Science literature review addendum

Senior syllabus redevelopment

February 2016

Queensland Government

Queensland Curriculum & Assessment Authority

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For all Queensland schools

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Key findings

- Examinations consisting of multiple-choice, short response and/or extended response items are the usual form of external assessment in senior science across other jurisdictions.
- In most jurisdictions, the external examination contributes at least 50% of a student's overall result. In South Australia, the external examination contributes 30%; this is the only jurisdiction that has a system of moderation of internal assessment that is comparable to the moderation system in Queensland.
- In the Australian states reviewed, Year 11 is assessed internally; Year 12 is assessed using a combination of internal and external assessment. Only Year 12 assessment results contribute to a student's final result for the subject.
- Most jurisdictions do not prescribe the techniques used for internal assessment. However, they usually prescribe the knowledge and skills assessed and the relative contribution of these components.
- Across jurisdictions, the most commonly used internal assessment techniques in science are student-designed practical investigations, research investigations, examinations and reports of practical investigation/s.
- Most science syllabuses support an approach that involves contextualisation; however, this is not usually reflected in the design of external examination items.
- The majority of learning expectations identified in science syllabuses are categorised as either science understanding or science inquiry skills. Science syllabuses usually also identify an additional set of learning expectations related to the societal or philosophical nature of science. These expectations are variously described using labels such as science as human endeavour, 21st century skills or the nature of science.
- A number of issues have been identified with the current Queensland suite of science syllabuses. These include:
  - standards that are difficult to understand and apply
  - methods of making judgments about student work that result in variable interpretation and application
  - a lack of clarity about assessment conditions and the design of assessment programs
  - a disproportionate focus on tasks requiring extended written responses
  - the need for a clear list of content knowledge to be covered by all schools.
- The science education literature outlines two visions for science education: traditional/disciplinary and contextual/interdisciplinary.
- The issues used to justify recommendations for the reform of science education are the:

  - general population’s lack of understanding about how science works (scientific literacy)
  - shortage of students undertaking science, technology, engineering and mathematics (STEM) related tertiary studies (the STEM pipeline problem).
- Fundamental components of a science education are:
  - domain-specific knowledge
  - an understanding of the processes of science
  - skills such as analysis of problems, evaluation of evidence and the ability to research new information.

  Different stakeholder groups value these components differently.
- In order to be able to apply higher-order thinking and undertake inquiry-based assessment, students need to first attain foundational knowledge and skills.
- Constructivism and minimally guided pedagogical approaches to teaching and learning are increasingly criticised in the educational literature. These approaches to teaching and learning should not be conflated with teaching the processes of scientific inquiry.

Methodology

This addendum to the *Science literature review: Senior syllabus redevelopment* has been collated from research carried out by officers of the Queensland Curriculum and Assessment Authority (QCAA). It has been written to provide further information about issues that were raised in the literature review. This work comprised of a number of phases:

1. A desktop scan of current practice in a number of Australian and international jurisdictions was performed. This consisted of a review of relevant syllabus documents and, where available, samples of past external assessment instruments.

   The jurisdictions considered were:

   - those considered in the literature review, i.e. New South Wales, Victoria, Western Australia, the United Kingdom, Ontario, and New York State
   - South Australia, chosen because it represents an assessment system that combines external assessment with school-based assessment that is externally moderated using processes similar to those currently used in Queensland
   - the International Baccalaureate (IB), chosen because is an internationally recognised system that combines external and internal assessment results without scaling.
2. A summary of issues associated with the current suite of Queensland science syllabus was compiled by considering:
   - the recommendations from *The Assessment Methods Used in Senior Mathematics, Chemistry and Physics in Queensland Schools* (Education and Innovation Committee 2013)
   - unpublished comments provided in response to the *Senior curriculum and assessment working groups' survey* (Queensland Curriculum and Assessment Authority 2015).
3. A review of current science education literature was performed.

Findings were considered in relation to their impact on assessment, pedagogy, course structure and learning expectations.

Desktop scan of current practice in other jurisdictions

The scan of current practice considered a number of jurisdictions. The Australian jurisdictions were New South Wales,[1] Victoria,[2] Western Australia[3] and South Australia.[4] International jurisdictions were Ontario (Canada),[5] the United Kingdom (Assessment and Qualifications Alliance, or AQA),[6] New York State (USA)[7] and the International Baccalaureate.[8]

Assessment

External assessment

With the exception of Ontario, some form of external assessment is used in all the jurisdictions considered. The contribution of this external assessment to the overall student result ranges from 30% (South Australia) to 100% (United Kingdom); in most jurisdictions, it contributes at least 50%.

