education, which has the benefit of reaching a much wider audience in science.

1. Discipline-focused education journals

Journal of Chemical Education
Publisher/website: ACS publications/ <pubs.acs.org/journal/jceda8>
Status/audience: Peer reviewed/instructors of chemistry from middle school through to graduate school.
Examples of inquiry- or problem-solving-oriented papers published by the journal:
Bruck, L.B. & Towns, M.H. (2009). Preparing students to benefit from inquiry-based activities in the chemistry laboratory: Guidelines and suggestions. *Journal of Chemical Education*, 86(7), 820–822.
Richardson, V. & Renner, J.W. (1970). A study of the inquiry-discovery method of laboratory instruction. *Journal of Chemical Education,* 47(1) 77–79.

The Chemical Educator
Publisher/website: The Chemical Educator <chemeducator.org/>
Status/audience: Peer reviewed/ all chemical education professionals
Example of inquiry- or problem-solving-oriented paper published by the journal:
Weaver, G.C., Wink, D., Varma-Nelson, P., Lytle, F., Morris, R., Fornes, W., Russell, C. & Boon, W.J. (2006). Developing a new model to provide first- and second-year undergraduates with chemistry research experience: Early findings of the Center for

Authentic Science Practice in Education (CASPiE). *The Chemical Educator,* 11(2) 125–129.

American Journal of Physics
Publisher/website: AAPT/ <ajp.aapt.org/>
Status/audience: Peer reviewed/physics teachers and students at colleges and universities
Examples of inquiry- or problem-solving-oriented papers published by the journal:

Reif, F. & St John, M. (1979). Teaching physicists thinking skills in the laboratory. *American Journal of Physics,* 47(11) 951–957.

Zwicki, B.M., Finkelstein, N. & Lewandowski, H.J. (2013). The process of transforming an advanced lab course: Goals, curriculum and assessments. *American Journal of Physics,* 81(1) 63–70.

European Journal of Physics
Publisher/website: IOP/ <iopscience.iop.org/0143-0807>
Status/audience: Peer reviewed/ undergraduates, graduates, general and specialist physicists
Example of inquiry- or problem-solving-oriented paper published by the journal:

Planinsic, G. (2007). Project laboratory for first year students. *European Journal of Physics,* 28 S71–S78.

CBE Life Sciences Education
Publisher/website: American Society for Cell Biology/ <www.lifescied.org/>
Status/audience: Peer reviewed/ educators at all levels including K–12, undergraduate and graduate
Examples of inquiry- or problem-solving- oriented papers published by the journal:

Allen, D. & Tanner, K. (2005). Infusing active learning into the large enrolment biology class: Seven strategies, from the simple to complex. *CBE Life Sciences Education,* 4 262–268.

Goldey, E.S., Clarence, L., Abercrombie, C.L., Ivy, T.M., Kusher, D.I., Moeller, J.F., Rayner, D.A., Smith, C.F. & Spivey, N.W. (2012). Biological inquiry: A new course and assessment plan in response to the call to transform undergraduate biology. *CBE Life Sciences Education,* 11, 353–363.

Biochemistry and Molecular Biology Education
Publisher/website: Wiley/ <onlinelibrary.wiley.com/journal/10.1002/(ISSN)1539-3429>
Status/audience: Peer reviewed/ educators at undergraduate and graduate levels
Examples of inquiry- or problem-solving-oriented papers published by the journal:

Eberlein, T., Kampmeier, J., Minderhout, V., Moog, R.S., Platt, T., Varma-Nelson, P. & White, H.B. (2008). Pedagogies of engagement in science: A comparison of PBL, POGIL, and PLTL. *Biochemistry and Molecular Biology Education,* 36(4) 262–273.

Wang, J.T.H., Schembri, M.A., Ramakrishna, M., Sagulenko, E. & Fuerst, J.A. (2012). Immersing undergraduate students in the research experience: A practical laboratory module on molecular cloning of microbial genes. *Biochemistry and Molecular Biology Education,* 40(1) 37–45.

Kerfeld, C.A. (2013). Introduction: Sequences and consequences, *Biochemistry and Molecular Biology Education,* 41(1) 12–15.

Advances in Physiology Education
Publisher/website: American Physiological Society/ <advan.physiology.org/>
Status/audience: Peer reviewed/educators at all levels: K-12, undergraduate, graduate, and professional programs
Examples of inquiry- or problem-solving-oriented papers published by the journal:

Casotti G, Rieser-Danner L & Knabb MT, (2008). Successful implementation of inquiry-based physiology laboratories in undergraduate major and non-major courses, *Advances in Physiology Education*, 32, 286–296.

Luckie, D.B., Aubry, J.R., Marengo, B.J., Rivkin, A.M., Foos, L.A. & Maleszewski, J.J. (2012). Less teaching, more learning: 10-year study supports increasing student learning through less coverage and more inquiry. *Advances in Physiology Education,* 36, 325–335.

2. Higher education journals

Journal of Research in Science Teaching
Publisher/website: Wiley/ <//onlinelibrary.wiley.com/journal/10.1002/(ISSN)1098-2736>
Status/audience: Peer reviewed/science education researchers and practitioners (deals mostly with teaching and learning at high school level)
Examples of inquiry- or problem-solving-oriented papers published by the journal:

Roth, W. & Roychoudhury, A. (1993). The development of science process skills in authentic contexts. *Journal of Research in Science Teaching,* 30(2) 127–152.

Sadeh, I. & Zion, M. (2009). The development of dynamic inquiry performances within an open inquiry setting: A comparison to guided inquiry setting. *Journal of Research in Science Teaching,* 46(10) 1137–1160.

Research in Science Education
Publisher/website: Springer/ <link.springer.com.ezproxy.lib.uts.edu.au/journal/11165>
Status/audience: Peer reviewed/ examines school, tertiary, workplace, and informal learning as they relate to science education
Example of inquiry- or problem-solving-oriented papers published by the journal:

Hegarty, E. (1978). Levels of scientific enquiry in university science laboratory classes: Implications for curriculum deliberations. *Research in Science Education*, 8, 45–57.

