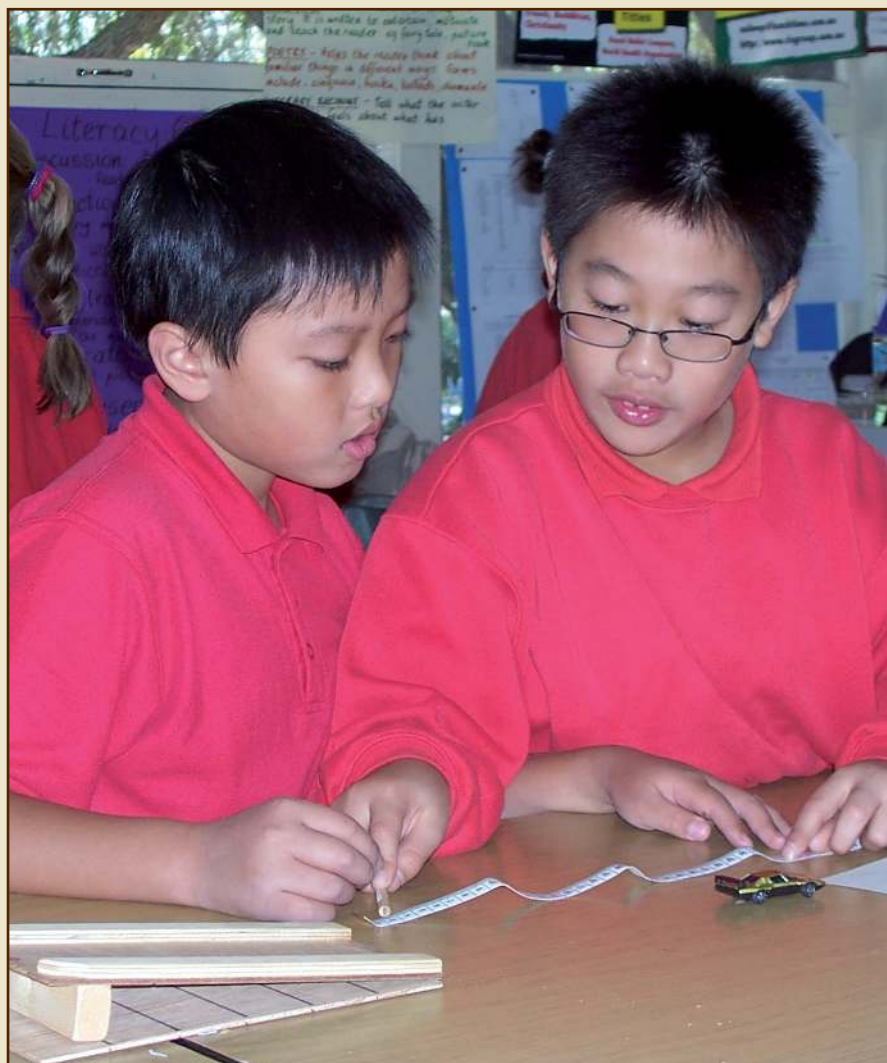


Australian Education Review



Re-imagining Science Education

Engaging students in science for Australia's future

Russell Tytler

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First published 2007
by ACER Press
Australian Council *for* Educational Research
19 Prospect Hill Road, Camberwell, Victoria, 3124

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Edited by Carolyn Glascodine
Typeset by ACER Project Publishing
Printed by BPA Print Group

A catalogue record for this book is available from the National Library of Australia.

ISBN 978-086431-725-4

Visit our website: www.acer.edu.au

Main cover image: Year 6 science class activity.
Thanks to Preston North East Primary School and photographer Peter Hope.

Foreword



I am passionate about the education of our young people, and feel we must support a system which more fully engages our youth in science and technology. But how should this system be designed? What is really important about science in our schools?

Professor Tytler, in his review, boldly aims to provide possible solutions to these questions. His key message is the need to re-imagine science education to suit today's world. The author believes there is a 'genuine mood for change' across all sectors.

I attended the Australian Council for Educational Research (ACER) conference on 'Boosting science learning – What will it take?' in August 2006, on which this review is based. For the final session of the conference, I was asked to comment on one of three propositions generated by teachers and other stakeholders at the conference: 'We need to re-imagine science education, accepting a shift that is occurring and must occur in the way we think of its nature and purposes.'

My response to this proposition was based upon three key ideas I believe to be important in school science:

- 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
- Teacher confidence and professional development is just as important as the students' learning materials.

We need to re-energise science. Unfortunately, secondary school and university students will not continue to fill our science classes just because we, as teachers, are passionate about our subject matter. We need to provide challenging units of inquiry to our students.

My perspective as a scientist

Professor Tytler argues powerfully in his review paper that the Australian school science crisis should not be the starting point for advocating and planning change; societal factors must frame our way forward.

And how society has changed! The way in which I learned science at school does not meet the needs of today's students. In my lifetime, scientific research has broadened from an individual-oriented approach to team-based work and collaboration with other researchers and industry. Collaborative science is essential if we are to address national impact and global problems such as climate change. A different skills set is needed in today's scientists. We can no longer focus on a niche area. Collaboration is now the norm. We are all living in a connected world.

School science education is operating in a world where students ‘connect’ to students thousands of kilometres away in real time through instant messaging and they can escape to virtual internet worlds. Traditional science education is not fruitful in such an environment. Our best teachers are already making use of the new connections technology affords.

Science is a constantly evolving field. Thus, much of the content knowledge I learned in school and university was not directly used in my career as a plant scientist. I learned to approach individual experts in a field, tracking information in how to tackle an unknown.

Every day we are faced with unfamiliar tasks and required to make decisions in unfamiliar contexts. 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.

What should school science look like?

In reading the review I was particularly interested in the research of Tytler and Symington (2006), in which focus groups of Australian scientists were interviewed to determine their perspective on the school science curriculum. Interestingly, these scientists believed the school curriculum held an outdated and discipline-bound view of science. They felt the focus should be on engaging young people, not on developing future scientists. I agree that we should not begin with a focus on recruiting, but on providing all students with opportunities to engage with science.

As Professor Tytler’s review points out, today’s students have a broad world view and are interested in social and global problems. One only need open the daily newspaper, or listen to the latest news podcast, to see and hear about science-related issues – for example, climate change, stem cell cloning and nuclear power. Science can be the bridge to understanding and engaging with many of these issues. Building a culture of interest in science will enable Australians to cope with a future that will be very much dependent on science and technology.

Science is becoming increasingly popular, as demonstrated through high ratings of television shows such as the ABC’s *Catalyst* and Discovery Channel’s *Mythbusters*. Through a focus on urban legends that interest students, such as ‘Can the unaided human voice shatter glass?’ and ‘Can diving underwater protect a person from gunfire?’, *Mythbusters* entices students into the world of investigation.

The clear message from Professor Tytler’s review is that the sort of science that engages students is a more ‘humanistic’ science.

I was also interested to learn of the Twenty First Century Science courses developed at the University of York. The focus of these courses for 14- to 16-year-olds is of students as ‘consumers not producers of science’. The idea of including content only when it might make a difference to a decision or choice a student might make, or to their viewpoint, represents a substantial shift from our traditional curriculum; however, it makes sense. If teachers are confident and supported in implementing such an approach, young people will be more engaged.

Students are naturally curious and love investigating. Let’s capture their imagination as the best teachers do by offering students flexibility in letting them explore ideas through investigation.

The Australian Government has a number of initiatives to address science engagement. In 2003, I was part of a Prime Minister’s Science, Engineering and Innovation Council (PMSEIC) Working Group entitled Science Engagement and Education. The Science by Doing program – a cooperative venture between the Australian Academy of Science, the CSIRO, the Commonwealth and other education authorities – developed from this.

Science by Doing aims to actively engage science students in Years 7 to 10 by encouraging them to investigate science. It works on the principle that ‘doing’ leads to understanding and

excitement. The Science by Doing concept paper was released in September 2006 and the project will soon move ahead with the preparation and trial of activity units.

Professor Tytler comments that such a curriculum fulfils some of the recommendations developed in his review, in that it moves towards ‘discussion, open questioning and higher order conceptual explanation’. It is good to see some critical commentary on this approach, as it provides ‘fuel for thought’. However, a curriculum is nothing without expert teachers to coordinate the learning process. I am always amazed at how our best teachers engage and challenge all students in their classroom in some way. Such teachers link the science concepts to the world of their students, who can catch and hold those concepts, because the learning has become useful.

Science learning in context

A key theme, which Professor Tytler returns to throughout his review paper, is the mismatch of science as it is taught in schools and how science exists in the ‘real world’. His review highlights factors that are stopping Australian teachers and schools from designing more contextual learning experiences; the rigid curriculum, the need for guidance for overworked or under-confident teachers, and the conservative attitudes of many parents, teachers and university academics.

However, many teachers are forging on in spite of these barriers, with our best teachers providing personally designed, engaging curriculum units. Their students are learning through the intersection of science with their own lives.

Schools and community

There are some excellent examples of learning communities linking school learnings in maths, science and technology with industry. Enthusiastic teachers are finding issues in the community on which to base their science curriculum; providing students with the opportunity to make decisions and deliver tangible outcomes in their own community. These projects often occur in rural schools and clusters, which raises the important role played by the community in creating effective learning environments and supporting effective learning. The Victorian School Innovation in Science project is highlighted in the review, along with the recent Australian School Innovation in Science, Technology and Mathematics project.

As Australian Chief Scientist, I have been advocating enhanced connections between researchers and industry, and I can certainly see the benefits of schools working together in sustainable partnerships with industry and the community. It is particularly important that Year 11 and 12 students have opportunities to link with industry, to discover possible career paths in science.

I think it’s so important for scientists in research laboratories, and for businesses and industry, to become involved at the school level. I agree with Professor Tytler that we need partnerships to be part of the ‘mainstream’ delivery of science.

Primary school science

As a proponent of the Primary Connections program, run through the Australian Academy of Science, I was pleased to see the focus on scientific literacy in Professor Tytler’s review. I have enjoyed being part of the development of this new way of teaching science through literacy and believe primary school teachers and students are currently benefiting from the national implementation of Primary Connections.

A key facet of the program is teacher professional development, and the confidence that such a program elicits in teachers is remarkable. Mean achievement scores for students after the Primary Connections trial were almost doubled, with Year 5 students working at or above the national standard for Year 6.

To see Primary Connections in action, in the classroom, with teachers modifying the program to suit their students and their students' worlds is remarkable. Through a 'do then explain' approach, students are engaged.

From its beginnings, the Primary Connections program had positive endorsement from education authorities across Australia. This was fundamental to changing the primary science curricula on a national scale. The Australian Government is currently mapping key school science initiatives across Australia through the Australian School Science Education Framework project. The aim of this work is to enhance collaboration between education authorities nationally. National coordination of our endeavours makes sense.

Change

In Section 6 'Teacher-led reform', Professor Tytler touches on reasons why change in science education has been resisted. Interestingly, he highlights the 'silent choice of teachers for the status quo; one which supports and reflects their identities as knowledgeable experts' as a key factor. I agree with Professor Tytler – it is an unfortunate fact that many science teachers do not have enough opportunity to upgrade their science knowledge and to be introduced to new teaching modes.

The demands on teachers are great. To re-invigorate the science curriculum, to make a new 'mainstream', places even more demands on our teachers. Our teachers will need much support – professional development incorporating both resources and training. Teachers need time to become involved in professional learning communities, in schools and in their regions. Teachers are the experts and teachers will lead change in our schools and make it happen, only if they understand, believe in and champion the necessary changes.

I believe teachers need the skills and confidence to engage and excite children in their quest for new levels of knowledge and understanding of their world.

The key question we must return to is: 'What are the skills our young people need in their lives?' Generic 'learning to learn' skills are important; however, in a future increasingly driven by science and technology, we must also engage students in the issues that surround them. We must challenge our young people to think.

The 'science crisis' experienced in Australia also exists in other countries, such as the United States of America and the United Kingdom. Australia can certainly lead the way in 're-imagining' science education. We must continue to support our teachers with 'real' professional development, not just resources. We must raise the profile of our teachers and encourage young people to consider teaching as a career.

I congratulate Professor Tytler on his efforts to further the science education agenda. His development of a set of strands, as outlined in Table 10 in Section 7, provides us with some guiding principles for a 're-imagined' science curriculum and summarises what our more forward-thinking educators are doing.

There is impetus for curriculum change, and not just from educators and teacher associations, but from government, universities and industry. Now is the time for a paradigm shift in science education across Australia. This review should assist us in developing strategies for implementing those changes.

*Jim Peacock
Australian Chief Scientist*

Dr Jim Peacock is Australian Chief Scientist, providing independent advice on science, technology and innovation issues to the Prime Minister and Ministers. He provides a link between government and science, engineering, innovation and industry groups, facilitating active communication and focusing national thinking on science.

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Introduction

Science education in Australia, as in other post-industrial countries, is in a state of crisis. The language of crisis is used by government, industry and educators alike to describe the diminishing proportion of students in the post-compulsory years who are undertaking science-related studies, particularly in the physical sciences. In itself this might not be such an issue, except that this flight from science is occurring in societies that are in increasing need of science and technology-based professionals to carry the nation into a technologically driven future. It is the pipeline into this pool of expertise that seems in danger of drying up. The concern is thus largely economic, but as this review will point out, the issue is wider than this, and encompasses the need to maintain a citizenry that is literate in and well disposed towards science.

The crisis has other dimensions, namely the shortage of skilled science professionals in the workplace in Australia and the shift in momentum of science-based development to developing countries, considerable evidence of student disenchantment with school science in the middle years, and a growing concern with a current and looming shortage of qualified teachers of science. This review will explore these developments in an effort to trace their common causes and interconnections, and will raise the questions of whether they can be seen as in a linked, downward spiral, and whether we have reached a point where significant damage has been done to Australia's future. We will attempt to assess the depth of the problem and explore ways forward for the future of science education and arguably for the country.

There have been many government reports, both state and federal, associated with the science education crisis, and these will be described in Section 2. The ACER conference 'Boosting Science Learning', held in Canberra in August 2006, had its origins in a concern to address the crisis, and a number of the presentations addressed the issue. In particular, the conference was significant in the strength of its call for change in the substance and delivery of school science. In the final plenary session of the conference, a series of propositions, based on papers presented at the conference and on the major ideas arising out of two teacher forums during the conference, were put to a panel of significant players and to the floor, and received strong support from all these stakeholders. The propositions called for a significant 're-imagining' of science education as opposed to a notion of the mere refinement of curriculum and assessment.

Table 1. The ACER 2006 conference plenary session propositions

Proposition 1: We need to re-imagine science education, accepting a shift that is occurring and must occur in the way we think of its nature and purposes. The implication of this is that any moves towards a national agenda for science education need to be premised on this re-imagining rather than refinement of the existing curriculum and assessment.

Proposition 2: To achieve this re-imagined science education we need to develop:

- a new metaphor for science education that will capture its nature
- rigorous assessment processes appropriate to this re-imagined science education.

Proposition 3: There needs to be a national teacher education agenda focusing on re-imagining the role of the science teacher and developing teachers' capabilities (knowledge, pedagogy, disposition) which enables the support of the new directions.

This review is not a report on the conference, but a research review paper in which the author will draw on many contemporary sources within the science education literature as well as the conference papers. It will explicate what a 're-imagining' of science education might mean, consistent with that final panel discussion. The aim is to look for a way forward for school and tertiary science and seek a way out of the current impasse in student engagement in science that has befallen most Western developed countries.

The review paper will argue that we need to re-imagine science education in order to effectively respond to the challenge of dealing with new times, new students and new circumstances that have fundamentally changed the social setting within which schools and students operate, compared to the circumstances that surrounded the growth of disciplines and ideals of scholarship that are represented in traditional formulations of school science. Part of the argument will be that school science has lost some of the character and quality that sustained it in earlier times.

We need to ask the questions 'what has changed in contemporary Western society that might demand a radical response from science education?' and 'how should school science respond to these changes in order to support a more prosperous and just society?' Sections 1 and 2 of this review paper will examine and suggest answers to those questions. The later sections will explore ways forward from a number of perspectives.

Science responding to societal change

Much has been written, and much was presented at the ACER conference, concerning the decreasing participation of students in post-compulsory science and the seemingly deep-seated disenchantment with aspects of the science curriculum and pedagogy in Australia and internationally. Some of this data will be presented and discussed in Section 2. However, while this 'science crisis' does provide an imperative for serious thought and action, for at least two reasons it would be a mistake to take it as our only reference point for advocating and planning changes to science education.

First, it seems possible that the science participation problem may relate to quite fundamental societal conditions, and not simply to details of the science curriculum. There is evidence, for instance Sjoberg and Schreiner (2005), that students' interest in and perceptions of the personal relevance of science differs in predictable ways, depending on a country's level of development.

Second, to start with a problem is to start from behind, in the sense of forcing a reactive response rather than allowing the problem to be seen at a deeper level. If we are to take science education in the 21st century in a productive direction, we need to be very clear about the societal factors that are shaping students' responses to science, and that should be shaping our thinking about the purposes and nature of science education from primary through to tertiary level.

The resilience of traditional school science

The broad shape of science education has remained relatively unchanged, at least in its official guise, for the last half-century at least, and this shape has been similar across the developed world. The emphasis is on conceptual knowledge, compartmentalised into distinct disciplinary strands, the use of key, abstract concepts to interpret and explain relatively standard problems, the treatment of context as mainly subsidiary to concepts, and the use of practical work to illustrate principles and practices. All these have been relatively constant features of science education across the 20th century and into the 21st.

During this time there have been shifting emphases and controversies associated with, for instance, the relative emphases on the 'processes' versus the 'products' of science, the need to better link science with its technological and social implications, as opposed to the current emphasis on inquiry as a predominant feature of school science, and the need to pay much more attention to context in supporting students learning science content. There have of course also been changes in the nature of what is taught, as contemporary science ideas are brought into the curriculum.

These are only some examples of changes that have challenged the status quo in the teaching of science. Largely, they have left relatively undisturbed the major narrative of the science curriculum that focuses on the establishment of a body of knowledge that is assessed largely by declarative means. The key nature of school science has been remarkably resilient to these controversies and recommendations for change. In a series of focus groups of scientists conducted in 2005, for instance (Tytler & Symington, 2006a), some of the informants were keen to point out that the textbooks their own children currently used looked much the same as those they themselves had used in the 1960s (although one informant pointed out the diagrams were more colourful), and that the view of science contained in them did not reflect what they understood as the current practice of science.

This review will explore the hypothesis that school science has not kept pace with changes in science and society. It will advance reasons for the lack of inroads made into practice by curriculum reform, in terms of the operation of disciplinary interests and commitment of science educators to traditional versions of science knowing. It will argue that, despite the failure of major reform in science education over the past 20 years, there seems now to be a genuine mood for change: among teachers, science policy makers at government level, and the science academy, as well as among that group of academic and reformist teachers who have been advocating and practising change for some time now. Such a consensus is new. The ACER 2006 conference was a good example of this advocacy and also demonstrated a new driving force behind this mood – the 'flight from science' is serving as a wake-up call.

So what has changed?

In line with the earlier argument that we cannot go forward simply by focusing on the external symptoms, but must look for a deeper level diagnosis, we must ask ourselves: what are the changing conditions that may be contributing to the crisis in science education? There have been a number of major changes, each of which has been written about as implying a need to re-imagine science education, if not schooling more generally. This review paper will explore the implications of each of the changes, a summary of which follows.

The changing practice of science

The practice of scientific research and technological development has changed substantially over the last 50 years. The traditional role of the scientist as a lone explorer, or one who worked in small teams, pushing the boundaries of knowledge as part of an intellectual pursuit over which he or she had close control, has largely given way to science that is practised on a large scale, with significant funding, in teams, on projects that can be global, commercial, multi-disciplinary, significantly technologically linked, and often having significant community implications. This review will argue that changing the nature of contemporary science and

the skills needed by scientists have implications for how science should be represented in the curriculum, and the skills and capabilities a science education needs to focus on.

The changing nature of public engagement with science

The increasingly technological nature of contemporary society, and the increasing need to manage resources and the effects of development carefully, places new imperatives on the way the public needs to engage with and respond to science and its products. Controversies involving conflicting views between science experts, or government and science expertise, such as with regard to climate change, stem cell research, inoculation, and a range of environmental issues around energy or conservation and management, imply an increasingly important role for science education in preparing future citizens to engage with these personal and public science-based issues.

The challenges to science

Public challenges to science from a number of directions have gained much air space in recent decades, and demand response in science education. Postmodernist critiques of science, attacking its claim to high status knowledge, have been hotly pursued and contested in what has become known as the 'science wars' (Ziman, 2000). Concern about public attitudes to and knowledge of science have been voiced at high levels (e.g. UK House of Lords Select Committee on Science and Technology, 2000). Postmodern, feminist and post-colonial critiques of science also challenge global science research and development practices and their representation in science education. The need to accommodate indigenous perspectives in science curricula in many countries has raised questions about the nature of science and its cultural antecedents (Aikenhead, 2001). Perspectives from a variety of religions have voiced discomfort over aggressively materialistic versions of science and the perceived lack of human values expressed in traditional science curricula. The recent debate over the inclusion of intelligent design in the science curriculum is one very public example of this type of challenge to science (Symington & Tytler, 2005).

The knowledge explosion

Since the late 19th century when the current shape of the science curriculum was largely put in place (Aikenhead, 2006), there has been an incredible expansion of knowledge in science, and in the accessibility of that knowledge in a wide variety of forms. For many people, engaging with current science-based controversies and science-based personal decision making requires background science knowledge (e.g. DNA, viruses, global cycles, modern materials) that was not part of the science curriculum they experienced in their schooling because it was not science that was known or understood at the time. Contemporary popular media include science programs and layouts that offer quite detailed insights and perspectives on a range of topics. The web has grown exponentially, both in accessibility by Australian households, and in knowledge representations, and has become such that students can tap into significant science knowledge bases independent of, or in tandem with, their school science. This has enormous implications for how expertise in science is represented in the classroom.

Changes to the nature of schooling

The knowledge explosion significantly challenges the traditional model of the teacher as expert knower who delivers significant and stable science concepts to dependent students. It also implies the need to focus more seriously on learning and the capacity to learn as a major aim of a science education rather than continuing to accept knowledge acquisition as the single prevailing metaphor. This is not to say, of course, that knowledge acquisition is not fundamentally important. However, changes in the way knowledge is accessed have led more generally to pressures to reconsider the nature of schooling.

The changing population of students

Up to midway through the 20th century, the proportion of the population completing a secondary school education was small compared to currently, and the curriculum was premised on the notion of preparing this select group of students for an academic education. The rapid expansion of secondary education over the last half of the previous century, and the consolidation of Australian students into a single-tiered schooling system, has meant that by the 1980s the science education curriculum had to accommodate a student population with a wide range of responses to what was essentially an academic program, and an accompanying broadening of its purposes. This need to make science relevant for all students, including those not proceeding to post-compulsory education, has underpinned calls for a 'Science for All' curriculum (Fensham, 1985), or the current scientific literacy focus for school science (Goodrum, Hackling, & Rennie, 2001; McCrae, 2006).

The changing nature of youth

In this post-industrial society, youth has responded with new life patterns that are different to those presumed in previous eras, and which have implications for schooling in general, and for the way the science curriculum and careers in science are envisaged. Richard Eckersley (2004) identified a range of indicators of deep malaise in Australian youth associated with increasing inequity and materialism. He posed a challenge for schooling and for science education to develop a curriculum that acknowledged this problem, emphasising community connections and sustainability. Johanna Wynn (2004) conducted a five-year longitudinal study of 200 young people immediately post degree. She argued that uncertainty and change are the conditions that predominantly shaped her subjects' values and choices. They valued flexibility – the capacity to make choices and be proactive about job mobility – rather than predictability, as a basis for future security. Her participants valued personal autonomy and responsiveness as capabilities they worked on developing, as part of a 'self as project' outlook on their pathways. They valued the notion of a career, but saw this in terms of flexible and opportunistic job shifts aimed at developing a flexible CV, rather than in terms of a stable and continuous job.

