Primary science education for the 21st century: How, what, why?

In 2010 the science education team at the New Zealand Council for Educational Research (NZCER) was commissioned to write a paper that would encourage debate on how we as a country could engage more young people in science, focusing in particular on the role of schools. The paper, entitled *Inspired by Science,* was published as part of *Looking Ahead: Science Education for the Twenty-First Century,* a report by the Prime Minister's Chief Science Advisor.[1] In *Inspired by Science* we argued that there was a need to acknowledge the many different purposes school science education serves, and to think carefully about which of these purposes matter most. We presented a scenario for the future that involves emphasising different purposes for learning science at different stages of the school system. This paper builds on *Inspired by Science*. It sets out to both inform NZCER's ongoing work in the area and to contribute to a wider debate about how primary science education in New Zealand might best be strengthened. We describe what we think quality primary science education looks like, and suggest some strategies through which this could be achieved.

Background

The New Zealand Curriculum, in common with the curriculum documents of many other countries, has a strong focus on "citizenship" science. It says that science education's goal is to develop students who "can participate as critical, informed and responsible citizens in a society in which science plays a significant role".[2] Learning about science is seen as important for *all* students, not just those heading for science-related careers. This emphasis, combined with other changes—changes in society, changes in what we know about how students learn, and changes in science itself—means that it is necessary to rethink past ideas about what quality science education looks like.

What do *today's* young people need to know and be able to do, and why is this important? What are the most effective ways of teaching science at the different levels of the school system? What skills and knowledge do teachers need? These questions need serious thought and require input from a range of people—science educators, researchers, policy makers, scientists and the wider community. Redeveloping our science education system for 21st century needs is not something that can happen overnight: however, we think that there are some relatively straightforward, immediate things teachers could do that would increase student—and teacher—engagement in science. This paper outlines a framework for science education in the primary years. This framework is consistent with *The New Zealand Curriculum* document, and takes into account research on the needs and capabilities of young learners, the needs and capabilities of their teachers and the literature on the likely future needs of citizens.

Its starting point is the argument that primary science education can best contribute to the citizenship goal by *nurturing children's interest* in the world around them and developing *positive attitudes* toward science.[3] Primary school science needs to build on the experiences children bring to school, and, if it is to be future-oriented, it also needs to provide opportunities for students to be involved in "knowledge building" activities.[4] We think this is best done by providing a *range of*

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[1] Available at http://www.pmcsa.org.nz/science-education/

[2] Ministry of Education (2007), p17.

[3] Research shows that although children start out enthusiastic, intrinsic motivation in academic subjects decreases as children progress through primary school (Perkins, 2009). Trends in International Mathematics and Science Study (TIMSS) and the National Education Monitoring Project (NEMP) also show declining levels of interest in science as students move through the primary school.

[4] We use "knowledge building" to mean more than simply active learning where the focus is on students developing knowledge and skills through participating in interesting activities. Knowledge building signals a "shift from treating students as learners and inquirers to treating

engaging activities; including lots of *purposeful classroom talk*; ensuring *literacy programmes include both narratives* and *factual writing* about science topics; and supporting teachers to be clear about *how all these activities contribute to the citizenship aim* of science education. In the early primary years the aim should be to provide students with a *broad range of experiences*, while in the later primary years (especially at Years 7 and 8), there is a need for students to study at least some topics *in depth*, and to participate in discussions of *socio-scientific issues*. The rest of this paper sets out what we mean by each of these features, and why we think they are important.

The importance of a range of experiences

Young children have the intellectual capacity to learn science. Contrary to earlier ideas about child development, recent research shows that children's thinking is surprisingly sophisticated. Children can, for example, demonstrate causal reasoning and distinguish between reliable and nonreliable sources of knowledge. Recent advances in cognitive science suggest that children think and learn in quite similar ways to adults, but differ from them only in that they have less experience to draw on when making sense of what they encounter. Children bring a range of experiences with them when they come to school, and it is these experiences that affect children's "readiness" to learn, not fixed age-related stages of development. Adults play an important role in young children's development by directing their attention and structuring their experiences.[5] [6]

A commonly heard argument today is that, in our information-rich world, knowledge is no longer necessary. Schools, the argument goes, should concentrate on developing students with the skills necessary to access and evaluate information as needed, rather than on teaching content. However, research in cognitive science does not support this argument. Thinking skills and knowledge[7] are bound together. Willingham (2009) describes a simple model of the mind, consisting of the working memory (site of awareness and thinking) and the long-term memory (where factual knowledge and procedural knowledge are stored). Successful thinking, he argues, depends on information from the environment, facts and procedures in the long-term memory and the amount of available space in the working memory. More information can be held in the working memory if it can be "chunked" but this depends on there being the relevant factual knowledge in the long-term memory. Knowing things makes it easier to learn new things. If the knowledge the child brings to school is different from the kinds of knowledge that are valued at school, over time they will fall further and further behind their peers. Schools need to ensure *all* students have access to the experiences that build the kinds of background knowledge necessary for success at school. Building a "library of experiences", in our opinion, should be a main focus of primary education.