3. Education in science research journals

PLOS Biology
Publisher/website: PLOS/ <www.plosbiology.org/>
Status/audience: Peer reviewed/researchers and academic science educators. Journal includes papers on university science teaching. *PLOS Biology* is an open access journal, freely available online.
Examples of inquiry- or problem-solving-oriented papers published by the journal:

Chen et al. (2005). Discovery-based science education: Functional genomic dissection in drosophila by undergraduate researchers. *PLOS Biology,* 3(2), e59.

Kloser, M.J., Brownell, S.E., Chiariello, N.R. & Fukami, T. (2011). Integrating teaching and research in undergraduate biology laboratory education. *PLOS Biology,* 9(11) e1001174.

Science: Education Forum
Publisher/website: American Association for the Advancement of Science/ <www.sciencemag.org/>
Status/audience: Peer reviewed/researchers and academic science educators. Articles in the *Education Forum* are usually reviews and/or opinion pieces.
Examples of inquiry- or problem-solving-oriented papers published by the journal:

DeHaan, R. (2011). Teaching creative science thinking. *Education Forum,* 334(6062) 1499–1500.

Moskovitz, C. & Kellogg, D. (2011). Inquiry-based writing in the laboratory course. *Education Forum,* 332(6032) 919–920.

Physical Review Special Topics on Physics Education Research
Publisher/website: American Physical Society/ <prst-per.aps.org/>
Status/audience: Peer reviewed/researchers and academic science educators. This journal publishes experimental and theoretical research on the teaching and/or learning of physics. It is an open access journal, freely available online.
Example of inquiry or problem-solving-oriented papers published by the journal:

Chen, S., Lo, H., Lin, J., Liang, J., Chang, H., Hwang, F., Chiou, G., Wu, Y., Lee, S., Wu, H., Wang, C. & Tsai, C. (2012). Development and implications of technology in reform-based physics laboratories. Retrieved 25 June 2013 from <link.aps.org/doi/10.1103/PhysRevSTPER.8.020113/>

4. Local science education journal

International Journal of Innovation in Science and Mathematics Education
Publisher/website: Institute for Innovation in Science and Mathematics Education, The University of Sydney <http://ojs-prod.library.usyd.edu.au/index.php/CAL/index>
Status/audience: Peer reviewed/ academic science educators. This journal has a focus on Australian universities and links to the Australian Conference for Science and Mathematics Education.
Examples of inquiry- or problem-solving-oriented papers published by the journal:

Kelly E Matthews, Yvonne Hodgson (2012) The Science Students Skills Inventory: Capturing Graduate Perceptions of Their Learning Outcomes. *International Journal of Innovation in Science and Mathematics Education,* 20(1) 24-43. Retrieved 25 June 2013 from http://ojs-prod.library.usyd.edu.au/index.php/CAL/article/view/6648

Good practice examples

Scientific inquiry appears in some form in all Australian undergraduate science degrees. However, the range of skills to be developed, the independence of the students involved in an inquiry, and the scope of the task vary enormously. Tasks range from quite controlled exploration of a specific phenomenon to independent research into an open-ended question. The most suitable and effective inquiry task for any one course or subject is dependent on the resources available and the experience and diversity of the student cohort.

This collection of good practice examples is intended to illustrate the range of good practice currently offered in Australian undergraduate science degrees. The examples selected illustrate effective assessment and, where possible, demonstrate the influence of the task or activity on student learning outcomes. This Guide cannot attempt to reference all the good practice happening in Australian universities but the leadership and innovation of all those academics passionate about developing inquiry skills in their students is acknowledged and applauded.

The case studies are presented in two groups. The first group features a range of tools and formats for inquiry tasks. Case 1 (Williamson) uses a defined inquiry pedagogy, POGIL, and peer-group learning to explore concepts in large classes. Case 2 (Ross) presents a final year subject built as an immersive experience in fieldwork. Case 3 (Wegener and McIntyre) asks students to construct authentic model to investigate a real-world problem. Case 4 (MacGillivray) engages students in sophisticated statistical analysis with real-world data either from pre-existing sets or gathered by the students. Case 5 (Wang, Daly, Hall, Schembri, Tyson and Hugenholtz) demonstrates how student can contribute to authentic research through the collection and analysis of samples. Case 6 (Irving and Elliott) uses online simulation to create a virtual laboratory where student can investigate scenarios not easily reproduced in a student laboratory. Selection of tools and formats for an inquiry curriculum is primarily dependent on the learning outcomes sought and on the resources available. All of these cases emphasise the importance of the careful selection of the learning environment and materials to suit the student cohort.

The second group of cases illustrates aspects of broader curriculum design. These cases have been selected to show how inquiry learning can be built across multiple subjects or used to connect disciplines. Case 7 (Lawrie, Gahan and Matthews) describes inquiry tasks in a first year subject which asks students to look outward from their discipline and explore implications of disciplinary knowledge. Case 8 (Rayner, Thompson and Hughes) shows the parallel introduction of an inquiry format for practicals in foundation first year science subjects, reinforcing inquiry as characteristic of science. Case 9 (Burke da Silva) describes careful scaffolding towards independent inquiry across first year biology subjects. Scaffolding to gradually build student confidence and skills is a recurrent theme in inquiry tasks (Elliott et al., 2010) and features in a number of the cases presented here. Case 10 (RMIT) describes a cross-disciplinary capstone that houses authentic research similar to an honours year. Case 11 (Zimbardi, Colthorpe, Lluka, Chunduri and Smith) describes the construction of an inquiry curriculum across a whole discipline. Skills development has been carefully mapped alongside conceptual progress as is described in the accompanying table.

Construction of an inquiry learning curriculum on this scale depends on the collaborative work of disciplinary teams but offers great advantages in reinforcing effective student learning.

Many other effective examples of inquiry learning are available from higher education literature, from higher education meetings and conferences, and from peer and online networks. Adaptation to the local environment is usually essential to achieve effective outcomes.

Examples of inquiry tasks can be found in many Australian science degrees although they may be unconnected by curriculum design or carry relatively low assessment weighting. The implementation of TLO3 is a call to design, build and re-develop inquiry and problem-solving activities. Bringing prominence to these activities as well as enhancing their coherence across a degree program will result in a greater impact on intended student learning outcomes.