These findings were strongly echoed in the author's study of Year 10 and 11 students concerning what would encourage them to enrol in a science degree (see Tytler & Symington, 2006). The other aspect of the life realities of contemporary youth is the multimedia world in which they increasingly find themselves. Many younger students now are developing multimedia literacies in advance of those of their teachers.

In summary

Taken as a group, the societal changes outlined above have profound implications for science education. There have been many changes in school science over the last 50 years, and many contestations that have led to reforms, or at least changes in emphasis. Nevertheless, throughout these changes the basic shape of school science has been kept in place, maintaining its emphasis on distinctive knowledge structures of science, in its treatment of context as applications of the central ideas, and in its emphasis in practical work on illustrating concepts and techniques. This basic shape has been supported by assessment regimes that have remained remarkably stable over all this time.

This review will scrutinise the assumptions underpinning this traditional science curriculum. In doing this, it will challenge the proposition that the structured canon of abstract concepts represents the defining feature of science as an enterprise, and is the appropriate major focus for school science. What is essentially at stake here is how knowledge in science is best characterised. The question 'what knowledge or knowledges should be the appropriate focus in science education' is central to the work of re-imagining science education.

The structure of this research review paper

This review paper, focusing as it does on providing an interpretation of the ‘re-imagining’ that was called for in the final ACER conference session, will be structured to tell a story that will explicate for readers:

- a recognition of the issues in science education that led to the conference and the call for a new direction
- a body of research into a variety of aspects of science education that will allow us to see more sharply the nature of these issues and how they are interconnected
- implications for re-imagining science education.

The review will thus attempt to bring together some major areas of science education research, and hold them up for inspection to see if they can provide a suitable road map to chart possible new directions that will address the current impasse in which science education finds itself.

The review will be shaped as an argument that is in many respects supportive of current system initiatives and perspectives, but which will also apply a critical lens to the perspectives and emphases of current opinion and policy, including some perspectives represented at the conference. In pursuing this goal of looking for a path forward, the review will draw on research and issues that were dealt with explicitly at the conference, but will also tap into issues that received little ‘air play’ at the conference but which are important themes in the literature.

Thus, while the review will take as its main focus the need to boost student learning in (and engagement with) science, in line with the ACER conference theme, it will also chart a somewhat independent path towards considering how we might re-imagine:

- the purposes of science education
- the content of what is taught in school science
- the way science is taught and assessed
- the role of the teacher and how she or he can best be prepared for teaching science in the 21st century.

These aspects of science education can be linked to the three propositions that were discussed by the panel in the final session.

Following an explication of the nature and extent of the crisis in school science in Section 2, Sections 3–5 will substantially concern themselves with what might be meant by a ‘new metaphor’ for science education, and what assessment processes this might imply. In Section 6, the review will examine the proposition that changes of this nature imply a significant re-imagining of teacher education, for practising teachers who need support in taking on new perspectives and for trainee teachers.

The crisis in science

It was argued in Section 1 that the broad societal changes identified imply a need to substantially rethink the nature of science education. However, there seems to be an ongoing tendency for science educators to imagine that, despite all these changes, the nature of science and science knowledge remains sufficiently stable, that enough science-enthusiastic students will continue to fill our classes and that we can fix the problem by a process of adjustment. In this section of the review it will be argued that there are enough significant cracks appearing in the edifice to demonstrate beyond doubt that we are in the midst of a science crisis that is showing no signs of diminishing. Further, there is circumstantial evidence that the problem lies in part in a mismatch between the nature of the science curriculum, and the societal trends outlined above.

Main aspects of the crisis in science education

There are four main elements to the crisis in science education:

- evidence of students developing increasingly negative attitudes to science over the secondary school years
- decreasing participation in post-compulsory science subjects, especially the ‘enabling’ sciences of physics and chemistry, and higher mathematics
- a shortage of science-qualified people in the skilled workforce
- a shortage of qualified science teachers.

Of course these four aspects are closely linked. The shortage of qualified science teachers will impact on the quality of science classroom practice, and hence the enjoyment and learning of science by students, and this in turn will lead to a drop in numbers taking up science, and going into science teaching. Arguably, we are in a downwards spiral which will almost certainly need to be addressed at a number of points if it is to be arrested. A number of papers at the ACER conference addressed these aspects of the science crisis, either directly or indirectly, and this and other data will be used to sketch out the nature and magnitude of the problem.

Student attitudes to science

There have been concerns both locally, and internationally, about the increasingly negative response to science across Years 7–10. A number of Australian studies over the last two decades have shown a general decline in students’ interest and enjoyment of science across

the compulsory secondary school years, with a particularly sharp decline across the primary to secondary school transition (e.g. Adams, Doig, & Rosier, 1991; Goodrum et al., 2001). This decline in interest in science in the early years of secondary school is particularly of concern, since it is in these years that attitudes to the pursuit of science subjects and careers are formed (Speering & Rennie, 1996).

In a questionnaire and interview study of student attitudes to science across the primary to secondary transition years, Speering and Rennie (1996) identified a number of interconnected factors that affected student attitudes across the primary to secondary school transition. They were:

- the diminished personal nature of the teacher–student relationships forced in part by fragmented timetable arrangements
- a change from an activity-based science program to one dominated by transmissive approaches
- a curriculum that allowed little flexibility for the tailoring to individual students' needs.

Students' negative view as to the relevance of science course content for their lives was a strong theme in the report on the status and quality of the teaching and learning of science (Goodrum et al., 2001; Goodrum, 2006; Rennie, 2006).

A survey of several hundred teachers of science in Victoria (Gough et al., 1998) found a somewhat depressing picture of teacher perceptions of students' attitudes and interests in science. Table 2 shows the number of teachers responding to each attitudinal assertion with 'agree' or 'strongly agree'.

Table 2. Teacher perceptions of student attitudes to science

Student attitudinal statement	% of teachers who agree or strongly agree	
	Primary	Secondary
<i>Students:</i>		
Think science is interesting	70.3	35.9
Are enthusiastic about their science studies	59.6	24.5
Think science is relevant to them	37.5	21.8
Have an out-of-school interest in science	13.6	3.8
Think a career in science would be worthwhile	10.5	15.2

(Gough et al., 1998, p. 36)

The table shows a very clear difference in the levels of student interest perceived by secondary teachers compared to primary teachers. A national study of teachers of science (Harris, Jenz, & Baldwin, 2005) found high levels of disillusionment with teaching among this group, with concern about student behaviour and attitudes to learning/science coming second to workload issues, as a significant negative aspect of the job. While it is not uncommon for teachers in other subject areas to experience and express concern about similar student attitudes to school and learning in general (such concerns form the basis of much Middle Years programming in schools), evidence will be considered in this review that student attitudes to science are of particular concern.

Sue Thomson (2006), in a review of the results of the Australian attitude data from the TIMSS 2002 survey (Thomson & Fleming, 2004), reported reasonably high levels of student self-confidence in science although the percentage reporting a 'high' level dropped from 66% to 49% between Year 4 and Year 8 students. The numbers of students reporting they like science 'to some extent' were 87% for Year 4, dropping to 67% for Year 8. An improved result, compared to 1994, was achieved with an increase to 36% of Year 8 students who reported they liked science 'a lot'. This figure was lower than the international average and broadly consistent with the trends described above.

There have been a number of such studies and reports over the last two decades that have traced students' increasingly negative attitudes to science over the middle years of schooling and the associated decrease in student participation in post-compulsory science. Many presentations at the ACER conference referred to this student negativity either explicitly or as a background to their work (e.g. the addresses of Jonathan Osborne, Leonie Rennie, Sue Thomson, Denis Goodrum, Peter Fensham, Deborah Corrigan, Kerrie-Lee Harris, and Russell Tytler and David Symington). A number of studies have explicitly linked this decline in student interest with the nature of the traditional science curriculum and its inability to make science meaningful and interesting to students (Aikenhead, 2006; Fensham, 2006; European Commission High Level Group report HLG, 2004).

International comparisons: the ROSE study

While these studies of student interest in science demonstrate the commonality of both the curriculum and pedagogy in developed countries, and of students' response to this, the similarity of the settings masks some interesting international trends. The Relevance of Science Education (ROSE) project conducted by Norwegian researchers Sjøberg and Schreiner (2005) surveyed students from many countries around the world to probe their interest in science, responses to various science topics, intentions with regard to science, and their responses to other dimensions of science education. On questions relating to youth orientation to science and technology (e.g. views of its relevance and usefulness, and intention to work in this area) there was an extraordinarily high negative correlation (between 0.77 and 0.94) with a country's index of development. In other words, the more developed the country, the less positive the view of science. Hence, it seems plausible that there is in fact a link between student attitudes to science and the nature of post-industrial societies, as argued in Section 1.

To put some extra flesh on the bones of the ROSE study, in the United Kingdom (UK), the percentage of 14- to 15-year-old students agreeing with the statements 'I like school science better than other subjects' and 'I would like to become a scientist' were 11% and 8% respectively (Jenkins & Nelson, 2005). These figures are consistent with studies in Australia and elsewhere.

Understanding student disenchantment with science

The studies described above chart the phenomenon of decreasing interest in school science but give us little insight into the reasons for it. Such insight must come from closer studies of student perceptions of the nature of school science and the factors determining their engagement with it as an interesting subject or a potential career. Such insight is needed if we are to find productive ways forward for the development of an engaging science curriculum.

Recently, there have been three separate studies conducted which have sought to locate answers to the questions of what is really turning our students off science, and what can be done about it. The three studies were from Australia (Lyons, 2006), Sweden (Lindahl, 2003) and the UK (Osborne & Collins, 2001) and they were similar in that they were substantially interview-based and dealt with students in the years in which they made choices about their future studies.

Lyons' (2005) meta-analysis of the findings of these studies highlighted three major themes:

- the transmissive pedagogy that characterised school science
- the decontextualised content that did not engage students' interest or commitment
- the unnecessary difficulty of school science.

Lindahl's (2003) study, a longitudinal design following 80 students from upper primary school to the point of choosing their senior school subjects, found that students resented the lack of opportunity for personal opinion and expression in science, caused by the narrow range of transmissive pedagogies used. They were also not attracted to what she called the semiotics of the classroom: the smell of the laboratory, texts crammed with facts and teachers who did not laugh. In her study there were a number of academically strong students with an interest in

science as presented in popular media, who rejected school science as something very different. She also found the importance of early exposure to science-related careers, in that students tended to be consistent in their intended career choices from primary school, yet many had no idea what sort of work a study of science could lead to.

Lyons (2005) characterised the transmissive pedagogy of science as a feature reported so widely that it seemed to be regarded as an inherent characteristic. Osborne's and Collins's (2001) informants talked of 'right or wrong answers' with no room for creativity or time, in the rush to ingest concepts, to discuss or reflect or offer opinions. They argue that this aspect of school science is a response to an overfull curriculum in which students are 'frog-marched across the scientific landscape, from one feature to another, with no time to stand and stare, and absorb what it was that they had just learned' (p. 450). They also found a perception of the irrelevance of school science to be 'a recurring theme' among students regardless of whether they intended to continue with science study (p. 449). They concluded that teachers too infrequently attempted to link science concepts to everyday life.

It is a sad indictment of school science that it is not considered to relate sufficiently to the 'real world, technology and the future', preserves that ought to be its own.

(Lyons, 2005, p. 599)

Students in all studies recognised the importance of science content but nevertheless affirmed its 'boring' nature, characterised by Lyons as 'science is important – but not for me' (p. 600).

Lyons' study was of high-performing Year 10 students, and involved questionnaire data from 196 students, and more detailed interview data from 37 students. Lyons (2006) identified from his interview data that the students choosing physical science were those who had (a) supportive relationships with members of their family, and one of (b) parents who emphasised the strategic value of formal education or (c) family members advocating or supporting an interest in science. Most students with all three conditions in place chose physical science. He also found that students taking physical science had higher levels of self-efficacy, and from the student narratives in his interviews identified this quality as being instrumental in the decision to take difficult science subjects. He explained these findings in terms of 'cultural and social capital' associated with supportive family relationships and family views that were aligned with school science. He argued that it would be wrong to think of the diminishing numbers in post-compulsory science in terms of students being drawn away by more attractive options, or by a lack of career prospects (his interviewees expressed no view on particular career or status implications of choosing science). He describes how:

it became increasingly obvious that the most cogent single force acting against the choice of physical science courses was the culture of school science itself. While emphasising the status and strategic utility of physical science courses, students in this study considered school science to have fewer intrinsically satisfying characteristics than it might have.

(Lyons, 2006, p. 308)

Given this, Lyons argues that it is school science that needs to be the focus of change, and not a recasting of tertiary science courses or an emphasis on scientific career opportunities. He argues that the lack of attractiveness or interest of school science set a very high bar on choice of physical science, which needed considerable cultural and social capital to overcome.

This is consistent with the views of Aikenhead (2006) who argues that there is abundant evidence that traditional school science is not meeting the needs of students, and that curricula with the characteristics he identifies with humanistic science are of more interest. He argues that for many students, especially Indigenous students, coming to appreciate science requires an identity shift whereby students come to consider themselves as science-friendly: 'to learn science meaningfully is identity work' (p. 117).

The last point made by Lyons (2005) relating to ‘difficulty’ is complex. Difficulty was associated by some students with passive learning and memorisation, by other students with unfamiliar terminology and concepts leading to disorientation, and by still others with intellectual challenge (though this was not necessarily cast as a negative). The willingness of teachers to listen, explain and support was highly valued. It seems likely the difficulty of scientific ideas is not a problem per se, but rather it is the lack of supporting pedagogy that is the problem, and the lack of student motivation due to insufficient attention being given to making the content meaningful. In fact, research into student learning in the middle years of schooling emphasises the need to present students with intellectually challenging material to engage their interest and commitment, a circumstance for which one would have thought science was well placed.

Science and the middle years of schooling

The concern regarding the attitudes to schooling of students in the 11–15 age group (the middle years of schooling) is not confined to science. A range of projects have focused on issues of engagement of students across the middle years more generally, associated with the particular responses to schooling of adolescent students in a period of their lives when issues of identity, commitment and independence are central to their experience and concern. An example of this coordinated approach to middle years issues can be found in the suite of projects run by the Victorian government over the last decade. The School Innovation in Science (SIS: Tytler, 2005, in press) project incorporated middle years pedagogical principles, as did the Project for the Enhancing of Effective Learning (PEEL) (Baird & Northfield, 1992) before it. PEEL pioneered strategies to promote higher order thinking, including metacognition. These and other projects have focused on pedagogy as their major lever for reform. The particular pedagogical focus within the Victorian Middle Years Research and Development (MYRAD) (Victorian Department of Education and Training (DE&T), 2002) project included higher order thinking (generating a set of school explorations of the ‘thinking curriculum’), student-active engagement with learning (focusing on explicit attention to the learning process), differentiation, and classroom relationships. The Queensland New Basics project (Department of Education, Training and the Arts, 2004) has generated descriptors of generic ‘productive pedagogies’, and a process by which teachers can monitor and improve their practice.

In Victoria, the Middle Years Pedagogy Research and Development (MYPRAD) (Victorian DE&T, 2003) project developed a framework to describe effective learning and teaching in the middle years. The MYPRAD framework consists of five components.

Table 3. The MYPRAD components

1	<i>Students are challenged to develop deeper levels of understanding;</i> emphasising student questioning and exploration, and engagement with significant ideas and practices.
2	<i>The learning environment is supportive and productive;</i> emphasising a classroom environment where students feel able to express themselves, take responsibility for and occasionally take risks with their learning.
3	<i>Teaching strategies cater for individuals’ interests and learning needs;</i> emphasising the monitoring and accommodation of diversity, and the encouragement of autonomy as learners.
4	<i>Assessment is an integral part of teaching and learning;</i> emphasising continual monitoring feeding into planning, and feedback designed to encourage students’ self-monitoring.
5	<i>Teaching practice meets the developmental needs of adolescent learners;</i> emphasising the active engagement of students in their learning, their involvement in decision making, and the linking of classroom learning with local and broader communities.

As part of MYPRAD, a snapshot of Middle Years practice was undertaken, (Tytler, Doig, Groves, Gough, & Sharpley, 2003) involving 224 secondary teachers mapping their practice against the MYPRAD components, and student responses to questionnaires. The results showed that science as a subject was less likely than most to exemplify these recommended pedagogical practices. Science teachers mapped themselves as low compared to teachers in most other subject areas, on the following components:

- challenging students to explore, question and reflect
- encouraging and supporting students to take responsibility for their learning
- monitoring and addressing individual students' learning needs.

The student responses to the questionnaire (from 3685 Years 7–9 students) confirmed and extended these findings. Compared with students in other subjects, science students expressed low levels of agreement with the following statements:

the teacher encourages us to express our ideas and opinions in class discussions; the teacher has a good idea of what my interests are; we study things which are interesting to me; the teacher varies the lessons so we do lots of different types of things; the teacher sometimes gives different types of work to different students; the teacher knows when we understand things well; and we are interested and involved in our learning.

(Tytler et al., 2003, p. 11)

These findings are broadly consistent with the findings described above about prevailing pedagogies and student perceptions in science. Science is a subject that delivers non-negotiable, abstract knowledge, tending to use an authoritarian and narrow pedagogy which is arguably insensitive to the diverse learning needs of students. Nor does it provide the intellectual challenge associated with exploration and questioning, and substantive discussion of ideas, that middle years principles recommend. It might be argued that some aspects of these traditional characteristics are inevitable, given the specific, structured, and often difficult nature of science concepts. However, interviews with effective teachers of science (Tytler, Waldrip, & Griffiths, 2004) yielded components very similar to those of MYPRAD, indicating that effective middle years teaching in science is both possible, and exists in practice, at least in some classrooms.

It can therefore be argued that this picture of traditional science teaching neither conforms to current understandings of effective middle years practice, nor does it represent good practice as evidenced in some science classrooms. The effect is that students fail to see the relevance of science for their lives and futures, and fail to engage with meaningful learning. This conclusion is consistent with the strong judgments made by the European Commission report (HLG, 2004) which examined the current and projected shortfall in supply of scientists in Europe, and found the core of the problem to lie with science education:

Unfortunately, science education has been inclined to isolate itself from the rest of education and has tended to be separated by society into its own subculture. There is a strong tendency to regard the teaching of science not as an area of educational development of the student, but solely for the pursuit of the subject matter. Science education is viewed as the learning of 'science knowledge', rather than 'education through a context of science'. There is thus pronounced confusion between science on the one hand and science education (that which is promoted in schools) on the other.

(HLG, 2004, p. 9)

What is clear from the literature discussed above is that the problem with student attitudes towards and engagement with school science relates to the transmissive and limited pedagogies used, and the major focus on canonical abstract content that fails to enlist student interest and renders science ideas unnecessarily difficult. The fact that this is the case for all students, including successful science students, must give pause for thought. This review argues that the framing of curriculum, and teacher practice, needs to position science, for all students, as

a way of understanding the world and engaging with issues that are meaningful to them, and needs to move beyond restrictive notions of sequential conceptual understandings. In terms of pedagogy, there is much to be learnt from research into student engagement and learning in the middle years of schooling, which is the period of compulsory science during which these attitudes consolidate, and when students make decisions about what they are interested in and what studies they will pursue. The promotion of middle years' principles in the teaching of science, and research into how this is best carried out, provides a potentially productive way forward.

Student participation in post-compulsory science

A major aspect of the crisis in science education, and the aspect causing most direct governmental concern, is the drop in proportional numbers of students undertaking post-compulsory science courses, especially in the physical sciences and advanced mathematics. A number of speakers at the ACER conference emphasised the magnitude of this problem of diminishing numbers of students entering university science-related courses (e.g. Masters, 2006; Osborne, 2006) at a time when the demand for science and technology expertise is growing. This emphasis at the conference echoes the concerns of many governments including the Australian government, of science academies, and university departments who are suffering significant downsizing. This problem of diminishing numbers in science is occurring against a background of concern that post-industrial societies need to increase involvement in science and technology-related innovation and enterprise, if they are to remain competitive in a global environment.

In Australia, the Department of Education, Science and Training (DEST, 2003) reported that there has been an overall decline in commencing enrolments in undergraduate courses in the physical and natural sciences between 1997 and 2002. The Victorian Parliament Education and Training Committee (2006) expressed concern at the declining enrolment of school graduates into mathematics and science-related university and trade studies and careers. Within the science community itself there is increasing alarm at the declining number of students opting to undertake science studies at the tertiary level. For example, the Royal Australian Chemical Institute released a report on the supply and demand for chemists (RACI, 2005), which expresses concern at the decline in the number of students taking chemistry at university, and the resulting strain on chemistry departments, in some cases resulting in their demise. The Federation of Australian Science and Technology Societies (FASTS) has organised conferences on this issue and is currently developing policy on science education and science teacher preparation as their contribution to this problem.

At the ACER conference, Geoff Masters' (2006a) opening address summarised some of the Australian figures, drawn from a range of sources, showing declining involvement in post-compulsory science. These included:

- a decrease from 1978 to 2002 in the Year 12 biology cohort from 55% to just over 20%, in the chemistry cohort from 30% to 15%, and in physics from 27% to 12%
- the number of university students studying physical and materials sciences nationally fell by more than 31% between 1989 and 2002
- the proportion of Australian PhDs in Science and Engineering dropped from 46.9% to 37.2% between 1989 and 2002
- In 2001, only 1% of tertiary graduates in Australia were in the physical sciences, compared to 5.2% in the UK, and an OECD mean of 2.6%.

Jonathan Osborne (2006) presented a picture of the problem internationally, with figures mirroring those in Australia. For instance, the percentage of the post-16 years UK cohort specialising in science and mathematics, over the period from 1980 to 1993, dropped from 30% to 17% and it continues to drop. In his presentation, Osborne presented newspaper reports that highlight, in one instance, the 'terminal decline' of physics as a subject, and raise the spectre of Britain becoming a 'third world' country as it fails to produce scientists and

engineers. Thus, the decline in the physical sciences is now becoming well publicised beyond government policy circles.

These dramatic drops in student involvement in post-compulsory physical science courses are of considerable concern to governments, since they prefigure a decline in a country's ability to support technology and science-based innovation strategies that are fundamental to the economic well-being of post-industrial nations. A number of high level reports have pointed to the current and increasing shortage of science trained professionals. For instance, the European Commission report (HLG, 2004) on human resources in science and technology was named 'Europe needs more scientists' and called for a concerted effort to attract more young people into science. In a similar vein, Masters (2006a) quoted Peter Andrews, the Queensland Chief Scientist:

Far from solving the problem of finding 75,000 researchers in Australia ... we are producing less of the very scientists we need.

(Masters, 2006a, slide 20)

A report by the US academies of sciences, engineering, and the institute of medicine (National Academies Committee on Science, Engineering, and Public Policy (COSEPUP), 2006) pointed to the increasing need for science professionals in post-industrial societies. In the United States of America (USA), the Science and Engineering share of total civilian employment has grown from 2.6% to 3.8% over the years 1983 to 2002. The US COSEPUP report linked the problem directly with the competitive international climate in science-based industries, and the threat of the USA being overtaken by developing countries in this area. The COSEPUP report pointed out that despite the growth in demand for science and engineering employment, the number of engineers graduating from the USA was less than one-eighth of those graduating in China, and that chemical companies are in decline in the USA while there is considerable construction of chemical plants in China. These US figures are also relevant to Australia, which produces fewer engineers per head of population than other OECD countries (Victorian Parliament Education and Training Committee, 2006). Thus, at government level, as represented in these high level reports, there is increasing concern about the capacity to pursue the science- and technology-based industry policies that are deemed necessary to maintain the economic well-being of the post-industrial state, given the decline in student uptake of post-compulsory science.