Wherever external assessment is used in science subjects, it takes the form of a supervised examination comprised of multiple-choice, short response and/or extended response items. Items range in complexity from low-order application in familiar situations to some high-order stimulus response and data-analysis items. Some items are specifically linked to prescribed or recommended practical activities. Items are not usually contextualised, even when syllabus documents indicate that material can be covered using a contextualised approach. However, contexts identified in syllabus documents can be used as case studies in stimulus-response items or as examples in student responses.

The amount of the course covered by the external examination varies. In some jurisdictions (e.g. the United Kingdom), it covers the entire two-year course. In Australian jurisdictions, the external examination covers the latter half of the course only, i.e. Units 3 and 4. In some jurisdictions (e.g. United Kingdom), a set number of items also refer to prescribed practical activities. Some jurisdictions (e.g. New South Wales) produce options papers to accommodate the flexibility in course structure allowed by the syllabus.

[1] HSC Syllabuses www.boardofstudies.nsw.edu.au/syllabus_hsc
[2] VCE studies www.vcaa.vic.edu.au/Pages/vce/studies/index
[3] WACE 2015-2016 wace1516.scsa.wa.edu.au/syllabus-and-support-materials/science
[4] SACE www.sace.sa.edu.au/learning/learning-areas/sciences
[5] The Ontario Curriculum: Secondary www.edu.gov.on.ca/eng/curriculum/secondary/science
[6] AQA AS and A-level Science www.aqa.org.uk/subjects/science/as-and-a-level
[7] New NYS P-12 Science Learning Standards www.p12.nysed.gov/ciai/mst/sci/ls
[8] IB Diploma Programme: Sciences www.ibo.org/programmes/diploma-programme/curriculum/sciences

Internal assessment

In all the Australian states considered, assessment of Year 11 (i.e. Units 1 and 2) learning is entirely internal. This assessment does not directly contribute to a student's final result for the subject. This final result is based on the learning in Year 12 (i.e. Units 3 and 4) which is assessed using a combination of internal and external assessment. This differs from some international jurisdictions where a student's result is based on internal and external assessments covering the entire course.

Most jurisdictions provide relatively little prescription over the internal assessment techniques used by schools. However, they usually prescribe the knowledge and skills to be assessed and the relative contribution of these components to the overall result, as shown in Figure 1 for Higher School Certificate (HSC) Biology (Board of Studies NSW 2009, p. 6).

Figure 1: Mandatory components and weightings HSC Biology internal assessment[9]

Component	Weighting (%)
Knowledge and understanding of: • the history, nature, and practice of biology, applications and uses of biology and their implications for society and the environment, and current issues, research and developments in biology • cell ultrastructure and processes, biological diversity, environmental interactions, mechanisms of inheritance and biological evolution.	40
Skills in: • planning and conducting first-hand investigations • gathering and processing first-hand data • gathering and processing relevant information from secondary sources.	30
Skills in: • communicating information and understanding • developing scientific thinking and problem-solving techniques • working individually and in teams.	30

The International Baccalaureate and Victoria are more prescriptive with regard to internal assessment. For example, Victoria Certificate of Education (VCE) Physics has the following internal assessment requirements for Unit 3 (Figure 2) (Victorian Curriculum and Assessment Authority 2012, p. 30).

[9] Other conditions include no more than 50% weighting allocated to tests and examinations, and 3–5 assessment tasks.

Figure 2: Internal assessment specifications for VCE Physics Unit 3

Outcomes	Marks allocated*	Assessment tasks
Outcome 1 Investigate motion and related energy transformations experimentally, and use the Newtonian model in one and two dimensions to analyse motion in the contexts of transport and related aspects of safety, and motion in space.	40	At least two different tasks selected from the following:** • a student-designed extended practical investigation • a summary report of selected practical activities from the student's log book • a multimedia presentation • a data analysis • a report (written, oral, annotated visual) • a test (short answer and extended response) • a response to a media article.
Outcome 2 Investigate, describe, compare and explain the operation of electronic and photonic devices, and analyse their use in domestic and industrial systems.	30	
Detailed study One detailed study is to be chosen in either Unit 3 or Unit 4, and will contribute to the study score at Unit 4.		**Across the assessment tasks selected in Unit 3 and 4, at least one of the assessment tasks must be an extended practical investigation and at least one of the assessment tasks must be a summary report of selected practical activities.
Total marks	**70**	

*School-assessed Coursework for Unit 3 contributes 16 per cent to the study score.

Commonalities to internal assessment techniques across jurisdictions are listed below.