Case 1: Inquiry pedagogy

Subject: Foundations of Chemistry IA and IB

University: University of Adelaide

Author: Natalie Williamson

Year level: First year

Subject Description: Foundations of Chemistry IA (Semester 1) and IB (Semester 2) courses at the University of Adelaide are undertaken by students from extremely diverse academic backgrounds enrolled in degree programs both within and outside of the Faculty of Sciences. Many of these students must complete a full year of Chemistry at level I (for example, in Animal Science, Viticulture and Oenology, and Health Sciences programs) and the courses also cater for students with little or no prior Chemistry experience. The courses enable students to develop an understanding of atomic structure, the mole concept and concentration, molecular shape and intermolecular forces, equilibrium, acids and bases, organic chemistry, thermochemistry, redox processes and kinetics.

Inquiry: The courses incorporate Process-Oriented Guided Inquiry Learning (POGIL)-style activities into lectures. A POGIL activity comprises three main parts: Model, Data and/or Information; Critical Thinking Questions (CTQs) and Applications. The activity begins by providing students with some background on the topic, in the form of a paragraph or two of text, a diagram or a table, followed by guided inquiry questions that, through scaffolding, allow students to make connections and draw their own conclusions, enabling them to reach answers on their own. POGIL can conclude with application questions but here small group learning exploring applications continues in separately scheduled tutorials.

In one activity, students are presented with a table containing the name and structure of selected alkenes and alkynes and are introduced to these classes of compounds by exploring the information provided using the accompanying CTQs. Students deduce the name suffix for each class by inspection of the table, and construct the general formula for an alkene and alkyne by working out and comparing the molecular formulae of the molecules within the table. Students compare the names of different structures to deduce that the numbers within some of the names indicate the position of the functional group within the molecule.

Assessment: Assessment items for both Foundations of Chemistry courses include a written examination at the end of the semester (up to 60 per cent of the overall course grade), laboratory work (20 per cent) and online tutorial assignments (20 per cent). All assessment items require students to display problem-solving and inquiry skills to varying degrees. The examination and online tutorial assignments are designed to test students' problem-solving and inquiry skills as used in lectures and tutorials by including questions that require application of concepts rather than simple recall.

Williamson, N.M., Metha, G.F., Willison, J. & Pyke, S.M. Development of POGIL-style activities for an introductory chemistry course. *International Journal of Innovation in Science and Mathematics Education*. Accepted May 2013.

Case 2: Fieldwork

Subject: Aquatic Ecology

University: University of Western Sydney

Author: Pauline Ross

Year level: Third year

Subject description: Aquatic Ecology explores temperate aquatic ecosystems – freshwater, estuarine and marine –the most of threatened ecosystems. On completion of this subject, students have knowledge of the main animal and plants in aquatic ecosystems and the techniques in experimental design and analysis to investigate these ecosystems. Results of scientific work and literature informing decision-making and conservation are emphasised.

Inquiry: In this subject, an inquiry-based, spiralled curriculum immerses students in three cycles of field work in freshwater, estuarine and coastal habitats over a 12-week semester. Field work is integrated with lectures and laboratories which combine identification of organisms and data analysis. The subject explores the scientific process of constructing models to explain observations, proposing hypotheses derived from models, designing experiments to test null hypotheses and hypotheses and then determining whether the scientific models are supported by the results of the experimental test. As students lack confidence in designing a scientific investigation on entry, the development of inquiry skills is scaffolded through each field trip in a five-stage process. Firstly, students practice experimental design and data analysis using existing datasets. Second, key research for the first aquatic habitat is reviewed. Third, students visit the field site where they propose and test a hypothesis. Students are given open-ended choices on what they will investigate in the habitat with advice from demonstrators but no recipe-like instructions on designing experiments. Fourth, students return to laboratory to identify organisms and analyse their data. Similar to the field stage, demonstrators in the computer laboratories assist students to decide which analysis is appropriate and provide advice on technical issues with software. Finally, students communicate in writing the main findings from their experiments and relate these to the scientific literature in a standard scientific report. The cycle is repeated across three field investigations with contexts selected to encourage increasingly complex and sophisticated experimental designs. The three cycles of investigations in different aquatic habitats build student confidence in the development of inquiry skills.

Assessment: The main assessment items are two 'traditional' scientific reports combined with a contemporary reflective journal to promote review of learning. The underlying philosophy is to provide a challenging but 'safe' environment where students can learn from mistakes through 'productive failure'. The multistage submission process for reports gives students a detailed criteria- and standards-based rubric and constructive feedback, 'feed-forward', on a first submission before assessment of the revised submission.

Ross, P.M. (2012). Student learning depends on what students do with feedback. Higher Education Research and Development Society of Australasia Incorporated (HERDSA).

Ross, P.M. & Gill, B. (2010). Past and present challenges to enquiry learning in tertiary science education. *Journal of Learning Design 3*(3) 45–57. <www.jld.edu.au/article/view/62/60/>.

Case 3: Real-world problems

Subject: The physical basis of biological systems

University: The University of Queensland, Brisbane

Authors: Margaret Wegener and Tim McIntyre

Year level: First year

Subject description: This subject provides an introduction to physics for students in the biomedical and life sciences. Students range from those with high school physics to those with little prior experience in physics or physics experimentation.

Inquiry: In an inquiry-based laboratory module, students develop and apply knowledge of heat to the real-world problem of how the temperature inside a building varies over time, depending on heat from the sun, atmospheric conditions and the building's construction. Students are introduced to relevant knowledge and skills in stages. The inquiry-based activity is conducted after students have gained some lab experience, through guided experiments, and have met the physics concepts in lectures. To optimise development and support, it is structured as two sessions, with students working in small teams. In the first session, students start with a guided experiment investigating heat conduction. They complete several short independent experiments while becoming familiar with digital sensors. Then teams build a simple model house using a modular structure, choosing from a limited range of materials. Houses are instrumented with digital temperature sensors and placed outside for 24 hours. Students view their houses, their internal temperatures (and outside conditions) via the internet. In the second session, students discuss class data and then teams decide their own goal for the temperature of a structure (e.g. comfortable for humans, as hot/cold as possible). Students take charge of experimental design with some guidance from tutors. In each possible experimental pathway, students aim to regulate an internal temperature in a model structure exposed to a varying external environment. Each group constructs and tests their design, based on their acquired knowledge.