Most commentators see this decline in uptake as directly linked to inadequacies of school science, and its failure to excite student interest and engagement. For instance, Masters (2006a) made the point that the decline in numbers in post-compulsory science courses should be seen as directly related to the decline in interest in science from Year 4 to Year 8, as found by the TIMSS study (Thomson, 2006). Masters (2006a) argued that the problem was that many high school students perceive school science to be uninteresting, unimportant and irrelevant to their lives, simply a matter of learning provided facts, and they found it difficult to learn. The COSEPUP (2006) report put a high premium on the improvement of school science courses, as a critical element in attracting more students into post-compulsory science and engineering. In recommending ways forward for science in schools, the report focused primarily on the quality of teachers.

The European Commission report (HLG, 2004) also focused on science education as the major underlying problem determining the supply of scientists. It argued that science education needed to change from an exclusive pursuit of subject matter expertise, to align it with a concern for the general educational development of the student. Their view was that school science should better link with real science practice, and align itself more effectively with the needs and interests of young people. The European Commission Group (HLG, 2004) emphasised the need to avoid elitist policies in science, striking a balance that promotes scientific excellence. It found that countries that appear to do well in terms of scientific literacy among young people and numbers of people employed as scientists tend to have policies aimed at increasing the overall performance of all schoolchildren.

In tracing the extent and nature of the crisis in science education, we see that there is clear evidence that the curriculum and classroom practice is failing to excite the interest of many if not most young people at a time when science is a driving force behind so many developments and issues in contemporary society. We see also that the main reasons behind this, at least from the students' perspective, are understood. This decline in interest clearly contributes to a decline in participation in post-compulsory science, particularly physical science, and this is seen to have considerable implications for the economic well-being of post-industrial societies. Section 3 argues that the implications of this decline in interest go well beyond a narrow economic focus.

However, before we leave this discussion of the crisis, there is another aspect that needs pointing out, involving a feedback loop. With decreasing student interest leading to decreasing participation in university level science, we have decreasing numbers of teachers coming into the system and a looming shortfall in qualified science teachers, particularly in the physical sciences. This will arguably make it more difficult to provide innovative and interesting science experiences in schools. We thus find ourselves in the midst of a downward spiral of engagement with science.

Who is teaching science?

In discussion and reporting of system-wide issues in relation to science education, it is widely and regularly acknowledged that the key to student learning and engagement in science is the existence of teachers who are qualified and committed to science, and capable of flexible approaches to teaching and learning (Goodrum et al., 2001; DEST, 2003; HLG, 2004; National Academies Committee (COSEPUP), 2006). In Australia, there is a current problem and a looming crisis in the supply of science teachers, especially in the physical sciences, and a number of commissioned papers and reports have focused on this issue (DEST, 2003; Harris et al., 2005). These Australian findings are consistent with overseas trends (see, for instance, the discussion on science teacher supply in Europe in HLG, 2004). The central findings in these and other Australian reports include the following.

- The number of students in secondary teacher education courses undertaking physics and chemistry subjects declined by 62% and 37% respectively between 1992 and 2000 (DEST, 2002, p. 11).
- Only a minority of junior to middle school teachers of science had studied physics beyond first year level (Harris, 2006; Harris et al., 2005).
- The percentage of schools that report experiencing difficulty in adequately staffing physics and chemistry classes is 40% and 33% respectively (Harris, 2006).
- Low levels of science teaching and learning are biting particularly in non-metropolitan areas, where, in a recent national survey (Lyons, Cooksey, Panizzon, Parnell, & Pegg, 2006), schools in regional areas and those in remote areas are respectively twice and four times more likely to report it was 'very difficult' to fill vacant teaching positions in science, ICT and mathematics than those in urban areas.
- The shortage of teachers in the physical science will worsen, given that existing teachers tend to be in the older teaching demographic. Half of science teachers under 35 years of age have predominantly biology backgrounds, and have studied no physics at university (Harris, 2006).
- There are high levels of disillusionment among current science teachers with work conditions and negative student attitudes. These are associated with low levels of expectation of staying in teaching in the longer term.

There is thus a current and looming crisis in the supply of qualified teachers of science, especially physical science, particularly in rural and regional areas. This will exacerbate the problem of reform in science education, given the importance of having trained and enthusiastic teachers of science leading innovative science teaching practices, especially in the physical sciences. Attracting talented students into science teaching is a serious challenge.

Concluding comments

The crisis in science has a number of dimensions relating to quantity – the numbers of students entering post-compulsory science courses, the numbers of qualified science professionals in the workforce, and the numbers of teachers of science in schools. It also has dimensions relating to quality – a school science that engages students in significant learning and attracts them to science-related studies, and teacher education that supports teachers to provide science learning experiences that engage students. These questions of quantity and quality are related in that the encouragement of quality experiences in science education at any level can be assumed to impact on the numbers engaged in science. It is with issues of quality that this review will mostly concern itself. The training and professional development of teachers to support them in implementing innovation will be discussed in Section 6.

Enriching science education

3

The challenges to school and university science implied by the societal changes described in Section 1 do not simply involve the content of the curriculum. Rather, these significant changes have implications for the way we conceive of the purposes of an education in science and what practices we imagine we are preparing students for in this changing, contemporary world. In this section, the different purposes of school science and the interests served by these purposes, will be considered to develop a better understanding of the way science education might be re-imagined to best serve Australia and its people in the 21st century.

Traditional school science

The point was made in Section 1 of this review that traditional school science has been successful in maintaining its core nature, in the face of considerable societal change. What are the reasons for this? The key players in deciding the shape and content of Australian school science curricula have been, and remain, academic university scientists supported by science educators steeped in a discursive tradition that is consistent across the secondary schooling years, and in university science, focusing largely on the acquisition of canonical abstract ideas. This discursive tradition is claimed by Aikenhead (2006) to stem from the early history of arguments to justify the inclusion of science in the curriculum. He traces the influence of the British Academy for the Advancement of Science (BAAS) in the mid-19th century in establishing an argument for pure science that served the 'twin ends of a liberal education and the advancement of science' (Layton, 1986, quoted in Aikenhead, 2006, p. 13).

By building the curriculum substantially around canonical disciplinary ideas that were held to serve the purpose of mental training, science managed to position itself alongside traditional subjects such as classics, languages, mathematics and history as part of a liberal curriculum, and to head off the potential criticism of its subject matter being utilitarian and tainted by association with manual labour. It also helped to establish a status for science that served the political purpose of recruiting members and advancing its cause generally. This twin set of principles – recruitment of a scientific elite, and the exclusive focus on canonical science as mental training – is significantly echoed in today's traditional curriculum. Aikenhead (2006) labels this the 'pipeline' version of the science curriculum providing training for future science professionals, as opposed to a humanistic version that would present science more broadly as a human endeavour rather than a technical disciplinary training.

During the 20th century, there have been many attempts to widen the school science curriculum in order to place greater emphasis on the cultural and the human aspects of science. Recent examples of such attempts include arguments for a 'science-technology-society' or a 'science-for-all' or a 'scientific literacy' perspective, which will be described in more detail below. However, like previous calls for change, they have not been successful in challenging the disciplinary status quo. Part of the reason for the persistence of status quo science relates to the strong discursive traditions subscribed to by teachers of science resulting from their enculturation during their own schooling and undergraduate studies (see Aikenhead, 2006, p. 64 for a discussion of teacher identity and allegiance). This culture is strongly represented in school science discursive practices, supported by resources such as textbooks, laboratories and their associated equipment, timetabling arrangements and by assessment and reporting traditions. Another aspect is the force of long habit of teachers who have developed effective ways of delivering canonical content, who may lack the knowledge, skills and perspectives required for the effective teaching of a different version of school science.

Fensham (2002) argues that academic scientists and science educators have been major players in the shaping of the school science curriculum and that their efforts have not led to appropriate programs for scientific literacy. He argues the need to look more widely to identify appropriate content for the contemporary science curriculum. A number of Australian studies have shown the influence of university science academics acting as disciplinary gatekeepers in opposing changes to the school science curriculum (Fensham, 1998; Hart, 2001, 2002). Hart's (2001) study of an attempt to humanise the Victorian Physics curriculum showed the influence of traditional conceptions of science held by non-science curriculum decision makers on such curriculum innovations. The need to gain the support of school community members and parents before we can successfully make changes in the science curriculum, when it is very likely they hold traditional views of the nature of science and science knowledge, was emphasised by teachers in the ACER science forums (Tytler & Symington, 2006). Commitment to maintenance of the academic status of school science is a key feature of commitments to its traditional forms. Venville, Wallace, Rennie and Malone (2002), in a review of curriculum innovation, found that subject status was an important factor in curriculum decisions, and high status tended to be accorded to those subjects with rigid, highly differentiated and insulated course content. This is consistent with the repeated failure of integrated science subjects with wider academic content (sometimes referred to by the pejorative term of 'soft science') to be accepted for entry into university science courses.

Aikenhead (2006) contrasts the educational failure of traditional school science (citing the overwhelming evidence of student disenchantment and disengagement) with its political success (citing its continuing survival and high status). However, the now patent concern in Australia, with the decreasing number of students choosing to take post-compulsory science, and the projected worsening of the situation with teacher supply, has drawn attention to this irony. It would appear that the traditional science curriculum, designed principally to train young people as a preparation for entering the science discipline, is the very instrument that is turning them away from science.

Broadening the purposes of school science

If the purpose of school science needs to be broadened, then we need to interrogate its different purposes and ask the question: 'Which are most relevant for informing our direction?' We also need to ask the question: 'If the influence of university science academics, teachers and some general members of curriculum committees has served to uphold the traditional disciplinary perspective on science education, what wider set of voices and interests need to be represented in charting a way forward for science education?'

Symington and Tytler (2004), as part of a program intended to widen the voices speaking to school science, interviewed 15 community leaders concerning their views of the purposes of

school science. Based on the interviews they modified a list of the purposes of school science generated by Driver, Leach, Millar and Scott (1996). This list is reproduced in Table 4.

Table 4. Purposes of science in the compulsory years

Cultural purpose: to ensure that all members of society develop an understanding of the scope of science and its application in contemporary culture.

Democratic purpose: to ensure that the students develop a confidence about science which would enable them to be involved in scientific and technological issues as they impact on society.

Economic purpose: to ensure that Australia has the number and quality of people with strong backgrounds in science and technology in business and public life, as well as in science and technology, that are needed to secure the country's future prosperity.

Personal development purpose: to ensure that all members of society benefit from the contribution that the values and skills of science can make to their ability to learn and operate successfully throughout life.

Utilitarian purpose: to ensure that all members of society have sufficient knowledge of science to enable them to operate effectively and critically in activities where science can make a contribution to their personal wellbeing.

(Symington & Tytler, 2004, p. 1411)

Symington and Tytler's (2004) community leader informants argued for an education 'for science in life', broadly conceived and designed to engage students at a personal level, rather than an education 'about science'. They emphasised the interconnection between the different purposes, and the discussion showed how difficult it would be to simply arrange these purposes in some kind of order of emphasis as the basis for curriculum planning. In the interviews there was notably little mention of the importance of accumulating knowledge in a traditional sense. Instead, the informants emphasised the need to develop in students a positive view of science that disposes them, on leaving school, to engage with science ideas and developments. This position is consistent with a 'humanistic' perspective on school science (Aikenhead, 2006; Fensham, 2006). As Symington and Tytler argue:

This image of the school curriculum as a launching pad into a complex and highly contextualized future, rather than the creation of a certified knowledge bank, raises considerable challenges for teachers, curriculum writers and policy developers. The two images need not be contradictory. However, the lack of concern with specific knowledge building on the part of the interviewees, and the questions raised of the usefulness of particular knowledge over a life span, provides a challenge to how we might think of knowledge within a scientific literacy oriented curriculum.

(Symington & Tytler, 2004, p. 1415)

As argued above, current governmental concerns about the lack of uptake of science in the post-compulsory years focus on the need to provide a science-trained workforce for the new knowledge economy (DEST, 2003). However, while this is a critical issue, research clearly demonstrates how the modern knowledge economy has a need for science-savvy citizens not simply in the science and technology workforce but in government and industry generally where science-related policy and decisions are made. There is also a need more generally for science-savvy citizens who deal increasingly with science and technology artefacts and issues at a personal and a public level, and directly influence policy through their responses and concerns (Symington & Tytler, 2004; Tytler & Symington, 2006a).

Based on this insight, we therefore need to think of the science curriculum, not simply as a recruiting ground for science-talented students, but rather as the setting for the development of a culture of interest in science by all, and an opportunity for all students to engage with

science ideas and learning. In fact, this point, that school science should not concern itself exclusively with an elite, but cater for science learning for all students, is now well accepted in most policy circles, worldwide (DEST, 2003; UK House of Commons Select Committee on Science and Technology, 2002; HLG, 2004). Part of the argument hinges on the realisation that the traditional curriculum, founded on disciplinary interests, is failing in the very job it is intended to do; that is, to attract high-performing students into post-compulsory science. This review is similarly arguing that the evidence points to the need to develop science curriculum and pedagogy that reflect a broad set of purposes, aimed at capturing the imagination of students in general, as the best way forward to recruiting science-enthusiastic students.

Scientific literacy as a focus for driving change in school science

The argument for a broadening of the science curriculum to better meet the needs of all students has shifted from the call for a science for all students (Fensham, 1985) to the call for a scientific literacy focus (Bybee, 1997; Goodrum et al., 2001). Scientific literacy has been defined in different ways, but a commonly quoted definition is that developed by the OECD. Barry McCrae (2006, p. 22) described the recently updated description of scientific literacy developed for the purposes of the PISA 2006 assessment project, which refers to 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
- willingness to engage in science-related issues, and with the ideas of science, as a reflective citizen.

Rennie (2006, p. 6), in her unpacking of the characteristics of a scientifically literate person, emphasises an action-oriented version of the scientifically literate person who:

- is interested in and understands the world around them
- engages in the discourses of and about science
- is able to identify questions, investigate and draw evidence-based conclusions
- is sceptical and questioning of claims made by others about scientific matters
- makes informed decisions about the environment and their own health and well-being.

Rennie's list could be seen as operationalising the PISA list of scientific literacy characteristics, but she also shifts the focus to scientific literacy as developing a sense of personal agency in engaging with science, and to a set of skills that would enable this.

Norris and Phillips (2003) also offer a list of conceptions of scientific literacy distilled from the literature, which includes the ability to distinguish science from non science, and some more explicit items dealing with willingness to engage with science ideas. For example, they argue that a definition of scientific literacy should include:

- appreciation of, and comfort with, science including a sense of wonder and curiosity
- ability and wish to be an independent, lifelong science learner.

Thus, there is a strong strand in writing about scientific literacy concerning students' orientation to science, as well as their capabilities in understanding and applying science ideas. Osborne (2006, p. 3) argues that a science curriculum for all can only be justified if it offers something of universal value for all. He offers a broadly liberal agenda for the science curriculum which includes scientific conceptual knowledge, awareness of the epistemic and social practices of science, the more broadly cognitive, and the affective and social elements of learning and engaging with science.

We can see, therefore, that there are differences in emphasis in scientific literacy challenges to the traditional science curriculum. However, these challenges are consistent in focusing

on school science for future citizens rather than for future disciplinary experts. It should be noted also that the argument for a scientific literacy approach to curriculum planning has been attacked on a number of levels.

Concerns with the scientific literacy construct

The term *literacy* has been challenged as inappropriate as a construct on which to build science education. We all need to read and write to be able to operate effectively, and also increasingly to be numerate. But the extension of this notion to science is problematic when it is clear that many citizens in technologically advanced societies operate very effectively, with only very rudimentary science understandings. Layton, Jenkins, Macgill and Davey (1993) argue that we should talk, not of an undifferentiated scientific literacy, but of scientific literacies. They argue that the needs of different publics in different contexts is sufficiently diverse to require specific science education strategies aimed at the interests of different 'market segments'. Tytler, Duggan and Gott (2001b), in a study of an environmental dispute in the UK, identified a range of different publics who were involved in the dispute, including members of parliament, lawyers, science-trained locals, engineers, and local farmers, and the identified levels of science understanding accessed by each. They thus argued against the notion of a unitary public or simplistic notion of citizen in considering the appropriate content for school science.

Shamos (1995) argued that the scientific literacy construct is too poorly defined to be of real use as a driver for science curriculum reform, and is essentially an unattainable myth. The complexity of the science involved in public science issues, for instance, is a stumbling block for the argument that citizens can engage meaningfully in debates where experts themselves can have widely differing views. Fensham (2002) points out that we do not necessarily need to understand the science we use. Modern technologies are designed so that they can be operated without an understanding of their scientific basis. On the other hand, making decisions on a personal level with regard to health, or voting on local science-based issues, could well involve accessible science knowledge. The need to act in science-related situations will differ widely depending on the circumstances of the individual, and on the extent of translation of science knowledge involved. These issues will be taken up in a discussion of science and citizens, in Section 3.

This review has argued that school science is currently not well served by its strong focus on abstract canonical ideas in pursuit of a predominantly disciplinary expertise purpose, and that we should emphasise the more general scientific literacy, or citizen preparation purpose instead. This still leaves open a range of questions about the detail, and also some important matters of principle. These questions include:

- What type of citizen are we thinking of, and in what set of circumstances?
- In what ways do we imagine a citizen could interact with science?
- What sort of knowledge would best serve the future needs of students as citizens?
- How do we balance issues of current and future relevance for students?
- What weighting do we give to 'insider' and 'outsider' perspectives on science (i.e. the epistemological vs. the sociological aspects)?

The hard conceptual and definitional work has still to be done. This review will approach these questions by considering the different emphases that the science curriculum might pursue, and the different ways in which students might use knowledge of science, currently, or in a variety of possible futures.

Curriculum emphases and questions of interest

Fensham (2002) argues that we needed new *drivers* for scientific literacy given the failure of scientists and science educators to engender significant reform in school science. He proposed the interrogation by a variety of societal experts of what knowledge would be worth including in a broadened school science. This concern to include new voices in the science curriculum debate also underlay studies of socio-scientific issues (Irwin & Wynne, 1996; Tytler et al.,

2001a, 2001b), the study of community leaders described above (Symington & Tytler, 2004), and the recent studies of scientists, science graduates and students reported at the ACER conference (Tytler & Symington, 2006). The findings of these and other such studies will be discussed in the following sections, as part of the attempt to work through an argument for appropriate foci for science education.

Science curriculum analyses

Rather than deal directly with competing curriculum purposes, a number of writers have found it more helpful to frame the content of the science curriculum in terms of different knowledge emphases. Roberts (1988) identified seven knowledge emphases in his analysis of science curricula.

Table 5. Roberts’s Seven Knowledge Emphases

<ul style="list-style-type: none"> • An everyday coping emphasis: what you need to know to understand and control your immediate environment (e.g. health, chemical use, technology artefacts)
<ul style="list-style-type: none"> • A structure of science emphasis: how science operates as a discipline (similar to the Nature of Science)
<ul style="list-style-type: none"> • A Science, Technology and Society emphasis: situating science knowledge within a social and technological perspective
<ul style="list-style-type: none"> • A scientific skill development emphasis: focusing on investigative skills and procedures
<ul style="list-style-type: none"> • A correct explanations emphasis: focusing on science theories and concepts, the products of science
<ul style="list-style-type: none"> • A self as explainer emphasis: science as a cultural institution, and a human endeavour, with the history of science being emphasised
<ul style="list-style-type: none"> • A solid foundations emphasis: as preparation for further studies.

(Based on Roberts, 1988, pp. 27–54)

Corrigan (2006, p. 51) describes a similar categorisation of approaches used by Ziman. Aikenhead (2006) also undertakes a similar analysis, identifying seven different types of relevance that could inform science curriculum content. These types of relevance amount to different knowledge emphases, which again align with different curriculum purposes. Aikenhead follows Fensham (2002) and Roberts (1988) in identifying these different emphases with particular interests, and also different informants for deciding what content should be represented. For instance, he argues his *wish-they-knew* type of relevance is typically embraced by academic scientists and education officials when asked what knowledge is of most worth, and the answer – canonical science content – is designed to prepare students for further disciplinary science programs. The content of *need-to-know* science would serve the interests of citizens, and could be explored by interrogating the general public and their encounters with science. *Personal curiosity* science serves the interests of students, and is best informed by students’ views.

Fensham’s (2006) presentation at the ACER conference addressed the question of whose interests school science is currently serving. He identified the competing interests which have been the major curriculum drivers to date, as being disciplinary science interests as opposed to students’ and society’s interests. He identified a new set of pressures on curricula that have the potential to subvert moves to build science education curricula that engage students. These come from world of work interests, based on an orthodoxy growing up around the demands of the knowledge society, which emphasise basic skills and competences as required of the new knowledge worker. They appear as generic elements in ‘new essentials’ curricula around Australia. In his presentation Fensham argued, as he has for some time, that science education

must be built around a capacity to engage and excite students, and thus lead them into the commitments to scientific ways of viewing the world that are presupposed by disciplinary-based science studies.

The nature of science

Calls for a science literacy perspective, or a humanistic perspective, have in common a focus on students' understanding how science works – the nature of science and its processes – as well as the content of science. Further, this review has argued that the traditional school science curriculum reflects in its intent and shape a narrow and outdated version of science. This argument also applies to tertiary science. At both secondary and tertiary levels the emphasis is on the acquisition of interlinked structures of abstract canonical ideas, supported by assessment regimes focusing on students' mastery of these ideas in set-piece situations. It has further been argued that the continuing resistance to curriculum change over the 20th century has largely been due to the allegiances of teachers, and to some extent the general public, to this version of disciplinary knowledge and expertise. We need to remember that teachers' professional identities are forged through their experiences of school and university science, with very few having practised science in a research or professional sense.

If we are serious about having school and university science reflect the nature of science as it is practised in contemporary society, then we need to interrogate directly the nature of contemporary science and how it might differ from schooling versions.

The changing nature of science

John Ziman, a respected commentator on the nature of contemporary science and the way it is practised, writes about the huge explosion in knowledge and the fundamental changes to the practice of science over the last century, from something being pursued by individuals to the collectivisation forced by 20th century imperatives. He argues that there have always been two parallel scientific cultures: one an academic culture which is intensely individualistic where a scientist gains the status and capacity to pursue knowledge through a publication record; the other an industrial science culture where team work is more common and the drivers for knowledge production are commercial. Ziman (1998) argues that more recently both cultures have come together into a 'post-academic' science, as a result of the increasing financial pressures on universities, and the success and pervasiveness of science. He points out that post-academic science is largely the work of teams of scientists, often networked over a number of different institutions, and that it:

is usually undertaken as a succession of 'projects,' each justified in advance to a funding body whose members are usually not scientists. As the competition for funds intensifies, project proposals are forced to become more and more specific about the expected outcomes of the research, including its wider economic and social impact. This is no longer a matter for individual researchers to determine for themselves. Universities and research institutes are no longer deemed to be devoted entirely to the pursuit of knowledge 'for its own sake.' They are encouraged to seek industrial funding for commissioned research, and to exploit to the full any patentable discoveries made by their academic staffs.

(Ziman, 1998, p. 1813)

While there are potentially many implications to be drawn from this for the contemporary science curriculum, Ziman's particular focus was the need for scientists to explicitly acknowledge the ethical implications of their work, something that science has traditionally eschewed in its maintenance of a disinterested ethical position in regard to knowledge production.

Challenges to science

Most scientists and science educators see science as universal, and scientific knowledge as having privileged status on the basis of the reliability of the methods of science. During the past two decades, this view has come under critical scrutiny from a number of different perspectives including feminist, postcolonialist, sociological, anthropological, and from critical and cultural studies. Critics of modern Western science have questioned knowledge production in science by asking what can be known and by whom, and what constitutes and validates knowledge. Such questions highlight the problems with a universal account of the nature and limits of knowledge, and raise issues about social context and the status of knowers (Alcoff & Potter, 1993, p. 1). Such issues have been debated in the so-called 'science wars' which pitted postmodern critiques against traditional, realist views of science.