Engaging activities

Today there is greater recognition of the interrelatedness of the biological, social, emotional and intellectual aspects of children's development, and the importance of the child's active

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them as members of a knowledge building community" (Scardamalia & Bereiter, 2006, p. 99). For Scardamalia and Bereiter the fundamental task of education in the 21st century is to enculturate young people into today's knowledge *creating* society and to help them find a place in it. Knowledge building activities contribute towards this. (See Appendix 1 for a more detailed account of "knowledge building".)

[5] For more information, see Alexander (Ed.) (2010) and National Research Council of the National Academies (2007).

[6] Kieran Egan argues that certain "cognitive tools" are particularly powerful at different ages and students become more engaged in their learning when appropriate tools are used.

[7] Knowledge is more than facts or information. Alexander et al. in *The Cambridge Primary Review* (Alexander, Ed., 2010) argue that the various domains of knowledge should be viewed "not as collections of inert or obsolete information, but as distinct ways of knowing, understanding, enquiring and making sense" (p. 248).

participation in their learning. Multisensory approaches to learning are important.[8] This is why concrete learning experiences are such potentially powerful learning experiences.[9] Direct experiences of nature, for instance, both enhance children's health and wellbeing, and support the development of long-term proenvironmental behaviour.[10] Involvement in community projects (such as cleaning up a local waterway) can provide powerful learning experiences, but requires a significant time commitment. We recognise that not all teachers or schools may currently feel able to offer such opportunities but there is a range of other less time-intensive activities that could be considered. "Nature tables" and "science discovery centres" in classrooms are possible ways of providing opportunities for students to experience the natural world, to observe closely, ask questions, look for patterns etc. (and perhaps also provide the motivation for writing). Bringing in "experts", visiting science centres or participating in virtual fieldtrips are all ways teachers can bring the expertise and passion of others into their programmes. We think such activities are an important part of primary science classrooms, and recent NEMP data suggesting that primary students are being offered fewer practical activities now than previously is a concern.[11]

Classroom talk

Talk is also important. Knowledge and understanding are developed, not only through the interplay of new experiences and what the student already knows, but also through conversation with others. According to the authors of the recent *Cambridge Primary Review* in the UK, "Talk—at home, in school, among peers—is education at its most elemental and potent. It is the aspect of teaching which has arguably the greatest purchase on learning" (Alexander (Ed.), 2010, p. 306).

Increasing the opportunities students have to talk about science has many benefits. It provides opportunities for teachers to learn about the knowledge students already have and makes students' thinking visible. In this way it is an important tool for formative assessment. Talk, however, does much more than just make thinking visible: it actually supports the development of thinking. A large number of studies have shown that structured classroom talk produces deeper engagement with the content under discussion, and develops subject-specific reasoning.[12] Resnick, Michaels and O'Connor (2010) call talk that attempts to make discourse norms and ways of behaving accessible to all, *Accountable Talk*. This sort of talk attends to, and builds on, the ideas of others; emphasises logical connections and the drawing of reasonable conclusions; and speakers endeavour to make explicit the evidence behind their claims. To begin these sorts of discussions, students need to have interesting and complex questions and ideas to talk about.[13]

Deep knowledge

As well as being exposed to a wide range of experiences there are powerful arguments for students to learn some things in depth. Novices and experts think in different ways. Experts think in terms of deep structure or functions whereas novices tend to focus on surface features. Seeing the deep structure allows experts to transfer their knowledge to new situations more easily than novices.[14] Another argument for deep learning is that if students' knowledge of everything remains at a

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[8] Research has shown "that learning is strengthened not only in relation to how many neurons fire in a neural network, but also by how they are distributed across different domains, such as the motor and sensory cortices" (Alexander, Ed., 2010, p. 96).

[9] See Zull (2002) for more detail.

[10] See Department of Conservation (2011).

[11] In 2007 (as compared with 1999), more Years 4 and 8 students participating in NEMP said that their classes "never" did experiments with everyday things, experiments with science equipment or visited science activities.

[12] See Osborne (2007) for more detail.

[13] Karen Gallas (1995) describes in her book *Talking Their Way Into Science* how very young students when presented with open-ended questions, the answers of which are unlikely to be known by them, can build on each other's ideas and display complex thinking.

[14] See Willingham (2009) for further discussion.

superficial level, they never develop an appreciation of what knowledge can do. In the process of learning something in depth, students learn about how claims to knowing are built and defended. Learning in depth engages students' imagination and emotion in learning—nurturing a disposition for lifelong learning.[15] However, becoming an expert takes time.