Assessment: After each session students download their data and write an individual report, presenting aims, methods, data and analysis. This report assesses technical skills such as using modern sensors, dealing with digital data and interpreting graphs, as well as students' ability to design and conduct investigations (based on techniques practised in guided experiments). Students must justify design choices as well as critically evaluate and interpret their data. Learning is evidenced by students successfully applying knowledge gained, e.g. final experiment designs informed by results of preliminary experiments.

Evaluation: In formal evaluation, staff involved in delivering the activity (academics and tutors) overwhelmingly agreed that "the experiment assists students to develop experimental skills" and "encourages students to think critically". Student outcomes are positive in both attitudes and learning. The activity has been very effective in engaging students in authentic scientific activity. They are interested in *their* experiments. They have to deal with problems that arise and learn more science in the process. Aspects of this activity that work particularly well are the realism of the scenario, student ownership of experiments, and controlled variation in what students do through the design choices possible (which makes the operational, supervising and marking load workable).

Case 4: Analytical tools

Subject: A first course in statistical data analysis

University: Queensland University of Technology

Author: Helen MacGillivray

Year level: First (or second) year STEM (Science, Technology, Engineering, Maths)

Subject description: This introductory statistics subject develops skills and understanding in the core statistical thinking, data analysis methods and integrated statistical investigation. Themed by the statistical data investigation process, the subject moves from types of investigations and exploratory data analysis to the statistical inference of estimation and testing built around types of variables. Introducing concepts of interval estimation and hypothesis testing in categorical data enables seamless progression to analysis of variance and multiple regressions, providing students with exciting, powerful tools to analyse real data even in their first course.

Inquiry: The statistical investigation process can be briefly described as a cycle of Problem, Plan, Data, Analysis, Discuss which reflects all aspects of statistical thinking and approaches in solving real problems, and is widely supported as an essential vehicle for student learning. Here, students combine experiential learning on real data with a semester-long group project on investigation of a topic proposed by the group and involving a number of variables. Students collect data on what interests them, discussing all stages – initial ideas, plans, problems, data collection, exploration, analysis and synthesis of interpretation – with staff. The subject emphasises student ownership in an environment designed to nurture students within the freedom of student inquiry and data-driven learning.

Assessment: The data investigation group project on topics proposed by students culminates in a full written report (20% of the marks in this subject). Formative assessment on the project includes discussing ideas and plans with staff and a written proposal identifying variables and data collection details, and meeting ethics, health and safety requirements. Exemplars, criteria and achievement standards for the project are provided and are described in terms of (i) problem, issues, plan & data collection and quality; (ii) data exploration, preparation and understanding; and (iii) analysis, interpretation and reporting. Other formative and summative assessment is aligned with the statistical investigation experience and develops and assesses operational knowledge and skills using short item response interpretations and reporting with real data, including previous student projects.

Evaluation: This subject and its data investigation projects have been successfully used for cohorts up to 600 since 1994, with ongoing research and student feedback refining and improving the subject and its resources. Qualitative and quantitative research demonstrates positive learning outcomes in student performance and engagement across disciplines and student capabilities. Feedback from graduates (including professional statisticians) is that the impact of the subject's approach greatly exceeds that of subjects using 'toy' data sets or pre-defined paths in case studies or research data. The subject's approach influences and is included in:

MacGillivray H, Utts JM & Heckard RF. (2013). *Mind on Statistics: Australian and New Zealand*, 2nd edn. Melbourne, Victoria, Australia: Cengage Learning Australia.

Case 5: Authentic research

Subject: MICR2000 – Microbiology and Immunology

University: The University of Queensland, Brisbane

Authors: Jack TH Wang, Joshua Daly, Roy A Hall, Mark A Schembri, Gene W Tyson, Philip Hugenholtz

Year level: Second year

Subject description: MICR2000 is an introductory microbiology and immunology course designed for students enrolled in science, biomedical science, biotechnology or medical programs. A core component of introductory microbiology is the ability to identify micro-organisms using a variety of diagnostic tools. A significant portion of the course revolves around laboratory sessions where students develop competencies in experimental, analytical and communication skills consistent with professional scientific standards.

Inquiry: The laboratory component of MICR2000 contains an Undergraduate Research Experience (URE) in mapping the bacterial composition of human oral cavities – the human oral microbiome. By engaging the large student cohort (> 400 enrolments annually), hundreds of oral samples were obtained from student volunteers to produce a holistic map of the human oral microbiome. Students were charged with selecting and conducting a wide variety of diagnostic tests to identify the microbial composition of the oral cavity. As this is an introductory course, the inquiry process was scaffolded with standard operating protocols for a set of core tests. Students could choose which of these tests to apply to their own oral sample, and collectively generated the diagnostic data for the entire cohort. Students then compared the diversity of micro-organisms identified using various testing approaches, and sought peer-reviewed literature to assess the validity of their findings.

Assessment: The laboratory classes (worth 25 per cent of the overall marks for MICR2000) were assessed by a weekly laboratory performance, a note-keeping mark, and a final laboratory report. The final report was formatted as a scientific publication, including introduction, methods, results and discussion sections. Students were assessed on their justification for the suite of diagnostic tests selected in mapping the oral microbial composition, their reasoning in comparing data sets generated using different testing techniques, and the effective sourcing of peer-reviewed literature to critically evaluate the validity of their findings. Written reports were submitted individually, with both written and verbal feedback provided by instructors.

Other: Student surveys before and after revealed significantly improved self-reported student learning gains in laboratory skills, confidence in designing and interpreting experiments, and in conducting scientific research overall following completion of the URE. Assessment showed high levels of student competence in maintaining accurate scientific records and sourcing up-to-date, cited peer-reviewed literature to substantiate their claims.

Wang, J.T.H., Daly, J., Patil, J., Hall, R.A., Schembri, M.A., Tyson, G.W. & Hugenholtz, P. Do you kiss your mother with that mouth? A large-scale undergraduate research experience in mapping the human oral microbiome. Submitted to the *Journal of Microbiology and Biology Education* in 2013.