- Student-designed practical investigations designed to assess investigative skills such as experimental design, and data analysis and evaluation. This technique is quite similar to the extended experimental investigation (EEI) technique used in Queensland science syllabuses, although usually with a greater degree of prescription around the choice of research question and the conditions of the response.
- Research investigations designed to assess scientific literacy, especially interpreting scientific texts. Like the student-designed practical investigations above, the range of topics for investigation is sometimes prescribed by the syllabus.
- Examinations or tests that usually reflect the design brief of the associated external examinations but cover different content, e.g. Units 1 and 2.
- Reports of practical investigation/s that differ from the student-designed practical investigations in that students are given the method of investigation (chosen by the teacher, sometimes from a prescribed list). The report focuses on data analysis and presentation of scientific information. In some jurisdictions, reports from a number of different investigations are assessed as a folio.

Pedagogy

None of the syllabuses considered prescribed a particular pedagogical approach. Some syllabuses encourage or support the use of a contextualised approach to teaching and learning. However, none of the jurisdictions use contextualised external examination items.

Learning expectations

Some jurisdictions, e.g. Ontario, structure their syllabus documents in a way that provides clear, cohesive links between different science syllabuses. All of the jurisdictions considered describe the learning expectations more specifically and prescriptively than current Queensland syllabuses.

Learning expectations are usually classified according to some variant of discipline knowledge and scientific process skills. Some jurisdictions specify particular practical experiments that must be completed, or prescribe a minimum quantum of hours that must be spent on practical work. Some also identify particular numeracy and literacy skills to be developed.

Additionally, most syllabuses identify a range of other learning expectations related to the societal impact of science and/or philosophical issues, which are described with various titles such as science as human endeavour, 21st century skills or how science works. In some cases, these learning expectations are linked to specific units; in other cases, they are integrated in a general manner across the course of study. There is also a trend towards valuing learning in areas such as global citizenship, sustainability, integration, and STEM. However, the value placed on these types of learning outcomes by syllabus documents was not always reflected in the style and composition of external examinations.

Syllabuses for external examination systems were characterised by a distinct lack of flexibility in learning expectations. Most described a linear course structure, composed largely of prescribed sequential units. Some syllabuses provided options.[10] Some, like Western Australia, offer flexibility through additional strands, e.g. Australian Tertiary Admission Rank (ATAR) or non-ATAR; Human Biology in addition to Biology.

[10] For example, the NSW HSC Chemistry course consists of 90 hours of core and 30 hours of options, with all students required to complete one of the options. This is reflected in the external examination which consists of 75 marks based on core modules and five options questions each worth 25 marks. Students are required to answer at least one option question (Board of Studies NSW 2002).

Issues identified with Queensland Science syllabuses

The Education and Innovation Committee's report *The Assessment Methods Used in Senior Mathematics, Chemistry and Physics in Queensland Schools* (2013) identified a number of issues with the current chemistry and physics of Queensland science syllabuses which were the basis for its recommendations.[11] Although the terms of reference of the report limit it to a discussion of the chemistry and physics syllabuses (for science), responses to the 'Senior curriculum and assessment working groups' survey' (QCAA 2015) suggest that many of these issues have relevance across the suite of science syllabuses. These survey responses also raise additional issues that were not identified by the report.

Assessment

Standards and judgments

- The current standards require a high degree of professional judgment and need to be more clearly articulated to support teachers in assessing student achievement.
- The methods of grading assessment tasks are not clearly described in the syllabuses or supporting documents.
- There is a perceived 'ban' against using numerical marks when assessing student work.

Design and implementation of assessment instruments

- Assessment techniques are too focussed on discovery and investigation, and should be focussed more on knowledge.
- The expectations surrounding the scope of EEIs and extended response tasks (ERTs) have not been modelled to support teachers.
- There is a lack of clarity with regard to assessment conditions, which has resulted in the inconsistent implementation of assessment and the inconsistent application of the standards across schools.
- EEIs and ERTs take up too much time (in class and at home), and require overly long written reports.
- Written reports and assignments disadvantage students with poor literacy skills.
- The current assessment techniques do not ensure authentic student work.

[11] Some of these issues arguably reflect stakeholder misconceptions about the content of these syllabuses and supporting documents. Others have been addressed through syllabus amendments or professional development subsequently provided by the QCAA. However, they are nevertheless instructive to the redevelopment of the senior science syllabuses.

Design of assessment packages

- The syllabuses do not seem to state an upper limit to the number of inquiry-based assessment tasks a student can do.
- The number of school-based assessment items is too large, creating an excessive load for teachers and students.
- The amount of time and work associated with extended assessment tasks is disproportionate to their contribution to a student's overall achievement.
- No two schools follow the same work program, teach the same topics or set and mark the same assignments and exams. Critics argue that performance comparisons between schools and between students from different schools are meaningless.[12]
- The current assessment practices, although seen as a good learning tool, apply too much workload, time pressure and stress on teachers as they implement them and other supporting activities within their classroom.