The science wars argument essentially hinged on whether science could claim its particular form of knowledge as privileged, given its epistemic program based on theory building around a sharply managed and contested evidential trail. The counter-argument claimed that science is a form of socially constructed knowledge like any other, and in its extreme version led to the relativist position that science was no more defensible than any other form of knowledge. Osborne, Ratcliffe, Collins, Millar and Duschl summarise the question thus:

The case made against science has been one where Popperian notions of an objective reality and the truth-seeking goal of science have been replaced instead by the idea that the best that science can achieve are socially determined theories that are internally coherent and instrumentally viable but bear no necessary relation to any ontological reality.

(Osborne et al., 2003, p. 695)

In fact many academic writers have pointed out the lack of consensus on what really constitutes science. Ziman complained:

Just when society ought to be getting sympathetic well-informed advice from their meta-scientific colleagues, they are being offered little but deconstruction and doubt.

(Ziman, 2000, p. 8)

In fact there has been considerable scholarship around the practice of science that raises serious questions about the universal nature of science knowledge and practice. Latour and Woolgar (1986) in their seminal study of a science workplace, wrote about the cultural practices inherent in knowledge production, and the central role of text in establishing a discourse about truth and universality. Ziman (2000), reviewing the social and cultural processes that underpin science, argued that:

scientists still have normative commitments to originality and scepticism, and the establishment of reliable knowledge still requires the processes of communication and critique, and an abiding commitment to arriving at knowledge that 'works'.

(Brannigan, 2002, p. 607)

Thus, Ziman argued, acknowledging the cultural practices inherent in science knowledge generation does not compromise but indeed strengthens the science claim to knowledge that should be accorded high status.

There is agreement among most curriculum commentators that a contemporary science education should include a substantial commitment to students understanding the nature of science (NOS). Driver et al. (1996) have argued that without explicit attention to this, students will leave school with a very naive idea about the nature of science knowledge and processes, and in particular the epistemic basis of science, the way knowledge claims are generated and tested. This review argues that for these reasons, and given the capacity for misunderstanding demonstrated by the science wars, it is important, that NOS be an explicit feature of school

science. However, representations of the NOS in the curriculum need to be based on established principles that can claim wide agreement inside and outside the science community.

Reaching agreement on the nature of science

With the suspicion that the claims of disagreement between sociologists, philosophers of science, science educators and scientists were exaggerated, Osborne et al. (2003) undertook a three-stage Delphi study in which 20 experts undertook a process of generating and reacting to statements about the nature of science that should be represented in the school curriculum. They went through a process of commentary and refinement until a set of principles was arrived at that had broad agreement among the group, which included leading scientists, historians, philosophers, and sociologists of science, science educators and those engaged in the public understanding of science or science communication. They concluded:

our findings provide empirical evidence of a consensus on salient features which are both significant and essential components of any basic knowledge and understanding about science and, in addition, uncontroversial within the relevant academic communities with an interest in science and science education. These data suggest, then, that these themes do have sufficient agreement to form the core of a simplified account of the nature of science suitable for the school science curriculum.

(Osborne et al., 2003, p. 712)

In this study, a number of themes emerged for which there was both consensus and stability in being rated as important for inclusion in the science curriculum.

Whereas Table 5 listed knowledge emphases in the school curriculum, Osborne's list of themes refers to how science should be characterised more generally. Six of the major themes are the subject of Table 6.

Table 6. Osborne's Characteristics of Science Themes

- Scientific methods and critical testing, as the core basis on which science is built, involving the establishment of evidence to test hypotheses
- Creativity, emphasized as opposed to learning stodgy facts, and enabling students to do science in a way that allowed room for exploration
- Historical development of scientific knowledge, emphasizing the human nature of science activity, and an appreciation of developments in science, and the social determinants and effects of science
- Science and questioning, emphasizing the need to explicitly teach questioning as representing the driving force in science, the continual testing and evolution of understandings
- Diversity of scientific thinking, emphasizing the breadth of science activity, its flexibility with methods, and its importation of ideas from other areas
- Analysis and interpretation of data, emphasizing that data does not speak for itself but must be interpreted, and that different scientists might come to different conclusions with the same data.

(Osborne et al., 2003, pp. 706–9)

Another three themes complete Osborne's set: science and certainty (emphasising the provisional nature of much contemporary science), hypothesis and prediction, and co-operation and collaboration in the development of scientific knowledge. These nine themes are a good fit with the scientific literacy capabilities described in the previous section, lending further support for the inclusion of NOS in school science curricula. They also have currency in, and are applicable to, many general literacy and student learning competency statements, across the full spectrum of school learning areas. However, they represent a challenge for traditional science teaching, which tends to come from a restricted perspective on learning.

A second set of themes which more than half of the expert participants judged to warrant inclusion in the curriculum included (p. 713) links with technology, moral and ethical dimensions, the empirical base of scientific knowledge, and the cumulative and revisionary nature of scientific knowledge.

Teaching the nature of science

As indicated previously, there are two dominant strands within NOS traditions. One deals with the epistemic nature of science, and is advocated by science educators such as Jonathan Osborne (2006) who advocate argumentation and reasoning, and studies of historical science episodes, as ways into the thinking and theory building processes of science, emphasising the habits of mind and cultural aspects of science. The other NOS strand emphasises the way science interacts with social settings, or technology, or the social aspects of scientific knowledge generation.

Another approach to teaching about the nature of science has been suggested by Hipkins (2006). Hipkins has pointed out that teachers generally do not feel comfortable with explicit teaching of the epistemological basis of science, despite substantial encouragement through curriculum formulations to do so. In a study of recipients of teaching fellowships in New Zealand involving teachers spending a year engaged in science research, she found them to be uninterested in formal interpretations of the way science knowledge is generated, but they expressed a passion for the practices and objects of their scientific inquiries. She argues that we need to develop an ontological approach to NOS which captures the passion and commitment of science teachers to the subject. Out of this exploration she suggested a form of curriculum organisation based on Latour's (2004) idea that science and science education needs to shift their emphasis from 'matters of fact' to 'matters of concern'.

In a science education incorporating matters of concern, the wider ethical, social and human questions intrude naturally into science topics. Thus, in a study of global warming, students would develop networks of questions that involved exploring the many aspects of the science of warming mechanisms, and the modelling and predicting of climate change and the way evidence is collected to establish patterns, together with a consideration of the choices humans have to respond to this. Hipkins argues on the basis of classroom observations that students are capable of considerable sophistication in generating networks of issues, and that such a curriculum organisation model could produce significant learning of scientific concepts, investigative concepts, and the nature of science.

Introducing the voice of scientists

As part of a research program aimed at widening the range of voices that speak to school science, Tytler and Symington (2006a) ran focus groups of scientists in order to interrogate the nature of contemporary science that spoke to major societal issues. Unlike the Osborne et al. study (2003) described above, this study directly probed the experience of scientists; the scientists worked in Australia's research priority areas, such as advanced materials, climate change, or preventative health care. Each group of community representatives was assembled by a key scientist in the field. The groups were broadly constituted to include government, university, industry, and education. The groups each discussed the key issues in their area, the skills needed by science workers in the area, and the skills and understandings needed by citizens to respond appropriately to advances in the area.

The focus group sessions provided compelling arguments for the importance of science to the country's future. There was a universal concern with the level of public understanding of, and response to science. The concerns were of two broad types. First was the need to develop a culture of innovation and willingness to engage with new technologies. This concern was mainly advanced by the technologically oriented groups (frontier technologies, protecting Australia from invasive pests and diseases, advanced materials, etc.). Second was the need to develop a better understanding of science and technology to promote reasoned debate concerning impacts on individuals and communities. This concern was mainly advanced by groups dealing

with societal issues (climate change and water resources). The groups commonly promoted the view that citizens needed to be able to respond critically and analytically to new technologies and associated issues. In relation to the knowledge needed by citizens, rather than mentioning specific conceptual areas, they talked of ideas such as uncertainty and risk, understanding how scientists work, understanding the impact of science on people's lives, and knowing who to trust in relation to the science behind controversial issues.

With regard to the nature of science, the view that emerged for all focus groups was one of science constantly evolving, of practice in science focusing around multi-disciplinary teams, of science linked with technology, and science dealing with complex systems with many interconnected effects such as the need to balance economic, social, energy and environmental factors. The groups had a great deal to say about school science, which many participants regarded as representing an outdated and discipline-bound view of science. They argued for a focus on lifelong learning aimed at future public attitudes through engaging students' interest, rather than on knowledge structures aimed at the selection of future scientists. They tended to advocate a focus on the processes, skills and habits of mind of science (problem solving, reasoning with evidence, representing and interpreting data mathematically), on personal relevance and engagement, and on science within social and ethical contexts. Thus, this high status group of scientists working in research priority fields gave a rather different perspective on science and school science than the narrow content view that curriculum panels in Australia seem to regard as their core commitment.

The findings of this study are consistent with Osborne et al.'s (2003) themes, and with previous work focusing on the appropriate purposes and emphases of school science (Tytler et al., 2001a; Symington & Tytler, 2004). They are also consistent with the curriculum of the Australian Science and Mathematics School (Davies, 2006). The findings lend support to those who advocate a strong curriculum focus on science investigative skills and dispositions. Thus, the voices of contemporary scientists can be added to those calling for a substantial re-imagining of the science curriculum, emphasising a diversifying of the purposes of school science, with greater weight being given to the practices and habits of mind valued in contemporary science settings.

Introducing contemporary science into the curriculum

At the ACER conference, discussion of the contemporary nature of science was to a large extent a silence, with most presenters focusing directly on school science, pedagogy and student learning. Science was taken for granted. There were, however, some exceptions. Lyn Carter and Philip Clarkson (2006, p. 89) argue the need for school science education to represent the way science is practised in a globalised world. Jonathan Osborne (2006) talked about the paradox that teaching the best that science has to offer, for the future scientist, inevitably involves it being seen as 'received knowledge' and thus not open to questioning. This process misrepresents the nature of science as it is actually experienced by the expert practitioner.

The dilemma, then, is how we might juxtapose the need to teach established scientific knowledge, with the need to represent science as it is practised in contemporary settings. Jim Davies (2006) emphasised the links in the curriculum of the Australian Science and Mathematics School (ASMS) between teachers, students and practising scientists. In the ASMS, science is made contemporary by contact with practitioners, by selection of socially relevant, interdisciplinary topics, and by 'weaving scientific understanding and logic into cultural, social, historical, legal and ethical perspectives' (p. 57). The ASMS provides a model of how contemporary science can be represented in the school science curriculum. There is, however, a question about how practical a model this is for schools more generally. This review will continue to probe ways in which science education can effectively represent contemporary science practice.

Science for future scientists

This review has argued that a scientific literacy perspective needs to be interpreted and operationalised in terms of the needs of a range of possible adult futures – science professionals and professionals more generally, and citizens in various capacities – as well as the needs of students themselves. The question of preparing students for possible futures requires that we ask what knowledge and capabilities need to be developed for each of these. We shall start with those for science professionals.

As scientists working professionally in their fields, the scientists in the Tytler and Symington (2006a) study described earlier emphasised the importance of scientists having the ability to communicate effectively to multiple audiences, to be able to work in multi-disciplinary teams, to have well-developed analytical thinking skills, to understand the social and ethical context in which they work and to have developed the desire and ability to be lifelong learners.

This list is broadly consistent with the views expressed by directors of Beijing's 11 top science research institutions, reported in a study by Fensham (2004), who were asked about the qualities they would wish for in their scientists, beyond a great deal of knowledge.

Ten qualities were identified by at least half of the respondents as important. Of these, creativity was the most common, listed by ten. Personal interest in science, perseverance, willingness and desire to inquire, and the ability to communicate, social concern and team spirit were all listed by half the respondents.

(Fensham, 2004, p. 7)

Fensham points out the illogicality of basing a school science system, designed to train future scientists, mainly on the building of a great deal of knowledge, and effectively ignoring these other, very important capabilities of practising scientists. These capabilities are of course desirable for anyone, but arguably they take particular forms in relation to science, and they require foregrounding in science courses.

The nature of science capabilities

The capabilities described by Tytler and Symington's scientists, and by Fensham's research directors, are similar to graduate attributes promoted by many universities, and also to generic dimensions of essential learnings curricula now appearing in some Australian states. In attending to these attributes/capabilities, there are two related issues to be considered; first, the appropriate balance between knowledge and other science capabilities in school science, and second, the degree to which these capabilities can be fostered separate from grappling with science conceptual knowledge.

Fensham (2006) argues that the danger for science as a subject, which is already grappling with the issue of student interest, is that it could become subservient to abstract generic capabilities, which once again would lead us away from meaningful engagement with science phenomena. In the Victorian Essential Learnings Standards (VELS: <http://vels.vcaa.vic.edu.au>), for instance, the disciplinary science structure based on vertical organisation of canonical ideas has survived with little modification. In a commissioned paper underpinning VELs, an *engaging with and valuing science* strand was argued for, but was subsequently excised on the basis of the need to streamline the document. In the Victorian case, much will depend on the quality of the ways in which these wider capabilities, such as imagination and problem solving, attend to the particular nature of thinking and acting scientifically, and are situated in contexts that are meaningful to students and engage their interest.

Science and the workplace

The research into the nature of scientists' work, described above, implies that the preparation of scientists is best served by a diversification of curriculum emphases beyond an exclusive

focus on canonical science ideas. School science needs to incorporate (a) a range of capabilities such as reasoning and problem solving, creativity, communication, and personal dispositional factors and (b) understandings about the nature of science and the way it interacts with society. The needs of society for science-friendly and science-savvy people is not restricted to the need for science professionals, but that such people are needed in positions of influence and management, wherever decisions are made on science-related issues. In point of fact, BSc graduates find their way into many positions outside their areas of speciality (Anderson, McInnis, & Hartley, 2003).

In a recent study of such science graduates, Rodrigues et al. (in press) identified a range of capabilities these science graduates felt they had gained from their degrees, and developed recommendations for how a tertiary science course could be better framed to attract and serve the needs of graduates in a variety of workplaces. Rodrigues et al. found that:

- The graduates had varied and successful career paths, indicating the possibility of promoting science education as a flexible career base.
- Most had drifted into science on the basis of interest in their school science, with little conception of the possible careers that might open up. This indicates a need for much better career advice, and material in the curriculum which raises awareness of these possible career paths.
- The interviewees described a range of capabilities that were important in their positions, particularly communication, working as part of a team, analytical thinking (often referred to as the 'scientific method') and problem solving. They argued that their tertiary science courses had provided good training in analytic thinking, but the other skills needed to be given much more emphasis.
- They argued that tertiary studies should give much more emphasis to representing science as it is practised in the community including industry, rather than focus exclusively on disciplinary structure, and give more space to discussion of social and ethical aspects of science.

Thus, science-trained professionals valued above all the capabilities which were conferred by their education, those of analytical thinking and communication and problem solving. These are similar to those valued by professional scientists and again support the case for a re-imagined science education that highlights these capabilities.

Science education for the future citizen

This review has argued that a major thrust of the scientific literacy purpose of science education was concerned with the development of the science capabilities of citizens. Two questions were raised; these will be explored in this section. First, there is a variety of ways, both personally and professionally, in which a citizen might interact with science. Second, having decided on what aspects of a citizen's life we might interrogate with respect to needing to use science, the further question arises as to what sort of school science might best be of use in each of these aspects.

How do citizens use 'science' in their daily lives or in making sense of socio-scientific issues? A series of studies of the interaction of the lay public with science ideas, in making personal decisions about actions, was carried out in the UK as part of the Science for Specific Social Purposes project (Layton, 1991; Layton et al., 1993). These included old people managing energy use in their homes, town councillors dealing with the problem of methane generation in a landfill, and parents dealing with the birth of a Down's syndrome child. Ryder (2001), in a meta-analysis of 31 case studies of people involved in a non-school science-related event or issue, concluded that when people need to communicate with experts or take action they usually learn the science content required. Thus, meaningful science learning can occur when citizens interact with science in their lives. Ryder found, however, that:

much of the science knowledge relevant to individuals in the case studies was knowledge about science, i.e. knowledge about the development of and use of scientific knowledge rather than scientific knowledge itself.

(Ryder, 2001, p. 35)

Thus, structured content knowledge seems not to be as directly useful for citizens interacting with science, as knowledge of the nature of science. For example, Lewis and Leach (2006) found that, while knowledge was important in enabling students to identify key issues when engaging with applications of gene technology, they also found that the level of knowledge required for engagement in reasoned discussion was sufficiently modest that it could be taught in brief teaching interventions to prepare students for engagement in reasoned discussion.

Aikenhead (2006, p. 33) argues that canonical science content is the wrong type of content to use in most socio-scientific settings. He argues for knowledge about science and scientists as an important aspect of a humanistic science curriculum. Duggan and Gott (2002) in a review of a number of case studies of the science used by employees in science-based industries, and by the public interacting with science in their everyday lives, concluded that:

procedural understanding was essential in the higher levels of industry and in interacting effectively with everyday issues, while conceptual understanding was so specific that it was acquired in a need-to-know way. The implications for science education hinge on a substantial reduction in the conceptual content and the explicit teaching of the nature of evidence (procedural understanding).

(Duggan & Gott, 2002, p. 661)

The study by Tytler et al. (2001a), which was also one of Ryder's case studies, identified a number of ways that the public engaged with the science knowledge. The case involved an environmental dispute over the burning of recycled liquid fuels in a cement factory. As with the findings that understandings about the processes of science are more useful than abstract canonical knowledge, much of the science engaged with by citizens in this dispute concerned the validity of evidence and the way it was used in the argument. They identified a range of types of evidence that fed into the argument, not only scientific but also economic and political. The outcome hinged on the extent to which a citizen's action group was able to articulate problems with the evidentiary trail proposed by the industry. Tytler et al. argued on this basis that a focus in school science on concepts of evidence (Gott, Duggan, Roberts, & Hussain, n.d.), particularly on a variety of science investigative processes such as modelling and sampling, was most likely to be useful to citizens in encounters such as these.

If pupils are to learn about the ideas which have emerged in our Roxdale study, they must experience a wide variety of investigative work. They need to develop confidence in investigations which are open or closed at different stages, multivariate investigations, ones where pupils are looking for relationships of various kinds from simple causal relationships to correlational relationships to the question of whether relationships are significant, and so on. At the same time, pupils should be encouraged to apply these same ideas to second hand data and to science-based articles in the press.

(Tytler et al., 2001a, p. 829)

Tytler et al. point out that practical work in traditional school science does not engage students in grappling with real issues and deals with a restricted set of processes. Thus, if we are to prepare students for interaction with science issues and decision making in their adult lives, this review argues that attention to the nature of science, and particularly the many ways evidence is gathered and used in science and in socio-scientific issues, must be an important part of the curriculum, at least as important as the knowledge products themselves.

Wynne (1991) argues that in public interactions with science, understandings of science are not simply filtered down from the more pure and coherent accounts that are characteristic of formal science, but actively constructed by the processes and circumstances under which the science is communicated and received. This process of reconstruction (Wynne, 1991; Layton, 1991) places science knowledge within a complex of local and often tacit understandings situated within socially shared views of the world, which include perceptions of the institutional nature of science and its trustworthiness with regard to a particular issue. This is particularly true about judgments concerning the nature of scientific evidence.

Layton (1991) similarly argues that formal scientific knowledge is not as universally agreed upon or unproblematic as is represented in most educational contexts. In the context of its use in practical social contexts, he argues that:

As for the centrality of science to practical action in everyday life, the researches indicated that the scientific knowledge offered or accessible to people is rarely usable without being reworked and contextualised. This involves, at least, its integration with other, situation-specific knowledge, often personal to individuals, as well as with judgments of other kinds.

(Layton, 1991, p. 58)

Layton argues that learning in science should not be seen simply as a progression from prior, intuitive knowledge to the construction of ideas concordant with authentic science (p. 63), but must include the deconstruction and re-construction of knowledge to achieve its articulation in practical action (p. 63). He argues against the constructivist, conceptual change view of learning that focuses largely on the inculcation of canonical abstract concepts, for a more context-rich view of learning that engages student in practical applications of science knowledge.

These arguments, that our understandings of phenomena are inherently context-bound, echo the theoretical position of the situated cognition school (Brown, Collins, & Duguid, 1989; Lave & Wenger, 1991). These writers argue that context is an integral aspect of cognitive events, and that one cannot hope to divorce thinking from the social and other contextual elements of a problem-solving situation. The situations in which an understanding is generated are an integral part of that understanding.

Concluding comments

In this section a consideration of the type of science that will be useful for future citizens, scientists, and science-trained professionals has supported once again the contention that science education needs to diversify its emphasis beyond focusing on canonical abstract ideas, and place greater emphasis on the nature of science and the way it operates. It needs to include a more sophisticated version of scientific investigation and the concepts of evidence, and an explicit focus on capabilities such as analytic thinking and problem solving, communication, and creativity.

The need to use science knowledge in practical contexts, as an explicit focus on the reworking of ideas in context has been emphasised. The science that students engage with should demonstrate the nature of science as it works in the world. That might involve historical case studies but must also involve contemporary science topics with social, personal and ethical dimensions, such that students develop an understanding of science ideas in practical action, translating between formal concepts and the way they are applied in the complex contexts found in real situations.

The link between the nature of the curriculum and the use of science in practice, and learning theory has been established, and will be explored in greater detail in Section 4.

4

Engaging the
science learner

In this review, it is argued that a number of knowledge emphases are essential components of the curriculum if we are to seriously interest students in learning science. These include knowledge of canonical science ideas, knowledge of how science works in society, knowledge of the investigative procedures of science, and a disposition to value and use science ideas. These objectives are very different in their demands on the learner. Designing appropriate content and pedagogy to engage students in learning science requires a coherent theory of learning. Questions of interest and engagement, as well as the promotion of knowledge and skills, are ultimately learning issues.

In this section we will review different theories of learning to interrogate their usefulness in supporting a productive teaching and learning agenda of the type being advocated in this review. The review will begin with constructivist theories and conceptual change perspectives that are allied to these.

Conceptual change approaches to teaching and learning

There has been, over the last few decades, an enormous body of research on the conceptions students bring with them to the science classroom, and how these affect how and what they learn. This interest in student conceptions has stemmed from the realisation that students can emerge from a science learning sequence with very different understandings to those intended by the teacher. Even where students can perform at a high level on classroom tests, it has been found that they may display a range of very different understandings when asked to apply these ideas to other situations, especially in an 'out of school' context.

These findings on student understandings have largely been interpreted through a constructivist view of learning which emphasises the active process of meaning making and the way prior experience shapes the way we construct new ideas out of experience (Driver, 1989; Fensham, Gunstone, & White, 1994). In the mainstream student conceptions literature, learning is conceived of as conceptual change, and learning the key ideas in science is seen as involving a revolution in students' thinking, from naive conceptions to scientific conceptions. This is somewhat akin to the paradigm shifts described in relation to science theories (Kuhn, 1970).

Conceptual change (CC) approaches to teaching science typically involve an exploration of and challenging of students' prior ideas, establishment of the science ideas, extension of these ideas to a range of phenomena, and explicit evaluation of the new perspective (Hubber,

2005). An example of this approach can be found in the Primary Connections initiative of the Australian Academy of Science (Hackling, 2006), which is modelled on a '5Es' approach. This involves five stages in a unit designed to establish a science idea: engage, explore, explain, elaborate, evaluate. Research studies into teaching strategies to support this CC approach have reported some success (Hubber & Tytler, 2004).