One way of laying the foundations for developing depth of understanding in science could be to provide opportunities for young students to play a junior version of the "whole game" of science. David Perkins (2009) argues that junior versions are a way of providing "threshold experiences" that make challenging knowledge and practices accessible even to young students without losing the holistic nature of the activity. The seamless nature of *The New Zealand Curriculum* potentially supports this notion of playing the junior version of the game of science in the primary school but it is easy for teachers (and students) to lose the holistic picture, focusing instead on specific learning intentions. According to Perkins, a "whole game" is generally some kind of inquiry or performance. (Although problem-based learning could be considered an example of playing a whole game, learning by wholes does not necessarily have to be such a big game. A short lesson could have the necessary features.) A whole game is never just about content—students are trying to get better at *doing* something. It requires thinking and allows for a number of different approaches. It involves explanation and justification. It is situated in a social context and involves curiosity, discovery, creativity and working with others.[16]

Socio-scientific issues

We have suggested that in the upper primary school it is appropriate that some things are studied in depth and that the science education programme should also include some focus on socio-scientific issues. During early adolescence, young people often begin to think more deeply about the world around them and their place in it.[17] This is thus a good time to actively involve students in thinking about socio-scientific issues such as diet, health, environmental issues and so on. A review of the research on teaching and learning science in the UK[18] suggests that "context-led" courses produce greater student interest and appreciation of the relevance of science learning to everyday life.

Literacy programmes and science

The development of literacy skills could be another major contribution that the primary years make to science education. Considerable amounts of time are allocated to literacy in primary schools and teachers have a great deal of expertise in this area. According to Osborne (2002), reading, writing and argument are "central to any conception of science as it is currently constituted". An understanding of science requires the ability to read texts. Children should become familiar with a variety of text types: reports, explanations, fact files and stories, for example. Narratives, in particular, play an important role in nurturing children's interest in the world around them and developing positive attitudes toward science. Stories help to make ideas coherent, memorable and meaningful and also help portray science as a human activity.[19] Story telling is part of all cultures and is a powerful—and universal—way of making sense of the world.

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[15] See *Learning in Depth* project for more detailed discussionhttp://www.educ.sfu.ca/kegan/A%20Brief%20Guide%20to%20LiD.pdf

[16] These characteristics of playing the "whole game" resonate with the "performances of understanding" that Gardiner (2006) argues are necessary for the development of the disciplined mind.

[17] Ministry of Education. (2008). *Teaching and learning in middle schooling: A review of the literature*. Wellington: Author.

[18] See *Science Education in Schools: Issues, Evidence and Proposals: A Commentary by the Teaching and Learning Research Programme* http://www.tlrp.org/pub/documents/TLRP_Science_Commentary_FINAL.pdf

[19] See, for example, Kieran Egan, Jonathan Osborne.

Teacher knowledge

Much of what we have described in this paper could be considered "business as usual". This we believe is both its strength and its weakness. The strength is that the strategies and practices we have outlined are already largely familiar to teachers. The weakness is that this could be interpreted as no change being required. The important point is that teachers need be very clear about the *purpose* of what they do and how this links to the overall goal of developing scientifically literate citizens. Ideally, teachers should, in relation to anything they do, be able to give a coherent justification citing evidence, pedagogical principle and educational aim.[20]

One of the difficulties facing primary teachers is that science for citizenship requires teachers to understand how science is "scientific", how science develops and how scientists work and think.[21] There is a need for professional development in this area but, in the interim, an awareness of a small number of concepts that are central to science would be helpful. The National Research Council (NRC) on K-12 science education in US schools identifies seven such concepts,[22] the first two of which are:

> *Patterns, similarity and diversity*: Observed patterns in nature guide organisation and classification, and prompt questions about relationships and causes underlying them.
> *Cause and effect: mechanism and prediction:* Events have causes, sometimes simple, sometimes multifaceted. Deciphering causal relationships, and the mechanisms by which they are mediated, is a major activity of science.

If teachers have an awareness of just these two ideas they could structure activities and direct students' attention in ways that contribute effectively to students developing a coherent scientifically-based view of the world. For example, students could talk about caterpillars on the nature table to explore the relationship between food and growth (cause and effect) which in turn requires noticing growth patterns.

In his recent report, *Looking Ahead: Science Education for the Twenty-First Century*, the Prime Minister's Chief Science Advisor advocates that "all primary schools should be encouraged to develop a science champion" (p5). While we agree that there is an urgent need for support for primary teachers, we think there is first a need for clarity about exactly what knowledge and skills are needed. The question of what knowledge students (and therefore teachers) need requires significant thought. What knowledge yields the greatest cognitive benefit? What are the unifying ideas of science? Which knowledge is centrally connected to the discipline of science but also resonates with the interests and concerns of students and teachers? Once these questions have been answered, we still need to consider how best this knowledge can be "packaged" so that both students and teachers do not lose sight of the "big picture".