Description of learning expectations

- The syllabuses do not place enough emphasis on content knowledge and focus too heavily on 'higher order skills'.
- The description of learning expectations is vague. The syllabuses have lost much of the content (including mathematics) required for successful entry into tertiary science and engineering programs. Syllabuses should have a clear list of subject specific content to be covered in each discipline.
- Content should be specified in a particular order to cater for students who move schools throughout their senior years.
- More detail is required within syllabuses to support teachers who lack specialist qualifications or who are teaching outside of their field.
- The syllabuses are not well understood in relation to the set of clear and high expectations of what students are expected to do/achieve.

[12] Queensland undertakes random sampling each year to evaluate the quality of school-based assessment programs and the comparability of teacher judgments of student achievement, with the purpose of answering the key question: 'How consistently do teachers around Queensland apply syllabus standards in determining students' levels of achievement in Authority subjects?' (QCAA 2015, p. 1). For an independent review of this process, see Marion, Peck and Raymond (2011).

Trends in science education literature

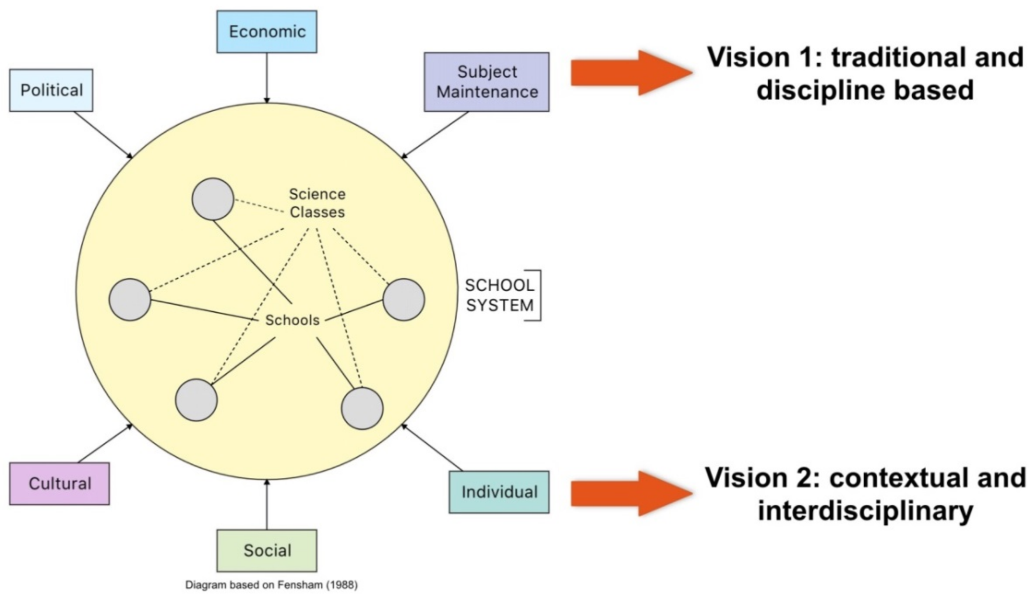
The following section provides a summary of the science education literature relevant to the development of the Science Learning Area senior syllabuses.

The purpose of science education

Science has a huge impact on society. It is hardly surprising, therefore, that society has a huge impact on the nature of science education. Fensham (1998) outlines this impact with a model (developed in conjunction with David Layton) that uses the relative weight of influence of six competing societal demands — political, economic, subject maintenance, cultural, social and personal — on school science education for determining its character.

The results of these factors can broadly be characterised, using a heuristic developed and described by Roberts (2007), as 'Vision 1' and 'Vision 2' of scientific literacy (see Figure 3). Vision 1 uses the knowledge and skills of science disciplines as the starting point for teaching science, which Roberts describes as '... looking inward at the canon of orthodox natural science, that is, the products and processes of science itself' (2007, p. 730). Vision 2 uses contexts or situations as a starting point for teaching science, where scientific literacy is defined as literacy '... about science-related situations in which considerations other than science have an important place at the table ... [starting] with situations, then reaching into science to find what is relevant' (Roberts 2007, p. 730).[13]

Figure 3: Competing societal demands on school science education for determining its character



[13] These visions can be considered as opposite ends of a continuum, where most would likely identify their values as lying on a point between either end, tending to one or the other, but not at the extremities.

The push and pull of these factors are evident in science curriculums, educational research, and government and industry reports, which reveal the following issues in science education:

- The general population does not understand how science works (scientific literacy).
- There is a shortage of students undertaking STEM-related tertiary studies (the STEM pipeline problem).
- There is a need to develop in students:
  - a solid foundation in science knowledge, understanding, skills and values
  - an interest in science and an understanding of how science works
  - problem solving, critical thinking and reasoning skills.