However CC approaches have been increasingly questioned on the basis of a comprehensive amount of research demonstrating difficulties in changing students' naive ideas to more scientific conceptions (Duit & Treagust, 1998). Wandersee, Mintzes and Novak (1994) and Limon (2001) pointed out the lack of clear results that demonstrate the superiority of this orientation. While small-scale studies have produced encouraging results as well as insight into student learning challenges, one has to conclude that CC approaches more generally have not convincingly fulfilled their promise of successfully moving students from a naive to a scientific view. Part of the problem lies in the ongoing challenge of conceptualising how to support students to make the transition from naive to scientific views.

There is also now a substantial body of critique of constructivist positions, and conceptual change perspectives, pointing out the narrowness of this purely conceptual view of learning, and the excessive focus on the learner at the expense of the teacher and classroom strategies (Duit & Treagust, 1998). The notion that student conceptions are stable, resolved entities akin to scientific conceptions has come increasingly under attack. They have been shown to be context-dependent and dependent on individual orientations (Tytler & Peterson, 2004). The earlier presumptions that learning is essentially a rational process (Posner, Strike, Hewson, & Gertzog, 1982) have been challenged as ignoring the complex motivational and attitudinal factors involved in engaging in learning (Sinatra, 2005). Research into the transferability of students' conceptions across contexts has led to claims that knowledge is fundamentally situated in the contexts in which it is learnt (Lave & Wenger, 1991). While the core claim remains controversial, this situated cognition perspective has generated substantial insights into learning. These will be discussed below as part of broader sociocultural perspectives on learning.

Thus, it has become clear that learning is a much more complex process than is captured by this simple conceptually oriented constructivist/conceptual change perspective on learning. The move away from an exclusive focus on canonical science ideas, as advocated throughout this review, also requires a move away from a traditional view of learning as conceptual change, and the development of a more nuanced theory that can capture the contextuality and the attitudinal components of the curriculum, which has been signalled in earlier sections.

Shortcomings of conceptual change approaches

From the discussion above it is clear that challenges to the classical conceptual change perspective on learning mirrors in many respects the critique of a science curriculum focused on abstract canonical ideas described in this review. The research on student conceptions through the 1980s and 90s served to focus renewed attention on canonical science by describing the nature of deficits in student knowledge and its offer of a promise of ways to close this conceptual gap. However, the lack of distinctive success must alert us to the possibility that this focus on conceptual change may have been in many respects a false lead, distracting attention from the real learning issues of conceptual engagement, context, meaning and interest. The conceptual change research agenda has been in many respects the handmaiden of disciplinary interests in promoting the possibility of establishing a successful learning agenda based on canonical abstract ideas, an agenda that now requires radical surgery.

The features of a learning theory capable of taking us forward will need to include a detailed perspective on three things – the learner, the task and the role of the teacher. This review argues that classical conceptual change (CCC) theory is deficient in each respect:

- *The learner* – CCC theory takes a one-dimensional view of the learner, acknowledging only his or her prior conceptions and not individual differences in perspective, motivation or interest.

- *The task* – CCC theory views the task as one of establishing canonical abstract ideas, but is insensitive to the role of context and of individual perspectival variations that are critical in framing student learning. Also unclear is the extent to which the task is one of conception replacement, or one of building incrementally on students' ideas. That is, it is silent concerning the pathways by which learning occurs.
- *The role of the teacher* – CCC theory has the teacher probing students' naive conceptions and challenging these in moving them towards a science view. However, research has clearly demonstrated that this cannot be characterised as simply a rational process, and CCC theory is silent on the detailed mechanisms by which the teacher might offer support in helping students bridge the gap from naive to scientific views.

Sociocultural perspectives on learning

Sociocultural perspectives on learning focus attention on the social and cultural processes underpinning learning. Part of the impetus for this focus has been an increasing interest in the role of new media, and the need for learners to engage with knowledge in a variety of settings and modes. There has been an increasing focus on the social and historical contexts of learning. Research in this sociocultural tradition, rather than focusing on what is in students' heads, pays attention to the ways in which a teacher promotes a discourse community aimed at the establishment within the class of shared meanings (Driver, Asoko, Leach, Mortimer, & Scott, 1994), or to the ways in which groups of students negotiate meaning in shared tasks (Wickmann & Ostman, 2002). The role of the teacher in this process is to work with students' ideas, scaffolding them to establish the very powerful discourses of the scientific culture and scientific ways of viewing and dealing with the world. Sociocultural perspectives accord a more fundamental role to language and culture in the construction of knowledge and even the way we think (e.g. Wertsch, 1991). More broadly, these perspectives deal with cultural aspects of learning science, and the difficulty of border crossing from indigenous to scientific ways of thinking (Aikenhead, 2001, 2006), or the socio-economic factors and power relations that impinge on learning in school classrooms.

These sociocultural theories are generally seen as being in opposition to personal constructivist and conceptual change views of learning, in that learning is seen as the increasing ability to participate in the discursive practices of the science community, rather than the acquisition of stable knowledge structures that mirror and interpret the world. The sort of classroom that flows out of sociocultural perspectives is one that encourages lots of exploratory activities and talk, but also one in which the teacher supports high quality conceptual discussion in groups, or in the whole class. The pedagogic skill lies in framing activities and conversations that challenge perspectives and that model the discourses of science that continually seek to interpret evidence and promote a richer way of looking at the world.

In point of fact, most conceptual change schemes in science, such as the 5Es model (see the previous discussion), have incorporated many of the elements associated with sociocultural perspectives of learning (Hubber & Tytler, 2004). These elements include:

- the active role of the teacher in providing opportunities for students to engage with and explore phenomena
- the support for students to engage with meaningful contexts
- the negotiation of meaning implied in the teacher's guidance of students towards the scientific views
- the metacognitive implications of making ideas explicit, and extending and evaluating these.

Sociocultural theory offers significant insights into the social process of learning, learner difference, cultural aspects of learning, and the conditions under which tasks are productively engaged with. As such it offers promise of supporting the agenda promoted by this review.

However, it offers only limited insight into the knowledge elements that need to be focused on in a re-imagined science curriculum, or the way they might interrelate.

Second generation cognitive science

This review has argued that school science needs to place more emphasis on engaging students with science ideas in richly contextual settings, focusing on a range of capabilities and dispositional attributes, beyond the acquisition of conceptual knowledge. We need a theory of learning that can support such a program and help make sense of how and what students learn in such environments. In recent years, an emerging strand of research in cognitive science has challenged the view of knowledge and learning based on canonical conceptual ideas.

Klein (2006), writing within a scientific literacy framework, reviews the work of major writers in cognitive science to argue that the ground has shifted away from what he terms 'first generation' (1G) cognitive science to a 'second generation' (2G) view of learning, which disconnects individual science learning and thinking from the formal structures of science research papers and science texts. Klein's argument is that first generation thinking, as with the science curriculum, has been dominated by the presumption that the way we learn and think science mirrors the public discourses of science research – that is, through well defined concepts interconnected by propositional structures. In contrast, research indicates that thinking involves 'expressive' concepts that are perceptually based, and that we make meaning through the processes of pattern recognition and associative thinking rather than formal logical relations.

The discursive conventions of science research reporting have been designed to allow clear and defensible ideas to be developed, debated and verified. However, in the process of reducing knowledge to ideas and assertions that can be publicly debated and agreed upon, those personal elements of science – the associative meanings, values, narratives and contexts – by which we come to know and invest meaning, have been written out of the story. In this 2G view, the pathways to scientific understandings, just as the personal practice of scientists themselves, must be imbued with those contexts, aesthetics and narratives which we come to acquire and value these understandings. Even though the end point of learning science includes the ability to manipulate key concepts according to scientific discursive conventions, part of the analysis concerns the interconnectedness of language (broadly interpreted) and thought, as well as the interconnectedness of the conceptual and the aesthetic. These aspects will be explored further.

Klein's analysis indicates that the way practising scientists learn and create new knowledge is more complex and interesting than the manipulation of resolved concepts. It will involve analogy and metaphorical thinking, affective responses and judgments, and the creation of multiple representations, as thinking is tied down and refined. Thus, the focus in science textbooks and in science classrooms on formal explanations of abstract concepts would seem to be misplaced, when what is needed is a more richly storied, metaphorical and representational approach to explanation.

As an instance of this point concerning representations, Latour (1999) argues that making sense of science involves understanding the process by which data is transformed into theory through a series of representational 'passes'. To analyse science theory building, he accompanied two scientists working together on soil profiles in the Amazon basin at the boundary between rainforest and savannah and traced the process by which they converted the raw data into scientific papers. This process involved a series of representational re-descriptions, from the ordered box arrangement in which they assembled their soil samples, through a colour chart and numbering system, and eventually to the table that was the representational form they carried back with them to Paris.

Klein's analysis implies that the key elements of thinking are not resolved concepts as such, but the discursive representational elements that underpin them, such as the representational passes described by Latour. As another example, the concept of air pressure is not a singular thing – using the notion in practice involves a variety of representations of force, of air and its properties perhaps through analogy, and the construction of a narrative that links these as a

causal chain. If the formal concepts and logical structures of public science are not the same as the way we think and live science, even though their mastery is the ultimate aim, then this would help explain the problems we have with engaging students in the formal science knowledge agenda. Such a realisation would open up a pathway to better engage students with science ideas.

Schaverien and Cosgrove (1999, 2000) have proposed a theory of learning based on biological selection and neuro-scientific research the implications of which support the thrust of Klein's analysis and of this review. They argue learning is an adaptive phenomenon that occurs not by instruction but by selection from a range of ideas, according to their adaptive value. They argue learning and knowing is a dynamic process based on the generating and testing of ideas, a process that is driven by values and involving a complex and subtle interplay between individual genetic and social histories, and environmental circumstances. The implications Schaverien and Cosgrove draw from this theory are that classrooms need to deal with contemporary and challenging science linked with students' everyday worlds, and that emphasis should be on the generation of ideas, and on significant value questions. The teacher is open to learning alongside students. This position is consistent with a range of research findings, and with the research findings described in this review, including Klein's analysis.

Representation and learning in science

This section will extend the points made above concerning representation as a key element of constructing and understanding science ideas and will link these with notions of scientific literacy and learning.

This review has discussed scientific literacy as a perspective that focuses on framing science education for citizens generally, including science professionals. Norris and Phillips (2003) have argued convincingly that this view of scientific literacy is inevitably underpinned by a more fundamental sense of scientific literacy – that coming to know science involves introduction to and the achievement of competence in a number of literacies.

This fundamental scientific literacy perspective challenges the idea that learning is purely conceptual, and argues that rather than think in terms of knowledge structures imagined to exist in a resolved form in students' heads, science knowledge should be seen as a set of subject-specific literacies. In Section 3 there was discussion of how sociocultural perspectives reposition learning as inculcation into the culturally developed and sanctioned practices, values and discourses of science. In this process, we need to consider the contextual, social, cultural and psychological factors that influence different learners' engagement with the task. Researchers such as Gee (2004) and Lemke (2004) have focused on the influence, for effective learning, of the diversity of learner resources needed to engage with the representational practices of science communities. These resources include cognitive (e.g. memory, procedural knowledge, reasoning), linguistic and dispositional capacities, as well as social and cultural orientations.

From the representational perspective, students need to understand and integrate different representational modes in learning science and learning how to think and act scientifically (Ainsworth, 1999; Kress, 2003; Lemke, 2004). Therefore, to learn science effectively students must understand different representations of science concepts and processes, be able to translate across these, and understand their coordinated use in representing scientific knowledge and constructing explanations.

There is a broad agreement in this expanding literature on representation in science that students need to develop an understanding of a variety of modes, rather than be dependent on particular modes for specific topics, if they are to develop a strong understanding of how to use and represent science concepts. Current science teaching practices involve the use of both authorised, multiple and multi-modal representations, as well as student-generated representations (such as the use of 3D models, diagrams, verbal accounts, role-play, and CD-ROM illustrations for teaching topics like the solar system).

These arguments relate also to the broader agenda claimed by Lemke (2005) that students will live increasingly in a multi-modal representational world, and that the representational sophistication that many students already have to some considerable degree, and that all students need to develop, must be part of the learning agenda of school science.

New information and communication technologies make it possible for students to learn about science and about the natural world across multiple media and multiple sites of learning. Research needs to help us understand better how to help students integrate learning through text, spoken language, graphical images, animations, audio, video, simulations, and three-dimensional models and virtual worlds. We must also learn how to effectively link learning in schools and other educational institutions with learning online, in nature, at technological sites, and through internships.

(Lemke, 2005, retrieved from <http://www-personal.umich.edu/~jaylemke/papers>)

Research is needed into ways in which student representational resources can be effectively harnessed to support learning of key science ideas and ways in which representational negotiation can support students. This view of the centrality of representational issues in learning science underpins the national Primary Connections project (Australian Academy of Science, 2005).

Primary Connections recognises that there are a number of science-specific, as well as general, literacies required by children to effectively engage with science phenomena, construct science understandings and develop science processes, and to represent and communicate ideas and information about science ... Primary Connections provides opportunities for children to develop the literacies needed to learn science and to represent their developing science understandings and processes.

(Hackling, 2006, p. 75)

Through linking science with literacy, Primary Connections holds the promise of assisting students to develop key generic literacies such as reading text and writing, utilising the engagement offered by hands-on activities. For science education, it offers the chance to:

- explore and develop understandings of the literacies more specific to science such as investigation report writing, data representation, and diagram and model construction and interpretation
- explore how such literacies can help students engage with and learn science
- establish representational issues as key to developing student engagement and understanding.

The project entails working with teachers and schools to develop units of work that attend to literacy issues in teaching and learning science. Experience in the project so far indicates that teachers need to develop a stronger understanding of the relationship between the conceptual challenges of individual topics and the value of different representational and re-representational tasks in engaging with these challenges. More research is needed to develop understandings of how the literacies of science relate to student engagement and learning, and of the challenges for teachers of science in incorporating representational work in their classroom practice.

The shift to a theory of learning that promotes negotiation of a range of multi-modal representations supports the development of a flexible and open approach to science ideas which emphasises transferability of ideas more so than if they are treated as formally structured concepts. Thus, for example, generation and exploration of particle representations of a range of evaporative processes can support the development of student thinking about evaporation, more so than the presentation of formal explanations (Tytler, Peterson, & Prain, 2006). Such a shift has the potential in investigative exercises to support a productive focus on investigative concepts by focusing on representational possibilities in data collection, display and analysis (Tytler,

Peterson, & Radford, in press). The explicit introduction of a range of modes of representation will also arguably support and extend students with different preferred learning styles.

The aesthetic and the conceptual in learning

One of the key claims established in this review concerning current practice in science education is that it is too heavily skewed towards the abstract conceptual canon of science, and too often ignores the realities of students' own lives, interests and feelings. Many studies have demonstrated that meaningful learning must involve the coming together of the conceptual and the emotional/aesthetic.

Bloom (1992) has shown children's thinking to be extremely fluid, progressing via a rich selection of episodic knowledge, metaphors, interpretive frameworks and emotional, ethical and aesthetic commitments. Tytler and Peterson (2001, 2004) have shown how students' interpretation of a science learning task is coloured by social and personal emotional factors, with each student constructing a view of the task, and indeed what it means to learn science, that is very individual and identity related. They talk of students' 'narratives of the self' to describe how they respond to a learning situation through their narratives of themselves as learners, members of the class, friends, etc. Thus, one student might see himself or herself as a neophyte science explorer, speculating and telling narratives in explaining phenomena; another student might search for a correct form of words to close off the explanation; and yet another might take an imaginative approach to dealing with phenomena, moving quickly across incompatible ideas. The task for each student is quite different, and they bring varying and different capabilities to bear on creating meaning.

Interest in the work of John Dewey (1996) has been recently revived, drawing on Dewey's pragmatic casting of the mind as an adaptive organism for making sense of the world, and his emphasis on the continuity between classroom learning and students' lived experience, and between conceptual reasoning and the aesthetic. This latter issue forms the theoretical basis for a Swedish research program exploring the role of aesthetic experience in Science Education. Wickmann (2006) argues that the traditional opposition between aesthetic and value positions on the one hand, and conceptual work on the other, is a false dichotomy, and that each is constitutive of the other in scientists' work. Aesthetic judgments are not separate from learnt ways of understanding, as general dispositions, but should be seen as an element of the culturally determined, learnt discursive practices of science.

To Dewey, it was clear that the scientist, like all humans, does not rely exclusively on cognition, but also on values and aesthetic meanings during work.

...

When reading scientists' own biographical remarks it becomes evident that aesthetics is not shunned in their research. Quite the opposite is the case. Aesthetic experience is everywhere evident in their daily life as scientists, in the creative moments, in finding new connections and results, and in communicating science with others, but also in the intimate relationship scientists often have with nature.

(Wickmann, 2006, pp. 17, 19)

By aesthetics, Wickmann is referring to matters of taste, appreciation, or of interest, and preference, related to science activity – expressions dealing with beautiful/ugly or pleasure/displeasure. He demonstrates how aesthetic expression intertwines with conceptual statements as students interact to learn science, and that approaching an understanding of the science of an object involves negotiating aesthetic categories also.

Corrigan (2006), working with teacher trainees on values in science, found that her students were well aware of values as being an important aspect of the human response to science, including human qualities such as honesty, teamwork, passion and openness to change, as

well as more 'within science' values such as respect for data, intellectual rigour (logic, creation, elegance) or the ability to solve problems. Corrigan implicitly links this question of values with the argument that science ideas need to be transformed if they are to be used in context, and that this transformation inevitably involves the construction of science as a story.

Narrative cognition and learning

Hellden (2005), in a 12-year longitudinal study of students' ideas about the recycling of biological matter and biological purposes, found a continuity over the years in the way the students explained phenomena, and in the references they used. In later interviews, in probing what underlay this individual continuity, he found that students responded to situations according to episodes from their earlier lives that coloured and shaped their explanatory views.

Bostrom (2006), in research into how Swedish teachers of senior chemistry make science meaningful for their students, found that they tell narratives that demonstrate the connection between chemistry and their lives. These narratives were often used as personal anecdotes, but included historical stories of science, and also units of work that were based on narrative, such as the class that traced the amount of greenhouse gas emission involved in each stage of manufacture of a chocolate bar. In interviews with adult and senior students, she found that they, too, told narratives about chemistry in their lives, in describing the meaningfulness of chemistry. Bostrom argues that the telling of narratives should be a recognised element of pedagogical content knowledge (PCK), and uses the ideas of John Dewey and Jerome Bruner (1985) to make sense of her findings. From Dewey she takes the idea of the necessary continuity between science ideas and students' (and teachers') lived experience, as a condition for meaningful learning. Bruner (1985) describes two modes of cognition: paradigmatic or logico-scientific cognition, which consists of formal knowledge structures aimed at establishing truth; and narrative cognition, which consists of stories of interest, rooted in human action and intention, aimed at creating meaning.

Each provides a way of ordering experience, of constructing reality and the two are irreducible to one another. Each of the two ways of knowing has operating principles of its own and its own criteria of well-formedness. But they differ radically in their procedures for establishing truth.

(Bruner, 1985, p. 97)

Darby (2005), in a video study of secondary teachers of mathematics and science, also found that teacher stories had a strong place in meaning making in science classrooms by relating the content of the subject to students' lives. She argues also that passion for the subject is a strong characteristic of teacher pedagogy when teaching in their area of expertise, and that this needs to be explicitly acknowledged as part of professional learning.

The story of science, from its inception, has seen the progressive exclusion of aesthetic or contextual statements from the scientific paper, with decontextualised abstraction established as the predominant mode of public scientific discourse. This tradition has tended to dominate science textbooks, and underpins science curricula. Yet popular writings of scientists are replete with narratives and aesthetic expression, and as shown in this section, teachers' and students' understandings are grounded in narrative, and aesthetic discourses. This needs to be more strongly acknowledged in science curricula, and also in the professional learning of teachers of science.

Concluding comments

This sketching of trends in learning theory has demonstrated that the learning theories aligned the traditional focus on canonical, abstract science ideas, which has been critiqued in Section 2 of this review, are increasingly being questioned as representing valid and useful ways of understanding student learning. Conceptual change theory has been useful in highlighting the

difficulties associated with learning the key concepts of science, and the approaches coming from this have helped teachers explore students' ideas and support students to grapple with scientific perspectives. Sociocultural approaches also emphasised the ways in which teachers shape a community of learners and develop language to express new ideas. Recent work on learning in science has emphasised the aesthetic and narrative elements of learning, and the need to attend seriously to the representational modes that constitute science ideas. Second generation cognitive science has emphasised a range of characteristics of learning that align with the focus on flexible, contextual and personally meaningful science advocated by this review, and holds promise of supporting a re-imagining of science education.

Framing the content of school science

This review has taken as its focus the diminishing appetite in Australia for school and post-compulsory science, and argued that this is linked to the changing nature of science and changes in society, and the fact that science education has failed to respond to these changes. The review has argued that in order to stimulate students' serious engagement with learning in science and prepare them for productive futures, we need to focus on content and pedagogy that acknowledge the different stakeholders, namely current students, and future citizens, scientists, and other professionals.

The very range of stakeholder voices referenced raises questions concerning the extent to which the characteristics of a school science based on these different voices and imagined futures are mutually compatible. Can a single science course be suitable for all? Do different futures imply that different forms of school science should be selected?

This section will examine a number of recent approaches to and emphases in school science that are innovative in some respects. These will be discussed as emphases that might make up a re-imagined science education, as will the implications for assessment.

The place of conceptual knowledge

In this discussion of curriculum emphases and voices, it should not be assumed that the primacy of conceptual knowledge is being challenged. Rather, it is the amount of emphasis and the form in which it is presented that is questioned. The argument being mounted in these critiques is that an exclusive focus on resolved, abstract, canonical ideas will not be meaningful to students without considerable 'translation' work to link it with individual narratives and contexts to render it useful in meaningful situations. The problem lies in a number of different factors. They are the non-negotiable nature of the way such knowledge is delivered, the fact it is not generally framed within contexts that are meaningful to students, and the disjunction between the formal logical structures in which concepts are presented and interrelated, and the aesthetic, contextual and/or narrative processes by which students come to make meaning (see Section 4).

So the answer to the question, 'is it necessary for students to know the periodic table?' is probably yes. Not as a set of declarative facts, but learned as part of a thinking process that arises as the properties of materials are interpreted and ordered. Further, precedence should be given to knowledge that arises naturally as a tool for interpreting phenomena that are significant in students' and adults' lives. Thus, knowledge of cells and genes and acids and energy and the

Earth's radiation balance are probably important for operating in modern society. Knowledge of lens formulae may be less so.

Knowledge is not only needed for understanding and explaining phenomena (such as knowing the function of cells in the body and using this to describe how cancer occurs), but it underpins any serious understanding of investigative processes and the nature of science. Clearly, one cannot engage meaningfully with investigative science without going through a process of knowledge generation and testing, and one cannot talk meaningfully about the nature of science without reference to the knowledge products of science. Part of the answer, then, to 'what conceptual knowledge is needed?' is that conceptual knowledge is important as part of an understanding of the processes of science, how scientific knowledge is generated and validated, and how it is used to answer human personal and social concerns.

It could be also that highly abstract knowledge not currently dealt with as part of the science curriculum has become an important aspect of science understandings because of its contemporary importance. System-level thinking, complexity theory, and large-scale data interpretation, for instance, might claim a place in a contemporary curriculum where it was not thought relevant before.

Interest in science – context and meaning

Student perceptions of science were discussed in some detail in Section 2, foregrounding perceptions of lack of interest and meaningfulness. The student voice is an important one for determining the nature of school science, a point that Peter Fensham (2006) made strongly in his conference presentation.

There are a number of aspects to engaging students' interest in science. This review paper has already pointed to the value of adopting middle years teaching and learning principles, which emphasise students being actively involved in questioning, exploring and using science ideas, being challenged, being able to make decisions about their learning, being exposed to a stimulating environment and a range of teaching strategies, interacting with other students and receiving appropriate feedback on their work.