Case 6: Inquiry scenario in a virtual laboratory

Subject: Biochemistry and Molecular Biology

University: Monash University and The University of Melbourne

Authors: Helen Irving and Kristine Elliott

Year level: Second year

Subject description: Biochemistry and Molecular Biology is a second year subject in the enabling knowledge stream in the Bachelor of Pharmacy. Through this subject students develop their abilities to integrate biochemical information as it relates to both desired and unwanted effects of therapeutics, and to appreciate the underlying foundation of biochemistry in the treatment of individual diseases and pathological conditions.

Inquiry: The Virtual Laboratory is an online learning environment using case studies drawn from real life to model the process of scientific inquiry. Each case presents an authentic, ill-structured problem related to a life science topic. Students assume the role of professional scientist and are guided through different stages of the scientific inquiry process towards problem resolution. This approach allows students to see how an expert might plan, design and conduct an investigation. Students perform investigations following a standardised science inquiry process requiring them to analyse the problem, formulate a hypothesis, plan an investigation, and test the hypothesis by performing virtual experiments and researching the body of available knowledge. The investigative process is explicit. The body of available knowledge is a carefully selected sub-set of information available from authoritative sources within the learning environment. Following investigation, students review their evidence (experimental data and additional information) and, if it fits their hypothesis, go on to draw and report conclusions. With a mismatch between the evidence and hypothesis, students continue further iterations of the research cycle, collecting more virtual experimental data and information, evaluating the evidence and, finally, drawing conclusions.

Assessment: Assessment of tasks using the Virtual Laboratory directly contributes to 10 per cent of the marks for this subject. It consists of tasks designed to judge students' ability to critically analyse and draw conclusions about experimental data at both an individual and group level. In the major assignment students work together as a team to develop and refine hypotheses as they work through a specific Virtual Laboratory exercise in their own time. They identify relevant data and explain the refinement of their hypotheses in addition to explaining concepts from the body of knowledge that underpin their conclusions. This task has been designed to develop collaborative team work while appreciating the processes underlying scientific inquiry. Students also work through two other Virtual Laboratory exercises where their ability to reach conclusions relating to experimental evidence and the underpinning concepts is tested individually.

The philosophical and pedagogical approaches informing the learning design that underpins each online inquiry project are described in:

Elliott, K.A., Sweeney, K. & Irving, H.R. (2009). A learning design to teach scientific inquiry. In L. Lockyer, S. Bennett, S. Agostinho & B. Harper (eds), *Handbook of research on learning design and learning objects: Issues, applications and technologies*. 652-675. Hershey, Pennsylvania: Idea Group Inc.

Case 7: Interdisciplinary problems

Subject: Chemistry for Science and Engineering

University: The University of Queensland

Authors: Gwen Lawrie, Lawrence Gahan and Kelly Matthews

Year level First year

Subject description: Large first year science cohorts typically comprise students possessing a diverse range of prior-learning experiences, professional aspirations, academic abilities, interest and motivation for their studies. Chemistry is required in many programs; however, students may not recognise its relevance or draw connections between the chemistry concepts they learn and other disciplinary contexts. An interdisciplinary scenario-inquiry task (IS-IT) for collaborative small group work has been implemented to enhance student engagement and increase the relevance of chemistry through socio-scientific thinking.

Inquiry: The IS-IT task is inquiry-guided learning where groups of four students are required to work both independently and collaboratively towards the construction of a collectively written response to an over-arching question (metaquestion) set in a contemporary context. There is no pre-determined answer to the metaquestion. The task develops interdependency among students in a group; each team member takes responsibility for retrieving a subset of information or data that are required to develop the collective response to the final question. To scaffold inquiry skills, dot point questions are provided in the individual component of the task that set the expectations for the nature of information they should retrieve. Scientific reasoning skills are applied during the collaboration phase where the group decides how to integrate the information to develop and communicate a logical response to the metaquestion.

Assessment: The task proceeds over the majority of the semester involving seven weeks of scenario selection, group formation, research and collaboration and four weeks of peer assessment. Assessment comprises four components: (i) submission of an information file by each student to the group collaboration website, thereby sharing the resources they have individually located; (ii) submission of a collectively written group report (through Turnitin) communicating their response to the metaquestion; (iii) internal peer assessment of the contributions and skills team members made during the task; and (iv) external peer review of reports submitted by other groups in response to the same scenario metaquestion, which develops skills in critical review and in reflective feedback on how other students approached the same task.

Other: The IS-IT task was developed through an ALTC Competitive Grant funding project and both the final report (including assessment rubrics) and scenario resource book are available online (<www.olt.gov.au/resources?text=IS-IT>). Learning outcomes include deeper engagement in chemistry, interdisciplinary thinking, scientific reasoning, and enhanced communication skills. Students report that they appreciate the opportunity to collaborate with other students (building on the prior experiences students bring to the task) and value the skills they have acquired in teamwork and communication for their later studies.

Case 8: Cross-disciplinary approach to inquiry

Subjects: Inquiry-oriented practical courses in first year biology, chemistry and physics

University: Monash University

Authors: Gerry Rayner, Chris Thompson and Theo Hughes

Year level: First year

Subject description: Biology, chemistry and physics are large enrolment (450–1200 students) subjects. All three subjects have laboratory and/or field-based activities that seek to deepen student understanding and apply concepts, but practicals in these units have previously relied on recipe-based approaches that do not engage students in active learning. Newly developed practical activities enable students to investigate questions, scenarios, issues and problems, in the context of the discipline studies. Students typically study in two of these subjects in parallel with inquiry practicals sharing common features.