The 2013 report *STEM: Country comparisons* points out that science education prepares students for

> … a broad range of occupations, including management … a generic vocational role as well as enabling entry to specific occupations. [Further] … governments want to lift the overall scientific literacy of their populations and to draw most students or all students into senior secondary school studies in STEM ('science for all') (Marginson et al. 2013, pp. 13–14).

In this view, then, science education serves two purposes — feeding human capital into STEM related careers and jobs in the economy, and developing scientifically literate citizens as a part of a broad liberal education. These two goals are not at odds. Secondary science curriculums can prepare students for further tertiary study in STEM disciplines by describing domain-specific content (that is, facts and processes that are unique to the discipline) that students are to be taught, whilst maintaining a clear focus on developing scientifically literate citizens.[14]

A recent study commissioned by the Australian Council of Deans of Science (Harris 2012) echoes the necessity of balancing these two goals. Examining the role that science has played in scientifically trained people's lives (personally and professionally), the study found that:

- people who identify themselves as scientists are in a wide variety of workplaces and have diverse roles in society
- a science background is strongly associated with a particular way of thinking that is analytical, objective, evaluative and questioning. Scientists are lifelong learners and problem solvers
- knowledge is a fundamental component of a science education, as is an understanding of the processes of science
- skills that were most strongly associated with science include:

[14] The senior secondary Australian Curriculum Physics, for example, makes this clear, stating:

> Studying physics will enable students to become citizens who are better informed about the world around them and who have the critical skills to evaluate and make evidence-based decisions about current scientific issues. The subject will also provide a foundation in physics knowledge, understanding and skills for those students who wish to pursue tertiary study in science, engineering, medicine and technology (Australian Curriculum, Assessment and Reporting Authority (ACARA), *Physics: Rationale/Aims*, www.australiancurriculum.edu.au/seniorsecondary/science/physics/rationaleaims).

- analysis of problems
- evaluation of evidence
- the ability to research new information

- workers in scientific research were more likely to specify the importance of domain-specific knowledge; workers outside research were more likely to discuss application of skills.

The results of this study are consistent with previous national and international research involving interviews with key stakeholders.[15]

Developing scientific literacy

Given the issues identified in the literature above, it is understandable that science education research in Australia and internationally has focused significantly on scientific literacy. The literature often describes an idealised way in which science educators believe science ought to be taught, usually advocating contextualised science teaching and developing scientific literacy.

The paper *Science Teaching and Learning in Australian Schools: Results of a national study*, commissioned by the Commonwealth Government, reported on a large-scale study that investigated the quality of teaching and learning in science in Australian schools. It recommended that:

> … the Australian Commonwealth Government assist educational jurisdictions to reform assessment practice so that assessment more effectively serves the purpose of improving learning. Assessment must focus on the learning outcomes associated with scientific literacy.' (Rennie, Goodrum, & Hackling 2001, p. 492)

Scientifically literate citizens are able to consider the impact science has on society, apply critical thinking to new technologies and associated issues, and know how to demarcate between trustworthy and untrustworthy sources. They see science as constantly evolving and interdisciplinary, understand uncertainty and risk, and appreciate that scientific issues are complex and include other interconnected issues (Tytler 2007, pp. 26–27).

The *Australian School Science Education National Action Plan 2008–2012* echoes this, arguing that the fundamental purpose of school science education is developing scientific literacy (Goodrum & Rennie 2007). This message is further reinforced in the 2014 report from the Office of the Chief Scientist *Science, Technology, Engineering and Mathematics: Australia's future*. It recommends that scientific literacy be developed in schools by:

> - … mandating study of the scientific method, the philosophy of science and the history of scientific discovery

[15] See Fensham (2004) for example.

- helping schools to teach STEM as it is practised, in ways that engage students, encourage curiosity and reflection, and link classroom topics to the ‘real-world’ (Office of the Chief Scientist, 2014, pp. 23).

It also argues that:

- ‘… curricula and assessment criteria … [should] promote the development of long-lasting skills — including quantitative skills, critical thinking, creativity, and behavioural and social skills — in parallel with disciplinary knowledge
- the skills of STEM graduates [should be] aligned with workforce needs [in part] through:
  - fostering partnerships between schools, higher education institutions, training providers and employers
  - identifying how required skills can be built into school and post-secondary courses
  - promoting inquiry-based STEM teaching in vocational education through the Vocational Education and Training (VET) reform agenda (Office of the Chief Scientist, 2014, pp. 23–24).