One component of the School Innovation in Science (SIS) framework – 'Linking science with students' lives and interests' – was the focus for many Victorian schools' initiatives. The SIS handbook makes clear the importance of linking science with students' deeper interests and concerns:

This component focuses on the need to develop classroom strategies, and curriculum topics and activities that are meaningful to students; their lives outside school, and their needs and hopes for their various futures. While this idea might include discussions of current fads or games or sports, or topics based around these, its full meaning goes much further than this. In a deeper sense it asks that student concerns and world views are not only accounted for, but central to the way science is framed, and that checks are continually made that the science program addresses these ... This Component would include the idea that science teaching and learning helps shape and improve students' lives and interests.

(Deakin University, 2003, p. 44)

Examples illustrating this component include the use of popular media, reference to students' personal interests and social concerns, providing opportunities for students to voice their perspectives, giving students responsibility, and providing a stimulating environment.

The characteristics of a science curriculum that engenders student interest relate to the pedagogy employed, to a stimulating atmosphere, and to content that relates to students' immediate and wider concerns. A major thrust in curricula that aim to engender student engagement is to situate the learning in contexts that are meaningful to students. The idea of contextual learning has been around for some time and underpins courses like the Dutch Physics Curriculum Development Project (PLON) physics course or the Salters Chemistry

course. Bennett, Campbell, Hogarth and Lubben (n.d.) undertook a review of studies involving controlled evaluations of context-based science courses, including an in-depth review of five studies, including the PLON and Salters courses. They concluded:

The review has, with some caveats, demonstrated that there is good evidence to support the claim that context-based approaches motivate students in their science lessons ... The in-depth review has further demonstrated that there is reasonable evidence to suggest such approaches also foster more positive attitudes to science more generally. The in-depth review also provides reasonable evidence from four of the five studies to suggest that context-based approaches do not adversely affect students' understanding of scientific ideas. The fifth study indicated understanding was enhanced.

(Bennett et al., n.d., p. 4)

Similarly, Pilot and Bulte (2006b), in a review of articles in a special journal issue on context-based chemistry courses, found evidence of increased personal relevance and the possibility of generating coherent mental schema in such courses. They raised the issue of transfer of learning as one needing to be addressed in the design of such courses.

Part of the rationale for contextual learning also relates to the notion that ideas need to be situated in the real world if they are to be understood and capable of transfer. This has been a driving principle for some curricula in Australia, but such innovations have at times struck difficulties with traditional assessment regimes that focus on the manipulation of abstract knowledge in set piece situations, and do not therefore encourage teachers to take context seriously (Hart, 2001, 2002). The idea of contextual learning was strongly supported in the teacher forums at the ACER conference.

Student interest and what is needed to support it

The teacher forums at the ACER conference involved groups of teachers discussing ways to make science more engaging for students, to boost science learning and to encourage more students into post-compulsory science. A list of ideas, many based on participants' practice, was generated during the session from reports of group discussions. These placed considerable emphasis on contextual learning, represented a wide range of teaching and learning strategies, and argued the need for schools to be able to control their own curricula.

Teacher comments on making the science curriculum more meaningful

- Tap into kids' interests by looking at using technologies such as mobile phones
- Use open-ended projects related to real-life issues valuing creativity, for instance the solar car challenge
- In our school, the curriculum is untied – all units are of relevance to students' lives, for instance a unit on science and art pigments, solvents etc. The units give choice so students own the topic
- A winemaking unit involving partnership with local industry
- Study the science of sport – interpret the intent of the syllabus and depend less on the text book
- Example: a country area using agriculture as the setting for science teaching
- Ask students before choosing contexts; use contemporary science issues; more debate; research in the classroom; interdisciplinary topics
- Develop skills in students on researching issues; courses are too content prescribed – they should be issue based
- Open up the curriculum more so schools can write their own courses; teach important daily issues; analytical thinking should be taught and developed.

(Ideas generated in teacher forums at the ACER conference, 2006)

Two major themes emerged from the discussion regarding what is stopping teachers and schools from developing such curricula more fully.

Teacher comments on the rigid nature of the science curriculum

- The prescriptive curriculum prevents innovation
- Media topics could be introduced if the curriculum was less rigid
- The curriculum is not relevant for indigenous students – we need to rewrite the course
- There is an advantage teaching in Years 7–10 where the curriculum is less rigid; (nevertheless) the Year 11 and 12 courses drive the curriculum and flexibility to design local programs is needed here also.

(Ideas generated in teacher forums at the ACER conference, 2006)

There were in fact some cautionary voices which emphasised the need for guidance in the curriculum, especially for overworked or under-confident teachers.

The other theme that appeared was the discouraging effect upon change, of (a) conservative attitudes of parents and some teachers opposed to context-based curricula; (b) the influence of university academics on examination panels; and (c) the effect of the media, in particular where individuals in influential positions can attack new ideas if they are seen to transgress notions of academic rigour attached to canonical conceptual knowledge.

Teacher comments on conservative forces in science curriculum change

- (There is a problem with) the cultural conservatism of staff in schools and parents
- Parents are conservative in their views – our role is to educate them about changes
- (There are) problems with assessment and making assessment valued
- (There is an) issue also for media, business and industry – cultural change is also needed here
- Senior science in ... is taught in context, with a multi-disciplinary approach but it is not valued for university courses
- (There is a problem with) university staff attitudes, training undergraduates for narrow discipline knowledge
- Science and engineering faculties in universities are out of touch with the reality of schools – academic scientists on panels for assessment and curriculum resist change
- We need to broaden the approach to setting assessment tasks.

(Ideas generated in teacher forums at the ACER conference, 2006)

There is a clear and coherent view here about what sort of science is capable of engaging students, one which is consistent with middle years pedagogy principles, and also with Aikenhead's (2006) description of a humanistic science curriculum. The difficulty, as perceived by these teachers, lies in the influence of the disciplinary guardians on the science curriculum and assessment, and similar commitments of many science teachers and also the general community. These teachers of course chose to attend the conference, and hence it could be claimed that they are not representative. Arguably, they could be taken to represent the more committed and forward-thinking science teachers. They spoke with a consistent voice.

Investigative science and scientific reasoning

Practical work has a long history within science education. Student surveys consistently identify practical work as a popular activity that should be maintained or increased. Curriculum writing for primary school science has long promoted 'hands on' approaches to science teaching and learning, on the assumption that experience is a great teacher (representing an empiricist bent), and that dealing with the objects of science contextualises the concepts of science and promotes student engagement with science ideas. These ideas are captured by the aphorism: 'I hear, I forget; I see, I remember; I do, I understand'.

Practical work in science fulfils a variety of functions: to illustrate, verify or affirm science concepts or principles; to engage students positively with the science enterprise (Hofstein & Lunetta, 2004); and to develop understandings of investigative methods in science, involving the gathering and use of evidence (Gott & Duggan, 1995). Recently, particular attention has been paid to this latter function, in ‘working scientifically’ or ‘investigating’ strands of Australian and other curricula. There are two important arguments for emphasising this aspect of science.

First, empirical investigation is a fundamental characteristic of the scientific culture and its epistemic base. The success of science in developing important and fundamental insights into the way the world works has been based on the development of a powerful approach to inquiry, based on respect for material evidence and careful reasoning, and set within a culture of openness, and critical scrutiny of knowledge claims. A central value position of science concerns a commitment to seeking material explanations of the world, and a commitment to upholding the centrality of evidence in deciding knowledge claims.

The second argument refers to citizens’ ability to engage with evidential issues in science in their personal lives and community issues. By engaging in investigations that involve a consideration of what constitutes reliable and valid evidence and how this evidence is used to establish knowledge, students will gain important skills in a variety of ways of reasoning, and develop a capacity to make judgments about evidence in scientific argument. There are many social issues that involve appeals to scientific evidence, such as the effects of waste disposal policies on the environment, of tourism on the Great Barrier Reef, or of personal lifestyle factors on cancer risk. An understanding of how such knowledge is generated and evaluated is therefore a powerful aim for science education. The OECD PISA (1999) defined scientific literacy as:

the capacity to use scientific knowledge, to identify questions (investigate) and to draw evidence-based conclusions in order to understand and help make decisions about the natural world and the changes made to it through human activity.

(OECD PISA, 1999, p. 60)

The varied methods of science

People often refer to ‘the scientific method’ as consisting of a procedural sequence of questioning, designing an experiment, measuring, analysing and concluding. The design aspects of scientific investigation are often reduced to the notion of variable control. At the primary level, this idea can be captured through the idea of a ‘fair test’ and pursued through experiments such as testing which type of ball bounces the highest or which absorbent paper works the best. This review however posits that experimental variable control does not adequately describe the full range of scientific endeavour. While fair testing may be an excellent introduction to the idea of isolating variables, it ultimately presents a restricted picture of the way science operates.

A number of writers have advocated changes to the nature and use of practical activities to more closely mirror what actually happens in science (e.g. Roth, 1995; Watson, Goldsworthy, & Wood-Robinson, 1999). There are many procedures within science that are followed when contesting or validating knowledge claims. The idea of variable control follows from the need to establish explanations that will withstand critical scrutiny. To establish an explanation or a theory as superior to other possible contenders, one must isolate the relevant factors from alternative possibilities. This process can be systematic, but in the history of science it has usually involved some inspired guesswork about which variables are relevant or not or even what question should be asked. There are many different traditions within science for isolating factors which students should experience, including inspiration and guesswork.

In physics, for instance, it is often the case that the experimental factors can be controlled explicitly, for instance weight and length and amplitude in determining what affects the period of swing of a pendulum. In biological fieldwork it is usually not possible to alter natural conditions to sort out relevant factors, and so control is achieved by appropriate selection of field sites and measurements, with sampling techniques and development of descriptive categories being

central to the establishment of evidence. In astronomy, where again control of experimental conditions is not possible, but where sampling is not appropriate, the generation of theory comes through a complex interaction of observation and deduction, similar in many ways to detective work. Theories of the evolution of humans, using anthropological evidence, are generated in a somewhat similar way. In applied science areas such as pharmacy, control in the testing of new treatments can be exerted by the use of control groups and sampling, but in other cases, such as the effects of passive smoking, a more indirect and complex design is needed.

Curriculum progression and rigor

In recent curricula, progression in knowledge of investigative design is often defined by the ability to deal with increasingly complex forms of experimental variables and their interactions. This notion has its roots in Piaget's genetic epistemological theories that identified variable control as a key indicator of students' development (Inhelder & Piaget, 1958). The Australian Scientific Literacy Progress map, found on the Science Education Assessment Resources (SEAR) website (<http://cms.curriculum.edu.au/sear/>) is cast in this form despite a statement acknowledging the variability of scientific methods.

Table 7. Variable control progression levels in the Australian Scientific Literacy Progress map

Level 3: demonstrates awareness of the need for fair testing and appreciates scientific meaning of 'fair testing'...; identifies variable to be changed and/or measured but does not indicate variables to be controlled

Level 4: identifies the variable to be changed, the variable to be measured and in addition identifies at least one variable to be controlled

Level 5: plans experiments in which most variables are controlled ... When provided with an experimental design involving multiple independent variables, can identify the questions being investigated.

(Curriculum Corporation, ACER, DEST, 2004. SEAR project scientific literacy progress map)

Metz (1997) has argued that Piagetian notions of stage development have misrepresented students' capabilities and have had the effect of 'dumbing down' the curriculum. She worked with teachers of students in their first three years of school, teaching ideas about form and function and adaptation, processes for measuring and representing time variation in animal behaviour and distribution, and experimental design, before supporting students to ask their own questions and investigate them. This approach is exemplified in Suzanne Peterson's small animal investigations in a Grade 3 class in Melbourne (Tytler et al., in press) in which she builds students' expertise in measuring, question asking and data analysis before supporting them in their small animal explorations, which involve speculation, multiple representations of data, and evaluation of their experiments. In both the Metz and the Peterson cases, students were operating at an investigative level far in excess of what tends to be the curriculum expectation based on progression in ideas of variable control.

In a similar vein, in the early days of the introduction of investigative science in the national curriculum in the UK, Tytler and Swatton (1992) argued, on the basis of research showing the autonomy and sophistication in investigative design shown by students in open-ended investigations (Tytler, 1992), that a narrow focus on variable control would seriously and unnecessarily restrict the way the scientific enterprise was represented in classrooms. A later study into the types of investigation that were being conducted in UK classrooms (Watson et al., 1999) confirmed the narrow range of types of investigation spawned by the fair testing tradition, and called for a greater range of investigations including modelling and exploration.

Further, in a longitudinal study of children's scientific reasoning in the early years of primary school, Tytler and Peterson (2005) have shown that Year 2 students can display higher levels of reasoning than generally acknowledged in curriculum formulations of progression of variable control capabilities. In this work, the authors identified higher levels of reasoning as the having of ideas and the seeking of evidence to confirm or contradict, and in particular with displays of

flexible reasoning involving sequencing ideas and evidence seeking. Tytler and Peterson argued that most standard variable control experiments (e.g. an investigation of the relative grip of different brands of sports shoe, or the factors that affect the swing of a pendulum) are limited to exploring patterns of correlations between experimental conditions, and tend not to engage students with hypotheses or conceptual ideas. Therefore they fail to represent the essence of scientific ways of reasoning.

While these types of investigation may be valuable for training in a common type of experimental design and procedure, to restrict investigative activity to these misrepresents the breadth and flexibility of scientific thinking, fails to engage students with the ideas that are the stuff of science, and limits the possibility of them generating their own ideas and meaning. Science knowledge generation is like a detective chase, with steps in the argument supported by experimental evidence, possibly involving variable control but not formally so. It thus becomes very important in science education to embed teaching about the control or isolation of variables in the context of a range of types of deductive argument. The danger with outcome sequences, such as found in the scientific literacy map, is that they encourage teachers and textbook writers to promote set-piece experiments that limit the potential to explore interesting ideas through investigation, and once again fail to capture the imagination of students.

Inquiry curricula

The close relationship between the processes, and conceptual ideas of science, is exemplified by 'inquiry' curricula in science. This term is common particularly in the USA, and across a range of educational disciplines. It has a long history in the ideas of educators like Dewey (1996), Bruner (1960) and Schwab. Schwab (1962, 1965) famously described the traditional science curriculum as a 'rhetoric of conclusions' and argued for a science curriculum that educates students in what he called the *syntactical* as opposed to the *substantive* structure of the discipline: the way science ideas are posed, experiments are performed, and how data is converted into scientific knowledge. Inquiry teaching has been a strong theme in the USA, and has counterparts in investigative and process emphases in curricula elsewhere. Inquiry is a strong theme in a current European Union project (Scienceduc: <http://scienceduc.cienciaviva.pt/home/>) that aims to 'renovate' primary science teaching with inquiry methods.

One of the difficulties of talking about inquiry curricula is that the term covers a multitude of methods, from illustrative, set-piece experiments, to investigations with strong guidance from instructions or the teacher, through to more open-ended investigations in which students pose and explore their own questions. In many documents for primary schools, the term seems to be used interchangeably with 'hands-on science', as in 'hands-on pedagogy' in many learning areas. There is thus a need to clarify the terminology.

Two papers at the ACER conference promoted inquiry approaches to science curriculum. Roger Bybee (2006) described a recent Biological Sciences Curriculum Study (BSCS) inquiry curriculum, and Denis Goodrum (2006) described an Australia-wide pilot secondary science program with a scientific literacy focus that included inquiry teaching methods. Both these curricula fulfil some of the recommendations developed in this review; namely that there should be a shift away from teacher delivery of knowledge, and more attention should be paid to discussion, open questioning and higher order conceptual explanation. However, both seem to limit the inter-relationship between conceptual ideas, investigative methods, and societal applications, which would represent how contemporary science is practised.

For instance, the BSCS program begins with an inquiry unit, then moves into a sequence of units dealing with canonical content, ending with a unit that uses problems and projects that are relevant to the lives of high school students. In neither case does there seem to be room for teachers and students to explore science ideas in local, contemporary contexts (as strongly advocated in the teacher forums at the ACER conference).

In the Collaborative Australian Secondary Science Program (CASSP) trial (Goodrum, 2006), questionnaire results showed a decrease in teacher-directed activities, and an increase in student-centred activities, in keeping with the design of the classroom materials. Of some

concern, however, was the finding that many high-achieving students did not feel the course was successful, purportedly because of the unstructured nature of investigations. There is a need to capture the interest and commitment of such students in any re-imagining of school science. This may require some imaginative curriculum writing, or it may involve engaging students in more significant inquiries using local, or case study resources, in ways that are discussed later in the review.

Osborne makes the point that:

Four decades after Schwab's (1962) argument that science should be taught as an 'enquiry into enquiry', and almost a century since John Dewey (1916) advocated that classroom learning be a student-centred process of enquiry, we still find ourselves struggling to achieve such practices in the science classroom.

(Osborne, 2006, p. 2)

Denis Goodrum (2006) refers to the lack of uptake of inquiry in Australian classrooms, despite the consistent rhetoric of curriculum documents. Osborne argues for an inquiry perspective in school science on the basis of the need for citizens to be part of the decision-making processes around 'the developments of science and technology which are most likely to pose the political and moral dilemmas for the generations to come' (p. 3). As described earlier in the review, Osborne argues for a need to focus on how evidence is used to construct explanations and what criteria are used in science to evaluate evidence. With this in mind, he and colleagues (Simon, Erduran, & Osborne, 2006) have worked with teachers to develop a model for introducing argumentation activities into science classrooms, aimed at modelling the way knowledge is warranted in science. The UK work on argumentation has produced curriculum materials: *Ideas, Evidence and Argument in Science Education* (IDEAS: <http://www.kcl.ac.uk/schools/sspp/education/research/steg/ideas.html>) which are being widely used. These involve activities that challenge students, and encourage them to hypothesise and resolve claims and counterclaims on the basis of evidence.

Socio-scientific investigations

Osborne's work focuses on epistemic processes within science, but is framed within an argument that acknowledges the broader setting within which science is practised and scientific evidence is considered, alongside other forms of evidence, in important decision-making processes. This review suggests there is a need to include inquiry within such expanded settings. There is considerable current interest in inquiry into socio-scientific issues as a means to develop students' scientific literacy. These might include open inquiry into a real current issue such as the utilisation of local wetlands (Jimenez-Aleixandre & Pereiro-Munoz, 2002), or structured inquiry into issues such as the use of gene technology (Lewis & Leach, 2006) or the effects of contemporary technologies such as mobile phones (Leach, Hind, & Ryder, 2003; materials are described at <http://www.nuffieldfoundation.org>).

A number of authors have pointed out the complexity of socio-scientific issues that render them difficult to engage with in the classroom, or by the lay public. Tytler, Duggan and Gott (2001a) describe the complexity and sophistication of the science in their case study of an environmental dispute:

- It deals with data that is difficult to treat statistically and is subject to experimental cost and uncontrolled initial conditions.
- It involves complex models that themselves introduce uncertainties into the interpretation of data.
- The outcome is intended to be an action, rather than the production of generalisable knowledge, and, as such, is subject to a range of dimensions that are value-laden.
- The science is highly contextual and subject to variation over which the scientists had no control.

- It involved measuring trace elements at the limit of detection, with resulting uncertainty.
- It involved the generation and comparison of two numbers (pollution indices), representing two conditions which themselves involved the problematic weighting of data based on previous epidemiological research.

If students are to be taught how evidence is developed and used in science in authentic settings, they need to grapple with features of scientific methods such as these. Ways need to be found to represent them in the curriculum. Researchers have advocated the use of packaged case study material as one way of managing this complexity. Such case studies might provide data from real situations, or simulated, to allow students to explore questions that might be posed, or that they themselves generate, through representations of the data and analysis. An example from the environmental sciences was produced by Gott, Duggan and Roberts (2000) in which the data bank from an Antarctic expedition concerning body weight, breeding patterns and mortality of mutton birds was made available electronically for students to pose questions and hypotheses and construct data sets to explore these.

Planning for variety in investigative approaches

In this review of practical work in science a variety of purposes and approaches have been described, extending the traditional role of illustration and verification of ideas and techniques. School science needs to accommodate this variety, from set-piece design experiments and measurement and representation exercises to investigations that ask students to make decisions. In particular, in line with the need for students to engage in meaningful learning and with middle years pedagogical principles generally, they should be involved in investigating questions they themselves pose, reasoning and argumentation activities, and undertaking investigations that relate to societal and personal contexts and represent a range of ways contemporary science operates.

Students need to be supported to develop investigative skills and knowledge, but as the work of Metz (1997), Tytler et al. (in press), and Tytler and Peterson (2005) described above shows, even young children are capable of high-level reasoning and investigation, and we should not withhold engagement with real questions and issues in science on the basis of a narrow view of a long apprenticeship in science research skills. From the earliest years, there needs to be a culture established in science classrooms concerning judgments about evidence and discussion of the reliability and validity of data, and of findings. The setting might vary from classrooms to fieldwork, to investigations involving community issues and perhaps links with community-based science researchers.

As described above, for some socio-scientific investigations, the complexity of the science and the lack of direct accessibility of data sources mean that secondary data provided in case studies may be an effective approach. However, there are also many examples of schools and teachers engaging their students in real investigations of this nature, and some of these will be described in the section on school–community links below. As an instance of such an approach, Jim Davies (2006) in his presentation on the Australian Science and Mathematics School (ASMS) described how students engage in open inquiry to learning with access to academic scientists and a culture of question asking.

Students are actively engaged in experimentation and investigation assisting them to make connections between their learning and the real-life application of the learning ... are challenged to see and develop different solutions to challenging, 'fertile' questions where objectivity and astute judgement is important ... are engaged in significant inquiry projects where they are formulating conceptualisations of situations in order to generate theories, models and conclusions.

(Davies, 2006, p. 59)

Framing content around citizens' needs

Osborne's (2006) argument concerning the difficulty of the school science curriculum simultaneously attending to the scientific literacy of future citizens, and also providing the first stage of training for future science professionals, is echoed in Millar's (in press) description of the background of *Twenty First Century Science (21CS)*, a significant science curriculum development for 15- to 16-year-old students in England. This course is of interest to this review partly because it has quickly captured a significant market share for students of this age group and has enjoyed a positive response from teachers, but also because it has seriously attempted to identify the content, and the ideas about science, needed for a functional citizens' literacy. The course consists of a compulsory core component focusing on scientific literacy and additional optional components with either a 'pure science' or an 'applied science' emphasis. The argument is that the canonical science that has dominated traditional school science has not and cannot enlist the interest of students generally, but is the necessary core of the training of specialists.

In deciding on the content of the curriculum, the writers argued that, rather than base decisions primarily on the accepted disciplinary structure:

the primary selection criterion (for content) was that an explanation should be included only if an understanding of it might make a difference to a decision or choice that a citizen could have to make, or to the viewpoint he/she might hold on an issue or decision at local or national level, or if it offered a culturally significant view on the human condition.

(Millar, in press)

Millar argues an important indicator of appropriate science content should be that people are likely to encounter it through the news media. He points out that the largest single category of science that shows up consistently in newspaper surveys is health and medicine. This immediately shifts the focus of the curriculum. Further, he points out that most articles on health and environment deal with a claim about a factor that increases or decreases the chance of a particular outcome, and consequently the concept of risk needs to be part of the science curriculum. Arguing in this way, the core curriculum is built around two major categories of ideas: science explanations and ideas about science.

The science explanations are a list of 16 major explanatory ideas including chemicals (the nature of a substance), the chemical cycles of life, the gene theory of inheritance, the germ theory of disease, energy sources and use, and the structure and evolution of the Earth. The ideas about science deal with aspects of the nature of science intended to prepare students for evaluating knowledge claims. Table 8 summarises these ideas.