Perhaps, initially, the role of "science champions" should be to strengthen links between schools and the science (and wider) community to maximise opportunities for students to participate in

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[20] The *Cambridge Primary Review* (Alexander, Ed., 2010, p308) argues that:
Mature teaching (as opposed to teaching to cope or survive) requires:
- command of a repertoire of knowledge, strategies and skills
- understanding of the evidence on which each element in the repertoire draws in order to justify its inclusion
- the judgement to weigh up each pupil need and classroom situation and determine how the repertoire should be deployed and translated into everyday decisions and actions
- a framework of well-grounded principles of learning and teaching, whereby the decisions and actions taken can be known to be right
- a set of educational aims and values to steer and sustain the whole.

[21] The importance of this in *The New Zealand Curriculum* is signalled by the central position of the Nature of Science strand.

[22] The full list is included in the Appendix 2.

engaging activities; work with literacy leaders in schools to ensure there is a wide range of science-related reading material available for students and to promote purposeful classroom talk.[23]

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[23] Robin Alexander’s five principles of dialogic teaching could be helpful. These are: collectivity (teachers and children address learning tasks together); reciprocity (teachers and children listen to each other and consider alternative viewpoints); support (children are comfortable to articulate their ideas freely); cumulation (children and teachers build on their own and each other’s ideas); purposefulness (teachers plan and facilitate dialogic teaching with well-defined educational goals in mind).

Appendix 1

Scardamalia and Bereiter (2006) identify six themes that underlie the shift from treating students as learners to treating them as members of a knowledge building society. These themes are:

- Knowledge advancement as a community rather than individual achievement
- Knowledge advancement as idea improvement rather than as progress toward true or warranted belief
- Knowledge *of* in contrast to knowledge *about*
- Discourse as collaborative problem solving rather than as argumentation
- Constructive use of authoritative information
- Understanding as emergent (p. 99).

In his book, *Education and Mind in the Knowledge Age,* Carl Bereiter (2002) describes three different student orientations to classroom learning activities. Some students, he argues, have *task-completion* goals. They are engaged in the activity at a behavioural level, rather than a cognitive level. Others have *learning* goals. These students have an idea of the educational purpose of the activity and adopt it. They are trying to learn what the teacher is trying to teach. A third group of students have *knowledge building* goals. These students are actively involved with problems beyond the immediate situation. Bereiter argues that schools need to produce students who are *both* intentional learners and knowledge builders.

According to Bereiter (2002), a student focused on learning goals might ask a question like, “Do I understand the formula? Can I apply it?” These are questions that are helpful in guiding the student’s learning. The focus is on what is happening in the student’s mind. A knowledge building goal would require a question such as, “Does this formula make sense?” This sort of question invites discussion, evaluating explanations, making connections etc. The focus is on “idea improvement”.

Bereiter (2002) explains:

- Knowledge-building is not just a process; it is aimed at creating a product.
- That product is some kind of conceptual artifact—for instance, an explanation or a design or a historical account or an interpretation of a literary work.
- A conceptual artifact is not something in the minds of the students.
- It is not something material or visible, either.
- It is nevertheless real and preferably something students can use. (p. 295)

Appendix 2

The seven cross-cutting scientific concepts identified by the National Research Council (NRC, 2010) on K-12 science education in US schools are:

- *Patterns, similarity and diversity*: Observed patterns in nature guide organization and classification, and prompt questions about relationships and causes underlying them.
- *Cause and effect: mechanism and prediction:* Events have causes, sometimes simple, sometimes multifaceted. Deciphering causal relationships, and the mechanisms by which they are mediated, is a major activity of science.
- *Scale, proportion and quantity:* In considering phenomena, it is critical to recognize what is relevant at different size, time and energy scales, and to recognize proportional relationships between different quantities as scales change.
- *Systems and system models:* Delimiting and defining the system under study and making a model of it are tools for developing and understanding used throughout science and engineering.
- *Energy and matter: flows, cycles and conservation:* Tracking energy and matter flows, into, out of and within systems helps one understand their system's behaviour.
- *Form and function:* The way an object is shaped or structured determines many of its properties and functions.
- *Stability and change:* For both designated and natural systems, conditions of stability and what controls rates of change are critical elements to consider and understand.

(Public Comment Draft—July 12–August 2, 2010, pp. 4-2, 4-3. Accessed from http://www.aapt.org/Resources/upload/Draft-Framework-Science-Education.pdf)

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