Inquiry-oriented activities: Biology, chemistry and physics practical programs were redeveloped to include specific inquiry-oriented activities. These were badged as 'IDEA Experiments', conceived from *Inquiry-Design-Explore-Answer*, as a reference to the scientific method invoked by authentic research practice. IDEA practicals were flagged as distinctive and different from the recipe-based practicals. In biology, IDEA practical themes included pathogenicity, feeding and nutrition, and biogeochemical cycles; in chemistry, spectroscopic analysis, crystal field theory, calorimetry and kinetics; and in physics, rotational motion, magnetic field oscillations, LCR circuits and black body radiation. These activities incorporated a blend of inquiry attributes such as hypothesis testing, critical thinking, problem-solving and collaborative learning to provide guided structure for students. Students took responsibility for elements of experimental design, data collection, analysis & interpretation, and the mode of results presentation (written reports, posters or oral presentations), which increased their engagement in learning and enhanced independence.

Assessment: IDEA practicals were assessed in the same manner as other practicals, with the value ascribed dependent on the time over which students conducted each practical or project. Assessment is based on varying combinations of: (i) submission of experimental design plans for feedback and refinement; (ii) submission of laboratory reports for evaluation, annotation and feedback; (iii) student laboratory performance, assessed by proficiency in equipment use, group interactions and discussions; (iv) peer and teaching associate assessment of group work such as posters and PowerPoint presentations, based on weighted rubrics; (v) submission of student-derived answers, drawings and figures for evaluation, annotation and feedback; and (vi) summative assessment of learning through end-of-practical tests and quizzes.

The IDEA practical framework and template is being extended to second year subjects where inquiry approaches are less structured and more open-ended., thus enhancing student skills in independent learning and problem-solving.

Rayner, G., Charlton-Robb, K., Thompson, C. & Hughes, T. (2013). Interdisciplinary collaboration to integrate inquiry-oriented learning in undergraduate science practicals. *International Journal of Innovation in Science and Mathematics Education, 21*(3).

Case 9: Scaffolding gradual development of skills

Subject: Core first year Biology

University: Flinders University, Adelaide

Author: Karen Burke da Silva

Year level: First year

Subject description: First year Biology is core for all Biology degrees and for 35 other degree programs it is core or elective. With no pre-requisite for these subjects, students are from different backgrounds –some with little/no science or Year 12 biology. Students develop a basic understanding of the molecular basis of life and the evolution of biological diversity.

Inquiry: The laboratory program in first year Biology focuses on developing critical thinking and problem-solving through inquiry. Practical activities are aligned to lectures to provide relevance and understanding of core concepts. A scaffolded approach is needed to deal with the range of student background knowledge and ability, starting with highly structured guided inquiry moving through to fully open-ended research projects by the end of the year. Conduct of an open-ended research project as part of their first year experience provides all students with an opportunity to act as a scientist. The research project integrates concepts and principles students have learned earlier in the year and formalises inquiry skills. Scaffolding of learning increases confidence and open inquiry enables high achieving students to excel and investigate an area of their own interest. As students develop open-ended inquiry, the role of the demonstrator shifts from that of teacher to facilitator. Each stage of the research project requires demonstrator approval before progression to build in scaffolded support. Students work in groups to develop a testable question and then design an experiment to appropriately answer their question, which is reviewed by the demonstrator. Finally, students conduct their experiment and analyse their data during workshops that provide guidance on statistical analysis. The research project is presented in poster format in a year-end poster competition where students communicate their findings to their peers and to academic staff. Prizes are awarded for the most outstanding research.

Assessment: The assessment of the practical activities is 50 per cent of the overall subject assessment: laboratory component (35 per cent) and the research project (15 per cent). For each practical activity students are assessed primarily on their ability to design, conduct, analyse and discuss their experiments. Initial reports requiring students to simply fill in a report template build to the final assessment, which requires a full scientific report with complete data analysis and literature cited. Practical sessions include group discussion, which must be used as part of the written report. Poster presentation includes answering questions from academic staff and students. Top prizes are allocated according to poster grade and student ability to discuss their findings during presentation. Several top research projects have been further developed by students through summer research scholarships or higher level subjects including honours.

Burke Da Silva, K.L. (2012). Evolution centered teaching of Biology. *Annual Review of Genomics and Human Genetics*, *13* 363–380. [Online]. Available from <http://dx.doi.org/10.1146/annurev-genom-090711-163749>

Case 10: Capstone research

Subject: Chemistry projects within the capstone course/subject ONPS 2186 Science Project

University: RMIT

Coordinators: Jeff Hughes (Chemistry) and Neale Jackson (School of Applied Science)

Year level: Final year

Subject description: This multi-disciplinary subject is the work-integrated learning (WIL) capstone for Applied Science degrees. Students in these degrees study in a wide range of disciplines, each of which contributes projects into the capstone experience. The subject has a total enrolment of over 350 students each year of whom ~35 study in Chemistry. In this subject, students integrate the knowledge and skills acquired in the laboratory, studio, fieldwork and/or industry experiences of their major discipline with skills in problem-solving and apply this to a project in a manner similar to that experienced in employment. This course is normally taken in the final semester of the degree program.

Inquiry: Students majoring in Chemistry undertake an authentic research project selected from a list of projects linked to research interests of Chemistry staff or can negotiate directly with staff to build a project that meets the interests of the student. It is most important that any project chosen must have clear research questions and be an investigation, not just 'work experience'. This is particularly relevant if the project involves working with external bodies or carrying out the work in industrial labs. During the project, the student is treated as a real member of the research group. With the guidance of their supervisor, students must organise a plan to carry out the research within limitations imposed by laboratory time available, instrument resources and costs, and availability of chemicals. The project must have feasible objectives given the abilities of the student. An important requirement prior to commencing laboratory work is the thorough investigation of the safety aspects of the project by completing a risk assessment. During the project, students have regular meetings with their supervisor to discuss progress and possible adjustment of the project. Other laboratory members also act in a supervisory capacity, so students must learn to discuss their work with other scientists not necessarily familiar with the specific research area.

Assessment: The project is assessed by a research report (67 per cent) and by performance in the research laboratory (33 per cent) as is common for an honours year. The research report uses a conventional format (abstract, introduction, materials and methods, results, discussion) with the addition of a formal risk assessment. The assessment criteria include presentation, referencing, the quality and quantity of the experimental work, analysis and interpretation of data. The performance mark is determined by the research supervisor based on capacity to plan and conduct the investigation. The report is expected to be at a professional standard. Students often produce their reports at job interviews and many students have obtained a position on the basis of their report.