The two key parts to the curriculum – science explanations and ideas about science – are intertwined in the content of a set of modules such as: you and your genes, air quality, keeping healthy, food matters, and radiation and life. The innovative nature of the course lies with aspects of its content, the focus on big picture ideas rather than detail, the emphasis on ideas about science, and a focus on science that will prepare students to look critically at scientific information. The course uses case studies of issues (gene technology, the reliability of air quality measurements, risks of UV and other radiation) and includes role-plays, and data and information on the risks and benefits of new science developments. The supporting materials are rich in representations and data displays for interpretation.

A preliminary evaluation has shown that teachers and students have found the course an improvement on the traditional course at a number of levels, although there is some indication, in the subsequent roll out, that the improvement could be extended and cemented if it was accompanied by an explicit focus on supporting teachers' development of new pedagogical strategies to match the content innovation (Millar, personal communication, 2006).

Table 8. Ideas about science in the Twenty First Century Science curriculum

Data and its limitations	Awareness that all observations and measurements are subject to uncertainty; use of the mean and the spread of a data set to assess its trustworthiness
Correlation and cause	Thinking about phenomena in terms of factors (or variables) that are associated with a change in outcome, or a change in the probability of an outcome; how a claim that a factor affects an outcome can be tested; awareness that correlation does not necessarily indicate cause
Developing explanations	Distinguishing data from possible explanations; awareness of role of imagination in devising explanations; testing explanations by comparing predictions with data
The scientific community	Awareness of the role and importance of peer review, and of replicability of findings; recognition of legitimacy of disagreement about data and explanation, and the possibility of external (non-scientific) influences on this
Risk	Awareness that all activities and processes carry some risk, that risks can be assessed and compared, and of the need to balance chance of occurrence and scale of consequences in taking decisions
Making decisions about science and technology	Recognition of the benefits of science-based technology, and also of the possibility of unwanted consequences. Ability to identify obvious costs and benefits of a new development, to separate the issue of feasibility (can it be done) from that of values (should it be done), and to discuss rationally issues with an ethical dimension.

(Adapted from Millar, in press, Table 5)

Given its popularity, the Twenty First Century Science approach to curriculum planning would seem a promising model for Australia across the middle years of schooling. It may be possible, for instance, to base school science in the lower secondary school on the ideas represented in the core component, suitably modified, but over the years progressively weighting the content towards more structured, conceptual versions of science. Students could be led to see the value of formal theory and ideas through their contextual studies including investigative and issues-based topics. At all points, however, the curriculum would need to deal with challenging ideas in a rigorous way, with an emphasis on the way science operates, and the generation and testing of ideas.

School and community initiatives

This review has argued that a major driver for reform in science education must be the voice of contemporary science and science professionals, and the practice of science in contemporary settings. It has also argued that school science must prepare students to engage in science as it impacts on the local and the personal in their lives. Two presentations at the conference demonstrated how school science can be made meaningful to students by linking it with outside communities.

Jim Davies (2006) described a secondary curriculum at the Australian Science and Mathematics School (ASMS) that is contemporary in its engagement with current issues and developments in science, and in its use of scientists and other community members to provide connectedness with issues and ideas beyond the classroom setting.

Rennie's (2006) presentation described school–community projects that were very successful in engaging student and community interest. One was a Year 9 air quality project that identified the major cause of air pollution in a mill town. The students began the project suspecting the local mill but soon established the cause to be domestic wood-fired stoves and heaters. They began a campaign for a buy-back scheme, and received an enormous amount of support and attention from the community. The case is a good example of a socio-scientific issue involving data collection (there were difficulties in negotiating a continuous on-line stream of meteorological data), argumentation, the intersection of science with social dimensions of

an issue, and social action. As such, it offers a more authentic experience of a contemporary science issue than the more structured socio-scientific packages described above.

Rennie argues positive outcomes from these community projects, and identifies a set of guiding principles for the success of school–community projects, including the following: they need to be based on issues coming from the community; they require local knowledge; they are integrated into science at the school; they involve negotiation and decision making with the community; and they have a tangible outcome.

There is an increasing incidence of such community projects in Australia, driven by a greater concern to make schooling more relevant to students and continuous with their lives. The Victorian School Innovation in Science (SIS) project developed a set of components of effective teaching and learning, based on interviews with acknowledged effective teachers, that included the component:

The classroom is linked with the broader community. A variety of links are made between the classroom program and the local and broader community. These links emphasise the broad relevance and social and cultural implications of science, and frame the learning of science within a wider setting.

(Deakin University, 2003, pp. 9, 40)

Many of the interviewees in the Deakin research project employed community links in their programs. Examples included a secondary science coordinator in a school in a coastal area who drew on local resources to run units on dune ecology, waves and the physics related to surfing. Some primary schools explicitly nourished a range of community links as part of the setting of the science curriculum:

Much of the school's integrated program is science based. The program includes major emphases on community links including science competitions, local environmental projects, and links with outside bodies, professional development initiatives, and assessment and reporting initiatives. Rachel (the teacher) has worked hard to develop a culture of parent involvement in the school, and sees this as a way to drive the science initiative.

(Tytler, Waldrup, & Griffiths, 2004, pp. 183–4)

The SIS component was reconfigured in later more generic versions to emphasise more strongly the link between meaningful learning and professional and community practice: 'Learning connects strongly with communities and practice beyond the classroom' (Victorian DE&T, 2004).

The SIS project spawned a range of school- and community-linked projects (Tytler & Nakos, 2003). In one school, a teacher with no previous history of innovation was encouraged by the SIS coordinator, who knew of his interest in winemaking, to initiate a *Chemistry of wine making* unit. The school is now producing award-winning wines. Other projects included a study, in partnership with the Victorian Department of Primary Industries, of the regeneration of the lower Snowy River, involving a cluster of primary and secondary schools; the construction of an environmental trail involving consultation with local botanists to advise on plant regeneration, a long-term study of frog ecology involving a group of Gippsland schools, and an on-line mentoring project involving robotics, in a number of primary schools. These schools generally report increased enthusiasm of students for science. The school reports make clear the significant engagement with science ideas that can occur in such projects.

It is quite striking, in SIS, how most of these community-linked projects occur in rural schools and in clusters. It is possible that the linking of school and community is easier to achieve in rural towns where teachers have more embedded relations with community members and the school is a more overtly acknowledged community resource. More research is needed on the conditions under which these projects succeed, on how the link between school and community is constructed, on how they might best be promoted in metropolitan areas, on

what learning outcomes proceed from them, and on the ways they might best be embedded in the science curriculum. There is a need to develop models of school and community links that are both embedded and sustained. It seems that often they are initiated and kept alive by the actions of enthusiastic individuals. We need such partnerships and programs to be more common in the mainstream delivery of science.

Organisation-instigated school initiatives

Other types of community-linked projects include visiting scientist schemes, family science nights, excursions to science centres with associated project work, and science and technology competitions such as the Science Talent Search in Victoria, or the solar car challenge, or the Energy Derby. There are many links also between schools and organisations that offer programs for school students, such as Water Watch and Salt Watch. In Australia, the recent Australian School Innovation in Science, Technology and Mathematics (ASISTM) project has sparked a great deal of activity linking schools with universities and outside agencies to bring expertise into schools. The program has yet to be evaluated, but at this stage it seems to have encouraged a considerable variety of activities in schools, involving schools liaising with university students, practising scientists, and industries to develop programs.

In Europe, a new primary science project, Pollen (<http://www.pollen-europa.net>) developed within the framework of the European Union, is described as a community approach for a sustainable growth in science education. Pollen is a joint initiative between the *French Academie des sciences* and other European bodies, and is initially working through 12 'Seed Cities' where municipalities work with a board, with representatives from universities, the scientific community, health workers, cultural institutions, families, industries and so on to develop a strategic plan which includes science education projects that involve community support and participation.

The UK Royal Society is supporting a 'Science Community Partnership Supporting Education' (SCORE) project spurred by the concern that:

The next generation of scientists could be lost if urgent, concerted action is not taken to address the major challenges facing science education.

(<http://www.the-funneled-web.com>: September 27, 2006)

SCORE's founding members are the Institute of Physics, the Royal Society of Chemistry, the Institute of Biology, the Biosciences Federation, the Science Council, the Association for Science Education and the Royal Society.

The partners will undertake collaborative projects, conduct joint studies, develop common evaluation procedures and share best practice. They will develop a programme whose focus will be on activities of a type already shown to have an impact and whose principal emphasis will be on providing support for teachers.

(<http://www.the-funneled-web.com>: September 27, 2006)

School and community-linked projects hold the promise of satisfying many of the conditions for an engaging and meaningful science education, argued for in this review paper. The linking of science with industry and community can ensure it represents contemporary science acting in a community setting, and it has the potential to ensure that the science content is meaningful to students, and that it relates to their lives out of school. There are a number of justifications in this. First, one can argue that meaningful learning entails situating the learning in contexts that are meaningful to the learner. Second, Rennie (2006) makes the point that in order for canonical science knowledge to be useful in everyday settings, it needs to be transformed into 'knowledge for practical action'. The science curriculum needs to explicitly include this transformation process if the knowledge students learn is to be useful in their adult lives.

Rennie argues that if students are to engage with science ideas once they leave school, they will do so in a community setting. We therefore need to model this as part of the school science curriculum.

Assessing learning in science

In this section a number of significant approaches to school science have been described that offer promise of productive ways forward. A significant issue that arose was the possible resistance of the community to new conceptions of school science. Any re-imagining of science education needs to be supported by a clear vision of the knowledge and skills that are being developed, and assessment practices that have the confidence and support of the community including teachers.

The history of education reform is littered with examples of assessment regimes failing to support the intention of the innovation. Hart (2002) describes the interaction between assessment demands and curriculum policy that compromised an innovative attempt at a context-based physics curriculum. The development of innovative assessment regimes to support new ideas can be challenging, and failure of imagination can lead to reversion to low-level content items. The current government passion for accountability can lead to an emphasis on very specific assessment that is reliable and uncontroversial, but low level. As an example, the curriculum and standards framework in Victoria (<http://www.eduweb.vic.gov.au/curriculumatwork/csf/sc>) was based on a set of sequential conceptual outcomes, which were written with a degree of flexibility to allow schools to reflect local circumstances in their curricula. However, in the interests of specificity, 'indicators' were written to tie these down, which inevitably became the descriptive statements that drove assessment and practice. Thus, the learning outcome 'Use a simple particle model to explain the structure and properties of solids, liquids and gases' had indicators including 'describe the structure of solids, liquids and gases in terms of the arrangement and motion of particles in each physical state'. This emphasises declarative, low-level knowledge rather than the interpretive understanding that might have been focused on. It certainly is not designed to provide a pathway to engage and interest students or challenge them to extend their understandings of the particle model.

What is needed are new models of assessment that can reflect an expanded range of curriculum purposes in science. There has been research internationally to develop such models. The Assessment of Performance Unit (APU) was set up in the 1970s to monitor the achievement of 13-year-olds in the UK. The assessment categories they developed were as follows: use of graphical and symbolic representation; use of apparatus and measuring instruments; observation; interpretation and application; planning of investigations; performance of investigations. The work in some of these categories was pioneering, but very little use is now made of the assessment approaches for investigation, for instance, which involve equipment and close monitoring of student responses. Such items are expensive to run at system level, and without such acknowledgment, teachers tend not to include them in their own assessment.

The Trends in International Mathematics and Science Study (TIMSS), which has achieved a high profile in Australian science education thinking, developed a framework that had three dimensions in the cognitive domain: factual knowledge, conceptual understanding, reasoning and analysis, and a scientific inquiry domain. TIMSS developed a bank of performance test items in mathematics and science, but again these seem to have had little impact on practice in schools or to be widely recognised. The TIMSS cognitive items were based on content that was common across all participating countries, and this means they are conservative in the science they cover. They are also traditional in form, focusing on the abstracted core canonical ideas of science, and aimed to minimise the role of context in interpretation. Thus, a focus on TIMSS as a measure of the health of science education in Australia, has the effect of asserting canonical science content as the dominant concern of school science, and inhibiting moves towards a more flexible and engaging curriculum that this review is arguing for.

In comparison, the PISA project (OECD, in press, referred to in McCrae, 2006) takes a specific scientific literacy focus and has generated items which, compared to those of TIMSS, show the promise of supporting a wider set of purposes and emphases in the science curriculum. PISA's knowledge component consists of knowledge of science (broken into the traditional strands), and knowledge about science (scientific inquiry and scientific explanations) categories. PISA contains items based on relevant contexts for students, involving reading and interpretation. There is also an attitudinal dimension consisting of interest in science, support for scientific inquiry, and responsibility towards resources and environments. The PISA regime demonstrates assessment is capable of supporting a wider agenda in science education, and provides a model that could and should be extended by Australian governments in national and state planning.

The Australian Science Education Assessment Resources framework, set up to provide a range of assessment resources for schools, bases its items on a Scientific Literacy Map linked to PISA, consisting of three dimensions described in Table 9.

Table 9. Dimensions of the Australian Science Education Assessment Resources (SEAR) framework

Domain	Description
A Process Domain: experimental design and data gathering	Formulating or identifying investigable questions and hypotheses, planning investigations and collecting evidence
B Process Domain: interpreting experimental data	Interpreting evidence and drawing conclusions from their own or others' data, critiquing the trustworthiness of evidence and claims made by others, and communicating findings
C Conceptual Domain: applies conceptual understanding	Using understandings for describing and explaining natural phenomena, and for interpreting reports about phenomena

(Extracted from the SEAR website; <http://cms.curriculum.edu.au/sear/>)

The assessment resources include diagnostic, formative and summative items, and deal with science conceptual understanding and the processes and applications of science in everyday settings. There are some items that involve the interpretation of news articles. There are few tasks focusing on the way science operates in society or the interpretation of science in personal settings, and the framework does not support items focusing on attitudes to science. The items tend to be short exercises and quite traditional in their framing. They mostly deal with conceptual understanding and applications of concepts and by their nature do not encourage engagement with substantial or context-based activities or tap into students' worlds.

What is needed to support a re-imagined science curriculum is the development of assessment approaches and resources that support student engagement with meaningful activities. Such approaches would include assessment situated naturally within significant scientific activities, including student-directed project work. The Queensland 'Rich Tasks' offers a model that may be worth pursuing:

The Rich Task is a reconceptualisation of the notion of outcome as demonstration or display of mastery; that is, students display their understandings, knowledges and skills through performance on transdisciplinary activities that have an obvious connection to the wide world ... (They make) available assessable activities that are intellectually challenging and have real-world value, two characteristics which research identifies as necessary for improved student performance.

(http://education.qld.gov.au/corporate/newbasics/html/about/about_rt.html)

An example of a rich task for Year 9 students, Science and Ethics Confer, involves the preparation of a briefing paper on an aspect of contemporary science with ethical dimensions:

Students will identify, explore and make judgments on a biotechnological process to which there are ethical dimensions. They will identify scientific techniques used, along with significant recent contributions to the field. They will also research frameworks of ethical principles for coming to terms with an identified ethical issue or question. Using this information, they will prepare pre-conference materials for an international conference that will feature selected speakers who are leading lights in their respective fields.

(<http://education.qld.gov.au/corporate/newbasics/html/richtasks/year9/year9.html>)

The criteria for high-quality performance on this task include mastery of the discursive practices of science writing, knowledge and practice of scientific techniques, and deep analysis of the biotechnological issue through the eyes of real people.

There is a need for considerable work to be done in developing approaches to and resources for assessment that would support a re-imagining of science education, but there are good examples to draw on which would support such a program.

Concluding comments

From the initiatives described in this section of the review, we can extract some significant principles and examples that provide ways forward for school science.

There exist in current practice, successful examples, which we can draw on, of school science practice that:

- bases science on contexts that are meaningful to students
- treats upper secondary school disciplinary knowledge within relevant contexts
- includes a variety of approaches to investigation beyond illustrative practical work and simplistic control of variables explorations
- explores science investigative work within socio-scientific settings, both using prepared materials and real-life exploration
- pays explicit attention to the nature of science, in both its epistemic and sociological aspects
- involves learning of science in community settings, and partnerships with community organisations to explore contemporary science in real settings
- requires innovative assessment regimes and item types that can accommodate the learning from such initiatives.

The discussion of these initiatives and associated issues has also exposed practices that fall short of the re-imagining that this review is arguing for and that need to be challenged in arguing for real reform.

The initiatives described in this section are different in varying degrees from current mainstream practice, and would place considerable demands on teachers. Section 6 will discuss the implications of this re-imagining for teacher education.

6

Teacher-led reform

The importance of teachers in any national science education reform agenda, and concerns with current trends in science teacher supply and quality, has been identified in a number of government reports and publications. These reports acknowledge that quality teaching is critical to successful outcomes for students and innovative and effective programs in schools. Goodrum (2006), Rennie (2006), and Goodrum et al. (2001) have pointed out the failure of many teachers of science to provide relevant and engaging science experiences for their students. Identification of issues with the teaching of science in schools, in the *Who's Teaching Science?* report (Harris, 2006; Harris et al., 2005) have been discussed earlier. The DEST (2003) report *Australia's Teachers, Australia's Future* focused on a range of issues for science education, including the need for innovation in school science, problems with teacher supply, the implementation of teacher standards (see also Ingvarson & Semple, 2006), the role and importance of science teacher education, and ways of supporting schools.

Implications for teaching

This review has argued that science education has been trapped in a cycle of practice that relates to its early roots, with its focus on disembodied, abstract knowledge, supported by a largely teacher-centred, transmissive pedagogy. Part of the reason for the largely successful resistance to the many attempts at reform, from progressive educational challenges to process approaches to Science-Technology-Society reforms, has been the commitment of academic scientists, and teachers who have been schooled in these disciplinary traditions to this version of science. Change has been resisted in the name of rigour and standards, but perhaps above all by the silent choice of teachers for the status quo; one that supports and reflects their identities as knowledgeable experts. Science teachers tend to teach as they themselves were taught in school and through university, supported by assessment practices which confer status on the ability to manipulate canonical science ideas, and very little else. One of the major issues we face, if we believe in this imperative to re-imagine science education, is how to break into this self-reinforcing cycle.

Yet there are abundant examples of teachers practising in ways similar to those advocated in this review. In the School Innovation in Science project (Tytler, 2005, in press) there were many stories of established teachers changing their practice, with the support of group processes, external consultants and materials. There were stories of students putting pressure on teachers to change, through comparing what was happening in other classes, and there were stories of

teachers with serious interests feeling they were being given permission to import these into the classroom. Many teachers at the forums in the ACER conference told stories of context-based science units. There are also examples in Europe and elsewhere of significant interest in reform incorporating context-based curricula (e.g. Pilot & Bulte, 2006a).

Similarly, learning sequences that link school and community have been initiated in a great many instances in Australia, supported by government projects such as SIS or ASISTM, or by industry or special groups such as the Gould League.

The challenge for change lies in putting these various innovative practices together as a coherent vision and establishing them as mainstream practice. For this, teachers will need to develop new knowledges and skills, and in some respects new identities as they re-invent themselves in terms of these knowledges. This section of the review will discuss in turn the implications of change for pre-service teacher training, and for teacher professional learning.

Initial teacher education

For science teacher training, the needs associated with re-imagining science education are different for primary and secondary teachers. Primary teachers are generally not steeped in a discipline, but achieve a high degree of expertise in general pedagogical practice. Their problem in relation to science, particularly physical science, is one of knowledge and confidence (Goodrum et al., 2001). They need to have included, as part of their initial training, a mixture of science content knowledge and pedagogical content knowledge (PCK) in order to confidently teach science in primary school.

There are two major issues for secondary science teacher training, associated with the crisis in science explored in this review. First, there is the immediate problem of recruiting science teachers, particularly in the physical sciences. Second, there is the question of how to design a pre-service course that will support the changes in classroom practice argued for in this review. The problem requires a breaking of the cycle of commitment to a canon of abstract knowledge delivered largely by transmissive pedagogies, and all that implies for individual teacher identity.

Three investigations aimed at re-conceptualising science teacher education at Deakin University probed the views of science professionals concerning the nature of science practised in a number of Australia's research priority areas: the views of science graduates concerning the usefulness of a science degree as preparation for the workplace, and the views of students concerning what would attract them into post-compulsory science (Tytler & Symington, 2006).

Findings from the first two studies have been described earlier in this review. These indicated a need to rethink the nature of the science degree, as the major component of secondary science teacher education, such that it represented a more contemporary view of the practice of science, including the social and ethical implications of science, and it focused more explicitly on capabilities such as analytical thinking, communication, and teamwork.

The third investigation explored, through focus groups of 149 senior secondary students, what factors would influence their decision to enrol in a tertiary science program, and their attitudes to science teaching as an employment option (see Tytler & Symington, 2006). The findings of this study were that the features of a science degree course *most* likely to encourage student entry are that at the completion of the course they would have a chance (in priority order) to:

- have a variety of career possibilities
- get a job where they will be working with people.

The features of a science degree course *least* likely to encourage student entry are that at the completion of the course they would have a chance (in reverse priority order) to:

- become a science teacher (only 1–2% chose this option)
- work in a laboratory
- become a science researcher.

However, over half of the students indicated they would consider undertaking a course that would qualify them to be a science teacher provided the course prepared them for other employment options as well.

Thus, the problems of science teacher supply, and teacher capacity to engage in innovative curriculum reform, are both related to the nature of the science degree itself. A positive aspect of these research findings is the finding that the science degree characteristics appropriate for preparing graduates for work as professional scientists, or work generally, are the same characteristics that would enable teachers to be innovative and relevant in providing science learning experiences. The adoption of a strategic policy is made easier by this confluence.

A teacher education initiative

Deakin has modified its combined BSc/BTeach (Sci) program to respond to these findings, involving the close collaboration of science and education faculties and staff. The new program has the following distinctive features:

- students delaying decisions which would restrict their career choices, such that students can move between a science degree and a combined education/science education degree at the end of second year, rather than be locked into either from the start
- a focus on skills identified as critical in employment, alongside studies in their discipline sequences
- a focus on the contemporary practice of science, to produce science teacher education graduates capable of and disposed to significant innovation in school science
- a Professional Practice strand of four compulsory units common to the BSc and the combined degree, which focus on the nature of science and core attributes, and that articulate with four specifically school education focused units for those that take the combined degree (the professional practice units are – *Working with Science*, *Being a Science Learner*, *Science Communication*, and *Community Science Project*)
- opportunities for both science, and teacher education students to be involved in the development and application of science in community or school settings.

The *Working with Science* unit, which is running for the first time in 2007, is attracting larger than expected student numbers. It focuses on the nature of science and the people who work in science.

By examining the characteristics of scientific research, scientific progress and scientific practice, the methods of scientific research are explored. The significant role of scientific literature in scientific research is explored. Controversial science issues are used to critically analyse the role of science in our global society, including issues such as ethical considerations, sustainability and economic implications. The interaction between science and technology and their societal and personal implications are demonstrated and discussed. Linkages with and visits to contemporary scientific settings in the community provide opportunities to focus on the science that occurs in the setting as well as the people that work within them.

(Deakin BSc/BTeach (Sci) Course description <http://www.deakin.edu.au/courses/search>)

The other units in the Professional Practice sequence deal with the understandings and skills in engaging with and communicating science in contemporary settings, responding to the needs identified in the research described above.

The course is marketed as a flexible option leading to a variety of careers, in contrast to the images of scientists in laboratory or field settings almost universally featured on current BSc prospectuses. The intention is to broaden the range of university entrants attracted to a science degree. The course is designed to cater for students with traditional science career trajectories, but also to appeal to those who are capable and interested in science but whose

career aspirations lie outside laboratory or fieldwork, including teaching. It is designed to produce secondary science teachers better equipped to engage students in science that they find relevant and interesting.