As a consequence science curriculums and assessment in Australia and internationally increasingly reflect this view.[16] Examples include the:

- Australian Curriculum: Science, which has the strands *Science as a Human Endeavour* and *Science Inquiry Skills*
- United Kingdom: Key Stage 4 Science, which states that students should ‘… develop understanding of the nature, processes and methods of science, through different types of scientific enquiry that help them to answer scientific questions about the world around them’ (Department for Education (UK) 2014, p. 3); and A-level science subjects, which include content under the heading ‘How science works’[17]
- Programme for International Student Assessment (PISA), which assesses students’ scientific literacy, defined as:

  … an individual’s scientific knowledge and use of that knowledge to identify questions, to acquire new knowledge, to explain scientific phenomena, and to draw evidence-based conclusions about science-related issues, understanding of the characteristic features of science as a form of human knowledge and enquiry, awareness of how science and technology shape our material, intellectual, and cultural environments, and willingness to engage in science-related issues, and with the ideas of science, as a reflective citizen (Organisation for Economic Cooperation and Development (OECD) 2009, p. 14).

[16] This change in emphasis is even more obvious when comparing a science textbook commonly used 20 years ago, such as Bunn and Hirsch (1990), to one used today, such as Madden, Stelzer, Lindsay, Parsons, and Gaze (2007).

[17] See for example, AQA Chemistry A-Level, www.aqa.org.uk/subjects/science/as-and-a-level/chemistry-2420/subject-content/how-science-works

Engagement with science

Over the last 20 years there has been a decrease in enrolment and engagement in school science in Australia and internationally. In Australia, according to Kennedy, Lyons and Quinn (2014), the number of students undertaking a senior science subject as a proportion of the total Year 12 cohort has been steadily falling. They argue that broader curriculum offerings in Years 11 and 12, combined with students' perceptions of science (and their own self-perceptions) are the most significant causal factors in this decline.

Queensland's enrolment trends for science subjects generally mirror those in other states. However, since the mid-2000s there have been some small increases in enrolments in Queensland science subjects as a proportion of Overall Position-eligible students, which coincides with the introduction of the current syllabuses (QCAA 2014). Moreover, as noted by the Education and Innovation Committee, given the more significant declines in other states:

> … it could be seen as something of an achievement that the participation rate has not decreased further in Queensland for mathematics, chemistry and physics … [and] it [is] unlikely that any decreasing participation in these subjects is a result of assessment methods, given the similar national and international patterns of participation (Education and Innovation Committee 2013, pp. 55–56).

Research by Lyons and Quinn found that 55% of students who chose no science when entering the senior phase of schooling found lower secondary science uninteresting. They recommend that education authorities ensure science curriculums reflect teachers' and students' suggestions for increasing enrolments, such as making learning experiences more interesting, practical and personally relevant (Lyons & Quinn 2010, p. 111).

This point is emphasised throughout the introduction to *Re-imagining Science Education: Engaging students in science for Australia's future* (Tytler 2007, pp. iii-v), by Jim Peacock (then Australian Chief Scientist):

> Science education shouldn't be prescriptive — it is about the 'spark of excitement' that stems from discovery … Open-ended tasks and relevance are vital — students need to understand the world around them and make rational decisions on important issues … Students will become more effective citizens by being able to locate, analyse and critique information to form their own opinions rather than being able to provide the atomic number of an element such as lead … the sort of science that engages students is a more 'humanistic' science … with our best teachers providing personally designed, engaging curriculum units … offering students flexibility in letting them explore ideas through investigation.

It is clear that practical, hands-on, and inquiry-based science learning is identified as one of the major recommendations across the literature for improving student engagement. Therefore, science syllabuses should develop scientific literacy by focussing on critical and creative thinking skills, being practical and hands-on, and striving to engage students through investigating topics in which they are interested.

Constructivism and science knowledge and inquiry skills

The focus on learning scientific inquiry through hands-on investigations and practical open-ended tasks is often associated with the educational theory of constructivism. Constructivism argues that coming to know something is a subjective personal interpretation of reality, and as such, constructivist pedagogies focus on active engagement and place the onus of learning on the learner (Watters & Diezmann 1998). The link between inquiry-based learning and constructivism is a fair one to make, as constructivist pedagogies have been a significant area of interest in science education research,[18] and education in general.[19]

Given that learning occurs in the mind, then arguably it is trivially true that coming to know something is a subjective personal experience. However, it is a *non-sequitur* to assume *a priori* that constructivist pedagogies are therefore the most effective means of meeting either of the two main purposes of science education — ensuring the flow of human capital into the STEM pipeline and developing scientifically literate citizens.