External reference points: This subject has been closely mapped to each of the program learning outcomes for inquiry and problem-solving. The program learning outcomes for this subject match directly to the draft Chemistry TLOs (<chemnet.edu.au>), which are derived from the Science TLOs.

Case 11: Inquiry curriculum for undergraduate research

Subjects: Physiology speciality (five subjects) in a Biomedical Science major in B Sc

University: The University of Queensland, St Lucia

Authors: Kirsten Zimbardi, Kay Colthorpe, Lesley Lluka, Prasad Chunduri, Aaron Smith

Year level: First, second and third years

Subject sequence: The five, semester-length (13-week) subjects comprise a fixed sequence through first-, second- and third-level subjects of a major in biomedical science (specialising in physiology). Most students are enrolled in a three-year Bachelor of Science (BSc), a four-year dual degree combining BSc with another degree, or a four-year research-focused Bachelor of Biomedical Science. Typically, enrolments are ~800 students (Level 1), 400–600 students (Level 2) and 80–150 students (Level 3).

Inquiry: These vertically-integrated, inquiry-based, 'hands on' practical curricula have been designed to incrementally develop students' scientific thinking, communication and technical skills accompanied by a reduction in scaffolding and an increase in student autonomy and ownership of the research projects. Vertical integration between the subjects ensures that students are gradually introduced to more advanced and complex aspects of scientific thinking, experimentation and communication (see Table 3 below). Specifically, the first subject (Yr 1, Sem 2) emphasises the generation of testable and falsifiable hypotheses, matching hypotheses to appropriate methodological approaches using whole animals or tissues, and execution of basic technical and quantitative skills. The second subject (Yr 2, Sem 1) builds on these skills with greater autonomy in research design, and introduces clinical studies, statistical analyses and the interpretation of findings in relation to scientific literature. The third subject (Yr 2, Sem 2) furthers students' critical analysis of their findings in relation to literature, extends students into large, collaborative, clinical experiments and introduces students to skills in oral argument. The fourth subject (Yr 3, Sem 1) builds on students' skills in oral argument with a series of oral journal article reviews modelled on expert researcher workshops, whilst introducing students to cutting edge research techniques. Finally, the fifth subject (Yr 3, Sem 2) extends students' technical skills in a full range of macro to molecular methods, and inducts students into the professional scientific community with several assessment items focusing on accountability for research documentation, peer review and professional discussion.

Assessment: In each subject, the laboratory component constitutes 25–40 per cent of the summative assessment and is designed to students' skills in designing, conducting, interpreting, communicating and critiquing their experiments in relation to the published literature. Assessments progress from a scaffolded scientific report in Level 1 supported by an online manual (LabTutor, ADInstruments, NZ) (Level 1), to full written research proposals and reports using disciplinary conventions (Level 2), to scientific oral presentations (Levels 2–3) and authentic, peer-reviewed outputs approaching professional research standards (Level 3). See annotated examples at : <dev.ceit.uq.edu.au/vcop2/course/inquiring-minds> and further information: kzimbardi.pbworks.com.

Zimbardi K., Bugarcic A., Colthorpe K., Good J.P. & Lluka L.J. (in review). A set of vertically-integrated inquiry-based practical curricula that develop scientific thinking skills for large cohorts of undergraduate students. *Advances in Physiology Education*. Submitted 2013.

Table 3: Vertical integration of inquiry-based practical curricula across five semesters of a biomedical science major specialising in physiology

		Progression	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5
Subject code and name			BIOL1040: Cells to Organisms	BIOM2011: Integrative Cell and Tissue Biology	BIOM2012: Systems Physiology	BIOM3014: Molecular & Cellular Physiology	BIOM3015: Integrative Physiology & Pathophysiology
Timing			Year 1, Semester 2	Year 2, Semester 1	Year 2, Semester 2	Year 3, Semester 1	Year 3, Semester 2
Project duration		Increase depth, then increase breadth	5x3hr classes	2 blocks of 2x3hr + 1x1.5hr classes	1 block of 6x3hr classes	2 blocks of 3-4x 1-3hr classes	3 blocks of 1-3x3hr classes + independent lab time
Assessment		Increase in scientific complexity and professionalism	5 reports (4 summative); 4 core competencies	2Two experimental plans, 2 proposals and 2 reports (1/module)	1 draft hypotheses and methods, 1 proposal presentation, 1 report	2 quizzes, 2 journal article review presentations, 1 report	3 online lab books, 1 poster presentation with peer review, 1 professional letter
Openness of curricula	**Autonomy and independence**	Increase	LabTutor scaffolds each stage of experiments from hypothesis to discussion. Teaching assistants provide progressively reduced guidance to students across the semester.	Manuals for experimental paradigm. Example research questions and experiments. Teaching assistants provide guidance throughout, but students are expected to be working autonomously in the final class of each block.	Skill building experiments in the first two classes. Students use primary literature to develop research questions and experiments. Teaching assistants provide guidance throughout, but students are expected to be working autonomously in the majority of the classes.	Two expert workshops on current research from guest researchers precede students choosing related recent journal articles to present as critical reviews. Advanced cellular and molecular experiments with sequential steps split across cohort.	Given brief overviews and lab book templates for 3 diverse research areas, students design, conduct, analyse and interpret their own research.
	Student ownership of research question	Increase	4 set topics for which students begin by choosing a hypothesis from a set of examples and end with designing their own hypothesis and methods.	2 broad fields for which students can design their own experiment or choose from a set of example experiments.	Students are given freedom to investigate any aspect of cardiovascular, respiratory, renal and metabolic physiology in response to a wide range of perturbations.	Students have freedom to choose any articles loosely related to field or techniques of the expert workshops. Students need to collaborate across cohort to amalgamate entire experiment.	At all stages, students decide their research objectives. Students write a formal proposal as a professional letter to a UQ researcher working in the area of one of their three research projects.
Learning objectives	**Scientific thinking and experimentation**	Increase in complexity and difficulty	Hypothesis generation and experimental design. Basic technique with animal tissue.	Detailing the methods, statistical analysis, and interpretation of results. Basic animal and clinical experiments.	Integration of experimental design and findings with primary literature. Large scale, complex clinical experimentation.	Critical review of cutting edge of current research. Coordination of large collaborative research group. Cutting edge cellular and molecular techniques.	Understanding and developing skills in the professional etiquette of science. Professional accountability for documentation of research. Cutting edge cellular and molecular techniques.
	Scientific communication	Reduction of scaffolding. More advanced aspects of scientific writing and oral presentation.	Strategic questions scaffold entire report writing process. Core competencies ensure appropriate data representation methods.	Formal proposals, formal reports. Students provided guidelines and lectorials. Emphasis on genre conventions for methods and results	Verbal proposals, formal reports. Emphasis on integration of primary literature in introduction, methods and discussion.	Formal presentations modeled off expert workshops from leading researchers. Emphasis on integrating findings from collaborative efforts in formal report	Symposium uses two different angles on one research agenda – students present their work and are responsible for questioning, discussing and critically evaluating the work of peers from both methods. Professional letter combines justifiable research proposal with conventions for approaching potential research supervisors.