Rethinking the science degree

This recasting of the science degree to develop understandings of the nature of contemporary science, and specific capabilities, is aligned with a number of innovations in universities in Australia and Europe. For instance, a Monash University unit *How Science Works* (Edwards & Ling, 2005, p. 2), taken as part of a science degree, encourages students to consider the social context of the science and provides learning experiences that promote reflection on the critical interface between science and the larger community. A number of universities and university courses cite development of skills as a goal of their programs. For example, Peat, Taylor and Franklin (2005, p. 135) describe initiatives introduced into the curriculum of a first year science course, which are designed to help students develop the attributes required of a professional scientist. However, very few such innovations are reported in the research literature, either because they are rare, or because academics tend not to write research around such initiatives.

In the UK, the Select Committee on Science and Technology in the House of Parliament (2000) expressed concern about public perceptions of science, calling for support for communication training for scientists. Harris (2006, p. 39) called for the creation and promotion of science communication subjects for undergraduate science students, and there are communication units appearing in science degrees in a number of Australian universities. However, these initiatives tend to be small-scale and the work of enthusiasts, rather than embedded in wider conceptions of the nature and purposes of the science degree itself. There is a need for universities to develop a coherent and research-based approach to such innovations.

Supporting teacher learning

For many practising teachers of science, the changes to pedagogy and curriculum implied by the re-imagining of science education would involve a significant shift. Many teachers, however, have shown a willingness and capacity to shift their practice significantly, in a number of funded projects. Teachers at the ACER conference who participated in the forums, for instance, were almost unanimous in calling for more context-based teaching, and many had significant experience with innovative curricula. Teachers involved in the initial Primary Connections workshops had shown considerable flexibility and creativity in extending and refining the trial units focusing on science and literacy. Many teachers in the Victorian School Innovation in Science (SIS) project significantly altered their practice (Tytler, 2005, in press) and that of their schools (Tytler & Nakos, 2003). The current spate of projects in the Australian School Innovation in Science, Technology and Mathematics (ASISTM) initiative are testimony to the energy and initiative of teachers in a situation where resources are available.

Professional learning models to support significant change

However, the scale of the challenge in moving a system which is focused on a very specific view of science content, and with many teachers long used to a transmissive pedagogy, should not be underestimated. What is required in order for many teachers to make the change is a new set of beliefs about the nature and purposes of science education. Also required is a new set of teaching and learning skills that give more agency to students, and open up the possibility of new knowledges being produced, rather than simply rehearsals of well-known knowledge elements. These are significant changes, beyond the reach of simple content delivery models of professional development.

Many studies have shown that short-term professional development events are ineffective in promoting significant change in teacher and school practices (Hoban, 1992). The reasons for this are related to the lack of follow-through, the lack of connection with school priorities or the direct needs and concerns of participants, and the lack of long-term and systematic planning (Webb, 1993). Many writers (e.g. Hargreaves, 1994; Hall & Hord, 2001) have emphasised that change in professional practice requires teachers ground new ideas in their own personal experience. Joyce and Showers (1995), drawing on a large body of research, argue for the need to situate professional development within the school context. They discuss professional learning within a framework of cultural change, and argue the need for social support as teachers practise teaching strategies that are new to their repertoire or implement the difficult areas of a curriculum change. Contemporary large-scale reform projects in a number of countries have incorporated these principles (Beeth et al., 2003; Parchmann et al., 2006).

Pedagogy, curriculum resources and local control

There are currently two projects supported by DEST, intended to provide a platform for Australia wide science curriculum innovation. One is the Primary Connections program (Australian Academy of Science, 2005). The other is the mooted secondary science national program: 'Science by doing' (see Goodrum's address at a National Forum in Melbourne; http://www.qualityteaching.dest.gov.au/building_partnerships/national_forum.htm). The existence of these projects raises the issue directly as to effective models of teacher professional learning in supporting system-wide change.

Many large-scale projects have focused their attention on pedagogy (for instance Productive Pedagogies (Queensland DET, 2004) and School Innovation in Science (SIS) (Victorian DE&T, 2003)), leaving schools to make their own arrangements regarding the particular content they access. The argument for not specifying curriculum content closely is that content needs to be determined in part by local needs, and that once content has been decided, teachers can tap into a range of resource material to shape it to their needs, particularly if this is done on a network basis. However, the experience of SIS has demonstrated that this requires considerable support in schools. In SIS, as with other system-wide reform projects involving local control and attention to pedagogy (Beeth et al., 2003; Parchmann et al., 2006), there was a significant sense of ownership of the reform, and there was significant change in classroom practice.

In SIS, the support for pedagogical change involved an interview between each teacher and a coordinator, the development of an agreed pedagogical profile and a plan for action, a set of audit practices to examine curriculum and teaching against the framework, and a team approach to planning and reform, supported by an external consultant working with a network of schools. Some of these processes are now embedded within the Primary Connections program. It was interesting, within SIS, how often in discussion of particular teaching and learning strategies it was discovered there were science teachers operating at a high level in the strategy, with none of the other team members having been aware of this. Part of the power of SIS, as with other school-based initiatives, was to bring pedagogical discussion into the mainstream practice of school science teams.

SIS has spawned a wide variety of initiatives, and the school and teacher change model (Tytler, 2005, in press) became very well regarded in Victoria and was adapted to other projects. The teaching and learning framework underpinning the initiative, and adopted by schools, was consistent with the principles arising from the literature, laid out in this review.

On the other hand, many change projects, such as Salters Chemistry, Twenty First Century Science, or Australian projects such as ASEP or Primary Connections, have produced detailed resources, arguing that new ideas need new resources to exemplify them. The danger with a resource-driven approach is that the intention of the developers is all too easily subverted by teachers who overlay the materials with their own, possibly unreconstructed traditional beliefs and strategies. On the other hand, curriculum resources do have the advantage of clarifying the nature of the innovation. For maximum effect these models should be combined, as with the

German *Chemie im Kontext* project (Parchmann et al., 2006) which involved the collaborative development of resource materials by participating teachers and schools.

The CASSP trial project (Goodrum, 2006) on which *Science by Doing* is based, and Primary Connections (Academy of Science, 2005; Hackling, 2006) both have a professional learning model sitting within them, involving in CASSP a participative inquiry in professional learning element. Goodrum (2006) reports that in the CASSP trial the participative inquiry sessions did not occur in many schools because of time pressures. Thus, the project, rather than achieving local commitment and ownership, rested on the delivered PD sessions and the student resources. There are three problems with a project based on student materials, or to a lesser extent on teacher material resources: the sense of ownership of the reform is limited if there is no scope for personalising the materials; the materials will not be adapted to the specific needs of the school context; and the intended innovation may be subverted if teachers impose their own beliefs and strategies on delivery of the materials. In the SIS project, teachers in each school decided on their particular reform needs, framed by the pedagogical components, and planned around these. Two key successes of the SIS project were the change in teacher classroom practice, and the substantial improvement in school science curriculum planning.

The Primary Connections initiative is attempting to accommodate both these models, developing teacher unit materials to exemplify inquiry approaches within a conceptual change model, but also developing a set of pedagogical principles related to SIS, and a PD module supporting schools to take ownership of the way they use the program. This degree of flexibility has already paid dividends, with trial teachers introducing significant modifications to the learning sequences, adding and subtracting to adapt the units to local conditions. Such flexibility is needed if teachers are to be encouraged to be responsive to their students' needs, and to link science with the local context and community. Many ASISTM projects are good examples of this local relevance. Ways need to be found to promote Primary Connections to schools and teachers to support them in developing the new pedagogical approaches intended, while ensuring local school ownership and control.

Concluding comments

In the first part of this section research was reviewed and a related initiative, which could be a model for re-imagining secondary science teacher education, was described. What is needed, in the Deakin initiative and more broadly, is the development and sharing of experience on the way such units and courses can successfully operate. Additionally, focused investigation is needed, into the development of resources to support initiatives dealing with the nature of science in contemporary settings, and with ways in which the core science attributes such as analytic thinking and problem solving, communication and teamwork, can be supported in such initiatives. Such resources might include student material exemplifying science in industrial and community settings, practical exercises related to socio-scientific issues, or teacher material, including case studies of such initiatives, that would contribute to a bank of expertise, including the sharing of pedagogies that support these developments.

With regard to teacher professional learning, it is the contention of this review paper that any serious attempt to support teachers implementing a significant science curriculum initiative in Australia would need to encompass both resource development, and a significant professional learning approach that allowed local control and contextual variation, that attended to teacher beliefs, and was supported in local areas through networks and consultants.

Conclusions and implications

This review paper took as its starting point the concerns explored in the ACER conference, 'Boosting science learning: What will it take?' which had been planned with the express intention of addressing and developing a response to the current crisis in science education. In Sections 1 and 2 the different dimensions of this crisis were teased out and shown to interrelate, and the consequences for Australia as a nation were explored. The crisis was argued to relate to changed conditions in post-industrial societies, to which science education has not adequately responded. The review has explored the literature with a view to identifying the dimensions of the problem and potential solutions. The review has argued that the current scientific literacy perspective on curriculum is appropriate, but needs to be interpreted through voices representing the range of possible futures for students in using their science, and the implications of these for curriculum knowledge emphases. It explored the nature of contemporary science and the way science is used in many circumstances by many people, to argue the shortcomings of the current strong focus on conceptual knowledge, and to tease out what knowledges and capabilities would be worthwhile to develop.

In Section 4, it explored the implications of these challenges to science education for theories of learning, arguing for characteristics of a theory that will support productive ways forward: that learning is seen as an active, adaptive process rather than a pathway to resolved conceptual end points, where the literacies, or discursive elements of science are an important focus, and where values, aesthetics and narrative are given due emphasis. In Section 5 a number of issues and contemporary examples of school science initiatives to help frame the appropriate content for a re-imagined school science were examined. These included the role of conceptual knowledge, context-based curricula, investigative and inquiry-focused curricula, content planning based on citizens' needs, and linkages between schools and wider communities. It argued a major need to develop an assessment regime that supported a variety of curriculum emphases. Section 6 then looked at the implications of these ideas for teachers, separately for initial science teacher education where a potentially fruitful model was described, and for professional learning.

Shaping the way forward

In Section 5 a number of initiatives were reviewed showing that significant innovations at the teacher, school and system levels exist that can provide signposts of ways forward for science education. The concluding comments in that section summarised the dimensions of a possible

re-imagined school science. The task for us, and ultimately for curriculum developers, is to weave these into a coherent approach to teaching and learning science. Table 10 takes these and signposts from other sections to develop a set of strands which provide significant principles for a re-imagined science curriculum.

Table 10. Strands in a re-imagined science curriculum

Strand	Comment
Conceptual content and context	It is clear that the curriculum needs to seriously cater for student interest and be set within contexts that will be meaningful to all students. The content of science needs to be set within these contexts, and introduced on a need-to-know basis but structured so that major ideas are covered. The amount of content coverage needs to be reduced. Content should be chosen to represent contemporary practice, and with a view to its usefulness in students' current and future lives as citizens. Content should not be restrictive but needs to allow room for initiatives built around local conditions.
Pedagogy	Teaching strategies in science need to be more varied, with greater agency accorded to students to pursue ideas and have input into discussion. Ideas should be treated as tools to be used flexibly, rather than simply recalled and recounted, and a premium should be put on the having and testing of ideas. Explicit attention needs to be paid to: (a) the literacies of science and the role of representation in learning; (b) reasoning in science; and (c) aesthetics and narrative elements in science learning.
The way science works	Greater attention needs to be paid to the workings of science in contemporary society, including sociological and epistemic aspects. That is to say, the curriculum should strongly represent the way science interacts with society and technology and include concepts such as risk and questions of value and ethics. It should strongly represent the way knowledge is established in science, the nature of scientific evidence, and the processes of science investigation, via rich representations.
Investigative science	Science investigations need to be more varied, with explicit attention paid to investigative principles. Investigative design should encompass a wide range of methods and principles of evidence including sampling, modelling, field-based methods, and the use of evidence in socio-scientific issues. Investigations should frequently flow from students' own questions. Investigations should exemplify the way ideas and evidence interact in science.
Capabilities relating to science	The curriculum needs to explicitly aim to widen the capabilities currently associated with school science to include understandings of the nature of science and the way it works both in a research and a societal sense, the capacity to investigate and reason, dispositional capabilities such as interest and curiosity and appreciation of the workings and methods of science, and more broadly generic capabilities such as thinking analytically, communicating and working in teams, and creativity and imagination. In so far as these are part of generic sets of capabilities included in some states' science curricula, more work needs to be done on conceptualising what they look like and how they can be developed and assessed in science.
The setting of school science	School science should be linked more often and more closely with local and wider communities, and science should be studied in community settings that represent contemporary science practices and concerns. Ways need to be found to embed school-community initiatives into the curriculum in sustainable ways.
Assessment	Assessment approaches need to be developed that support the wider range of curriculum emphases advocated by this review. This includes assessment of investigative capabilities, the capacity to explore science in social and ethical contexts, reasoning and imagination, and understandings of the nature of science. Ways need to be found to embed authentic, learning-based assessment practices in mainstream practice, alongside more imaginatively conceived test-based items.
Teacher learning	There is a need for tertiary science to also align with re-imagined school science practices. Teacher training needs to reflect these principles, and there is a need to develop policy and strategies to support teachers to change their commitments and practices in ways which support a re-imagined science education. Teacher professional learning needs to be school-based, and should focus substantially on pedagogy.

The stances argued for in Table 10, in many cases, represent the type of school science that is advocated in contemporary curricula. What this review paper has attempted to articulate is both the dimensions of the problem, and the key elements of the way forward, as a coherent package, underpinned by a broader vision of the purposes of school science. The arguments are intended for the federal and state governments as policy drivers in science, in particular in the hope they might identify current policy directions and practices that need further support, and others that represent blind alleys in the search for a science education that engages students in significant learning. Specifically, the arguments in the review raise serious questions about the appropriateness of aspects of current national and state directions in curriculum development (too resource-focused with insufficient local flexibility), in the range of curriculum emphases that are listed (too narrow, representing a narrow view of science education, and often not including affective elements of capability, and too constraining of innovation), and in projected assessment regimes that emphasise accountability through benchmarking (too narrow and insufficiently imaginative). Additionally, there are developments at state and national level where exciting things are happening which need to be supported if they are to continue. The ASISTM project for instance has spawned a number of innovative initiatives, and in many states there is considerable local curriculum control, and curriculum projects that introduce students to authentic and contemporary versions of science.

Issues of freedom and control

There are some inherent contradictions within current trends and policies that foreshadow competing futures regarding the shape of school science. The contradictions are those between:

- a drive for curriculum uniformity and specific resource support vs. initiatives that involve considerable local freedom to act and support for flexibility of program
- national benchmarking and assessment programs versus open formulations of curriculum and resources (with an emphasis on local control).

These contradictions reflect tensions between the concepts of control and accountability, and openness in the treatment of schools and teachers and the presumption of local expertise, initiative and responsibility.

Such tensions are of course inevitable in the operation of the modern state; meeting its curriculum responsibilities focused on agreed student outcomes, but cognisant of the role of teachers as professionals whose effectiveness depends on them expressing their knowledge and expertise without undue constraint. We need to get the balance right. This review has argued that a re-imagined science curriculum must pay serious attention to local context arguably including links outside the classroom, and to contemporary socio-scientific issues which by their nature vary with time, and also may be local. This flexibility is professionally rewarding for teachers, as well as potentially meaningful for students. A re-imagined school science curriculum should be framed to not only allow, but actively encourage, local innovation.

Supporting a re-imagined science education

There are a number of implications for Australian state and federal governments, flowing from this review, which will be addressed under the headings of the relevant curriculum support structures: curriculum frameworks, pedagogy, assessment, resource provision, and teacher learning.

Framing the curriculum

The science curriculum needs to focus on an expanded range of student capabilities that include serious attention to understandings of the way science works in contemporary settings, an expanded version of the ways evidence is used to establish knowledge claims (working

scientifically), and dispositions in relation to science. The Australian *Statements of Learning for Science* developed by the Curriculum Corporation for Australia's Ministerial Council on Education, Employment, Training & Youth Affairs (MCEETYA, 2006) provides support for such a program, 'setting out the knowledge, skills, understandings and capacities that students in Australia should have the opportunity to learn and develop in the science domain' (p.iii). The Statements are organised around three broadly defined aspects: science as a human endeavour, science as a way to know, and science as a body of knowledge. Within the *science as a human endeavour* organiser, there are statements relating to dispositional aspects of students' response to science and appreciation of the personal and human aspects of science. There are also references to future-oriented thinking, interactions between science, technology and society, and skills such as communication built into the statements. Thus, appropriately interpreted, the statements are capable of supporting a re-imagined science curriculum of the sort identified in this review.

Pedagogy

Many of the innovations described by the literature reviewed in this document imply expanded and innovative teaching practices. One of the key criticisms of the current, traditional practice in school science has been of the pervasive use of transmissive pedagogies, and the lack of variety in teaching strategies. This is in part a response to the nature and volume of curriculum content requirements, and possibly the continuance of a long-standing tradition. Pedagogy, in a re-imagined science curriculum, will need to be more varied, more supportive of students' agency through more open tasks, increased discussion and negotiation of ideas, and involve more varied settings. Reform of science education will need to include a substantial re-think of pedagogy, linked to content reform and teacher development.

Assessment

Too often in the past, traditional modes of assessment that focus on conceptual knowledge, often at a low level, have been the default option that subverted attempts to widen the emphases in school science. This has been particularly true in senior science where there is a need to provide defensible state-wide comparisons of student achievement, and where there are strong, long-standing assessment traditions. There is an urgent need, if the curriculum practices described in this review as leading to a more relevant and engaging science education are to be promoted, to develop rigorous and defensible assessment practices to support this.

Given that many of these practices involve tasks that are student-led, local and current in context, and involve broader skills such as analytic thinking and communication, it is difficult to imagine the development of examination-based assessment that will do justice to these. Rather, it seems more feasible to develop approaches to assessment that are embedded in serious, longer term activity, and which therefore will involve teacher judgement and moderation. This would constitute a challenge to current directions in state and national assessment practice, which currently threatens to close down variation and innovation by pursuing a narrow version of accountability through tight specification of content.

Resource provision

Any major changes in curriculum direction need to be supported with resources that exemplify the approach. This need not imply a tightly scripted curriculum, but rather might involve the generation of activities or even lesson sequences or even approaches with illustration, to embed within locally produced curricula. The need to embed science learning in contexts that are meaningful to students might involve the generation of activities based around sport, or utilise computer simulation games, which can be done as a state or national initiative. There is a need, however, to support the use of local contexts (local environmental issues, a local park or river or industry) and local expertise (the local council, local scientists and engineers, CSIRO developed

projects) particularly in developing school–community linked projects. For this, the provision of exemplary case study material and advice and consultant support would be more appropriate. For dealing with contemporary issues, rubrics for selecting, comprehending and evaluating newspaper articles might be more appropriate than the provision of articles as such.

Currently, there are moves to develop national curriculum materials at primary and secondary level. The findings of this review would indicate that these should not be conceived of as documents that completely prescribe each school's curriculum, but rather allow room for and encourage the development of local content and approaches, within a specified model of pedagogy and content. This would represent a more flexibly conceived approach to accountability than that involved in completely specified curriculum with student resources, as has been attempted in the past.

Teacher learning

Teachers are the key to how and what students learn in their science classes, and any attempt to re-imagine the science curriculum must involve serious attention to teacher learning. As described in this review, teacher commitment to the traditional curriculum can involve deep-seated belief and identity issues. However, the review has described evidence of many teachers involved in innovative practice, and teachers changing their commitments. It has additionally described models that may provide powerful new directions in pre- and in-service teacher education. The issue of new directions of science teacher supply need to be addressed together, in a coordinated approach to science in schools.

Concluding comments

This review has explored the nature of the current crisis in science education, and linked it to wider changes in science and in society. The literature clearly shows that the problem is neither confined to Australia, and nor is the nature of governmental and professional concern peculiarly local.

What became clear, through the examination of the literature, is that the dominant mode of school and tertiary science has somehow got out of kilter with the needs and interests of contemporary society and contemporary youth. What is needed is a re-imagining of science education that involves a re-thinking of the nature of science knowledge dealt with in schools, moving away from authoritarian knowledge structures to more flexible, and more challenging, conceptions of classroom activity and more varied ways of thinking about knowledge and learning.

There are examples of innovation in school science internationally, which offer encouraging signs of pathways Australia could productively take to increase student engagement in learning and doing science. These pathways have in common that they focus on a science that is contemporary and contextually rich, on pedagogies that encourage student agency and engagement in significant learning, and on a multi-faceted view of the nature of science. In Australia there are currently examples of policy directions and practice that align well with this re-imagining, but also examples that fall short of the ideal.

What is needed is the development of a coherent national vision around which a future direction can be clearly charted. Over the next short time period, important decisions will need to be made concerning the future directions of science education in this country. Australia has the opportunity to establish science education as a leading plank in educational reform.

We need to draw on innovations in this country and overseas that exemplify:

- a rethinking of content, based on a rigorous pursuit of the guiding principle of scientific literacy
- the promotion, through teacher education and resource development, of more varied and open pedagogies known to elicit middle years students' engagement with learning

- the development of assessment policy and practice that support a more flexible and open, but challenging curriculum.

What is needed, above all, is the vision and will to establish a fresh and coherent vision to guide this process and bring all stakeholders on board. The time has passed where it is enough to tinker round the edges with a science education that belongs to the past.

List of 2006 ACER Research Conference papers

At the conference, three keynote papers (Osborne, Rennie and Bybee), 11 concurrent papers, 20 poster presentations, and ACER CEO Masters's opening and closing addresses were presented. A final panel session reviewed and responded to ideas from the conference.

Synopses of these presentations are available for downloading on the conference website. The link to that website is: <http://www.acer.edu.au/workshops/conferences.html>

Bybee, R. *Enhancing science teaching and student learning: A BSCS perspective.*

Carter, L., & Clarkson, P. *Poster presentation: Science education and mathematics education in the era of globalisation – Findings from early research.*

Corrigan, D. *No wonder kids are confused: The relevance of science education to science.*

Davies, J. *Re-thinking science education through re-thinking schooling.*

Fensham, P. *Student interest in science: The problem, possible solutions and constraints.*

Goodrum, D. *Inquiry in science classrooms: Rhetoric or reality?*

Hackling, M. *Primary connections: A new approach to primary science and to teacher professional learning.*

Harris, K-L. *Addressing the looming crisis in suitably qualified science teachers in Australian secondary schools.*

Ingvarson, L., & Semple, A. *How can professional standards improve the quality of teaching and learning science?*

Masters, G. (a) Opening address (ppt slides): *Boosting science learning – The challenge.*

Masters, G. (b) Closing address (ppt slides): *Boosting science learning – What will it take?*

McCrae, B. *What science do students want to learn? What do students know about science?*

Osborne, J. *Towards a science education for all: The role of ideas, evidence and argument.*

Rennie, J. *The community's contribution to science learning: Making it count.*

Rodrigues, S. *Creating powerful teacher education opportunities: The need for risk, relevance, resource, recognition, readiness and reflection.*

Thomson, S. *Science achievement in Australia: Evidence from national and international surveys.*

Tytler, R., & Symington, D. *Boosting science learning – What will it take?*

Panel discussion

Putting it to the experts: Boosting science learning – What will it take?

Panel members

Peacock, J. (Australian Chief Scientist), Carnemolla, P. (Australian Science Teachers Association), Rennie, L. (Curtin University of Technology), Osborne, R. (Kings College, London), Bybee, R. (BSCS, Colorado), Thompson, J. (Tertiary science student and 2005 Science Olympiad), Frazis, M. (Secondary student and 2006 Science Olympiad), Stuart, D. (Minerals Council of Australia).

Panel discussants

Tytler, R., & Symington, D.



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Russell Tytler, Professor of Science Education at Deakin University, Victoria, has had a long involvement with significant local and national science curriculum and professional development projects. His current research brings together his interests in curriculum, student learning, and school and teacher change, with its focus on exploring new directions for science education. An active contributor to debate in the field, he is the author of numerous academic and professional publications.

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