Over the last decade, there has been increased criticism of the constructivist approach to teaching and learning. Kirschner, Sweller and Clark's hugely influential[20] paper (2006), *Why minimal guidance during instruction does not work,* argues that guided instruction is superior, given the context of research into human cognitive architecture, expert–novice differences, and cognitive load. They state that research consistently indicates that minimally guided instruction (where learners are expected to discover or construct essential information for themselves) is less effective and less efficient than guided instruction. This point was further made by Sweller and others in the *Review of the Australian Curriculum* (Donnelly & Wiltshire 2014, pp. 124–126). In reviewing what the educational research reveals about the relative effect of different pedagogical approaches, Hattie argues that the kinds of statements related to constructivism '... are almost directly opposite to the successful recipe for teaching and learning …' (2009, p. 26). In general, those approaches related to explicit guided instruction are more effective and efficient than minimally guided approaches.[21] Learners require sufficiently developed prerequisite

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[18] For overviews of constructivism across the science disciplines see Matthews (2014).

[19] Ellerton (2015) points out that the inquiry approach is not new, given Socrates effectively employed it.

[20] As indicated by more than 3000 citations in Google Scholar, https://scholar.google.com.au/scholar?cites=11065780712206344145&as_sdt=2005&sciodt=0,5&hl=en, (accessed 7 Feb 2016)

[21] This, of course, should be viewed as a generalisation, and Hattie should be consulted in depth for further nuance and detail. For example, problem-solving teaching is high impact whereas problem-based learning is not; and the characterisation of problem-based learning as low impact is itself a generalisation, given the low impact is for basic science factual knowledge but it has a positive impact for learning skills and applying knowledge (Hattie 2009, p. 211).

knowledge and skills to solve problems in a broad range of familiar and unfamiliar contexts or to effectively undertake open-ended investigations.

It is important not to conflate curriculum structure or learning goals based on scientific inquiry skills with a pedagogical approach. That is, open-ended investigations should not be equated with minimal guidance. Teachers do not generally expect students to discover the procedures needed to conduct a rigorous investigation on their own. The inquiry skills required to do this are, more often than not, taught by direct and guided instruction, and then assessed using investigations that have varying degrees of open-endedness.

Foundational knowledge and skills

It has been argued that the current Queensland science syllabuses have de-emphasised the importance of basic knowledge and fundamental skills because of the style of assessment, the increased emphasis on higher-order thinking, and teaching science in a context (Education and Innovation Committee 2013). Two recently published papers provide some evidence to support this view. Fensham and Bellocchi (2013) found that while all Australian state and territory science syllabuses have objectives related to higher-order thinking, the assessment practices in Queensland tended to meet these objectives (i.e. assess students' higher-order thinking) to a greater degree than other states, which tended to emphasise assessment of students' understanding of factual knowledge.

Arnold and Sidhu (2015) examined the results of students from all states who undertook two first-year engineering subjects (Mathematics and Physics) at UNSW between 2007 and 2014. They found that Queensland students had statistically significant lower grades than those from other states and territories (even when accounting for tertiary entrance rank). That is, the Queensland students were not as well prepared to undertake their foundational tertiary study in these courses as students from other states and territories. While Arnold and Sidhu did not propose a hypothesis for the difference in performance, many submissions cited in the Education and Innovation Committee report on senior assessment criticised Queensland's current syllabuses and assessment for not preparing students for university (Education and Innovation Committee 2013).[22]

The content of Queensland's science syllabuses[23] and the fact that Queensland currently does not have subject-based external assessment is, at this stage, somewhat of a moot point. The *Education (Queensland Curriculum and Assessment Authority) Act 2014* requires that the newly developed senior science syllabuses will adopt the Australian Curriculum content and standards

[22] Monir, Hai, Daly and Boland (2014) set out to explicitly test this hypothesis. If an external or internal assessment system is superior to the other, we should see this reflected by students' tertiary results. They found no difference in academic performance. However, this research was conducted on a cohort of students undertaking a business degree, not engineering as with Arnold and Sidhu.

[23] More specifically, Biology, Chemistry, Earth Science and Physics.

as their basis. Further, the Queensland Government announced a new senior assessment and tertiary entrance system, starting with students entering Year 11 in 2018, that includes external assessment (Jones, 2015).

Inquiry-based assessment

Inquiry-based assessment needs to balance teacher direction and student autonomy. There are different levels of inquiry, ranging from verification (where the problem, equipment, procedure and answer are given) to open inquiry, where all of the steps are open or negotiated. The level of openness of an inquiry activity can be categorised as shown below in Figure 4.

Figure 4: Levels of openness of inquiry[24]

Level	Problem	Equipment	Procedure	Answer	Common Name
0	Given	Given	Given	Given	Verification or Demonstration
1	Given	Given	Given	Open	Guided inquiry
2a	Given	Given	Open/Negotiated	Open	Structured guided inquiry
2b	Given	Open/Negotiated	Open/Negotiated	Open	Unstructured guided inquiry
3	Open/Negotiated	Open/Negotiated	Open/Negotiated	Open	Open inquiry

The importance of developing the required cognitive skills used in inquiry processes is something Ellerton (2015) argues is essential to optimising students' thinking. This does not do away with the need for subject content knowledge, '… because cognitive skills involve the manipulation of higher-order mental representations ultimately based on this content (as it is commonly said in relation to thinking critically — you have to be thinking about something)' (p. 4). Where what is taught is settled and known, learning through memorisation and practice is legitimate, but this does not teach student how to think (Ellerton 2015). If learning how to think critically is one of the goals of science education, there needs to be opportunities for openness and uncertainty.