Directions in curriculum for inquiry and problem-solving skill development

Examples of inquiry and problem-solving tasks are accumulating in the higher education literature. Some emerging areas of focus are described below.

Whole of curriculum approach: Examples of the systematic development of students' scientific inquiry and problem-solving skills through the curriculum from first to final year are quite rare, but vital if such development is not to be left to serendipity or the endeavor of a few individuals. Inquiry pedagogies, such as problem-based learning, have been applied to whole degrees and even across institutions, demonstrating the potential of an integrated approach. Table 3 from work at The University of Queensland is a useful example of how activities supporting TLO 3 can be linked vertically through the curriculum, allowing students and academics to recognise a sequenced and reinforced development of inquiry and problem-solving.

Cross-disciplinary initiatives: Students, especially in their first year of a science, experience cultures and conventions that differ significantly across the physical and life sciences: a physicist's approach to problem-solving may appear to students to be quite different from that of a biologist. If academics engineer situations using cross-disciplinary approaches, students can see the common ground shared by science and also appreciate the strengths of diverse approaches. Case Study 8 from Monash University describes the co-development of a common philosophy between biology, chemistry and physics to develop activities that move away from those that could be characterised as recipe-type experiments to more inquiry-oriented activities. This initiative represents a significant development in the Australian science education landscape that could act as a starting point for others with similar ambitions.

Technology: The use of instructional tools that exploit the power and versatility of ICT to support inquiry and problem-solving will continue to grow. Simulations, remote laboratories and augmented reality, in which students interact with virtual and real objects, have the potential to engage students in activities that enhance their scientific inquiry skills (Chen et al., 2012). Computers have been used for decades to assist in the capture and analysis of data. The ever-increasing power, versatility and portability of computer-based technology means their role in enhancing students' scientific inquiry skills will continue to expand.

As an example, mobile devices such as iPads, allow students the flexibility of carrying out inquiry-type activities in almost any setting and at any time. Students, through their own initiative, are already capturing events using cameras on these devices, which can later be analysed. IPads and Android tablets can be connected using Bluetooth to sensors (for example, measuring air quality, pH, light intensity and sound levels) allowing data capture in real time (see, for example, <www.pasco.com/family/sparkvue-hd-for-ipad/index.cfm>). Similar options have also been developed for smartphones and will expand over time. With the computing power of these handheld devices increasing exponentially with time, it is not difficult to imagine many lab- and field-based investigations (for example, a study of lead pollution in the environment) being preferentially conducted with the aid of sensors connected wirelessly to iPhones or similar devices. These devices allow students to search the internet for information and expedite the analysis and presentation of data.

Partnerships with research and applied science: As inquiry is intrinsic to the practice of science, links between researchers, applied scientists and educators are an obvious way to make inquiry tasks authentic and meaningful for students. Large-scale involvement of undergraduate students in real research projects is beginning to appear more frequently (see Case Study 5). This process is assisted by the advent of 'big science' and systems biology where collection and analysis of large data sets make a tangible contribution to knowledge. Undergraduate students involved in research become participants in science and are more exposed to the passion that drives discovery.

Evaluation: Inquiry is a complex and nuanced activity and, consequently, is equally complex to assess. The lack of comparable measures of achievement for inquiry and problem-solving has hampered efforts to evaluate inquiry curricula. Educators are beginning to look beyond student satisfaction surveys to student self-assessment, validated problem-solving tests and peer review to measure efficacy. Henderson, Beach and Finkelstein (2011) note the importance of collaboration between evaluation experts and those promoting curriculum change.

Communities and forums supporting TLO 3 in Australia

Peer discussion and collaboration within and across institutions can be powerful initiators of curriculum reform and development. Colleagues wishing to explore or compare approaches to developing students' scientific inquiry and problem-solving capacities (and other TLOs) require an active and enthusiastic national community with opportunities to connect to, and interact with, other academics. In Australia, the ACSME conference (Australian Conference for Science and Maths Education), organised by the Institute for Innovation in Science and Mathematics Education (<sydney.edu.au/iisme/conference/>), and the Australian Council of the Deans of Science education conferences (<www.acds.edu.au/tlcentre/>) are prominent forums through which to promote national teaching and learning conversations.

Discipline-based networks and some scientific societies also offer opportunities for peer exchange of learning and teaching. The Office for Learning and Teaching recently funded the establishment of discipline-based education networks (Chemnet, CUBEnet, VIBEnet, AMSLaT) with others developing in parallel (Physnet). These groups have had a strong focus on graduate outcomes and the translation of the Science TLOs into disciplinary study. New connections groups are also emerging through other OLT-funded projects and initiatives. Together with the education and scientific meetings, they provide fertile ground to develop peer collaborations and to generate new ideas for supporting and promoting inquiry and problem-solving.

Education networks

ACDS Teaching and Learning Centre: <www.acds.edu.au/tlcentre/>

AMSLaT: <www.amslat.edu.au>

Chemnet: <chemnet.edu.au>

CUBEnet: <www.cubenet.org.au>

Physnet: D.Hoxley@latrobe.edu.au

VIBEnet: <sites.google.com/site/vibenet101>

SaMnet: <www.SaMnet.edu.au>.

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