It is clear students need to have the relevant foundational understanding and skills required for senior science before they begin senior science and/or perform open inquiries. This capacity needs to be built over time. Senior secondary teachers need to be content area experts and 'expert guides,' introducing students to the concepts and skills relevant to their content area, in a structured wa y (Krajcik et al. 2000). The vertical structure of the P–10 Australian Curriculum, where learning in higher year levels is predicated on successful learning in lower year levels (National Curriculum Board 2009, p. 6),[25] should go a long way to assisting this.

[24] Adapted from Hackling (2005, p. 2).

[25] For example, students find it difficult to predict the products of chemical reactions without having an

Some have argued that the type of practical work done in science courses should revert to a larger number of ‘traditional practicals’, whereas others are supportive of the current extended investigations (Education and Innovation Committee 2013, pp. 92–96). The approach to practical work in science classes can have a marked difference in student outcomes depending on how it is undertaken. Practical work that aims to have students question and explain, and engages them in higher-order thinking, is far more effective than simply using the laboratory to undertake a verification of previously learned content (Hattie 2009, p. 147).

Balancing the purpose and visions for science education

When developing science curriculums and courses it is important to reflect on key questions, such as, ‘What are the purposes of science education?’ ‘What should be the nature of science education?’ and ‘What do we value in science education?’ (Clark 2009). Responses to these questions will lie somewhere on the continuum between Vision 1 (traditional/disciplinary) and Vision 2 (contextual/interdisciplinary). As discussed, the science education literature tends to place more emphasis and value on Vision 2 of scientific literacy. Yet the views of many outlined in Education and Innovation Committee report, and the evidence from Kirschner et al. (2006) and Arnold and Sidhu (2015) shows that Vision 1 is emphasised and valued by many.

Balancing these two visions should be possible. The Australian Curriculum: Science has the three strands *Science understanding*, *Science as a human endeavour* and *Science inquiry skills*, and from P–12 has a clear vertical content structure. The importance of this balance and continuing the vertical curriculum structure into senior secondary is further emphasised on reviewing the newly developed *Threshold Learning Outcomes* (TLOs) for undergraduate science university courses. The TLOs are to be used for quality assurance and course design, and are organised as: Understanding Science, Scientific Knowledge, Inquiry and Problem-Solving, Communication, and Personal and Professional Responsibility (Australian Council of Deans of Science 2013).[26] It is clear these naturally build on the content and standards of the Australian Curriculum: Science and aim for a balance between fundamental content and skills, an understanding of the nature of science, higher-order thinking and scientific inquiry.

The ultimate goal of senior secondary science education is viewed by some as ‘science for all’ and developing scientific literacy, and by others as preparation for future science-based study. Either way a lack of fundamental science knowledge and skills in senior science graduates would be seen as a failure; and in both cases, the fundamentals are required for scientific literacy *and* for preparedness for further science education. As described by Kirschner et al., human cognitive architecture places a limit on how much a novice can learn on their own:

understanding of atomic structure or how to use the periodic table.

[26] See here for subject specific examples: www.acds-tlcc.edu.au/wp-content/uploads/sites/14/2015/09/Comparison-of-Science-TLOs-and-disciplines.pdf

> Any instructional theory that ignores the limits of working memory when dealing with novel information or ignores the disappearance of those limits when dealing with familiar information is unlikely to be effective (2006, p. 77).

While ultimately a syllabus will be silent when it comes to pedagogy, it should be clear that teaching science inquiry skills should not be conflated with inquiry-based learning or any other constructivist pedagogies. Similarly, teaching using direct instruction and expecting students to know some basic scientific facts should not be conflated with advocacy for content-oriented rote learning or other didactic teaching methods.[27]

The previously cited *Australian School Science Education National Action Plan* argued the primary purpose of science education is to develop scientific literacy. It adds, however, that science education:

> … provides firm basis for more specialised, discipline-based subjects in upper secondary school that lead to science courses at university, and prepares students for technical education courses that lead to science-related careers (Goodrum & Rennie, 2007, p. 3).

Balancing both these visions and purposes should be kept in mind in the redevelopment of Science Learning Area senior syllabuses.

[27] Teachers should look to evidence based research and teaching strategies that have validated efficacy. For example see Hattie (2009, 2012) and Marzano (2007).

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