Staying in science: Can understanding of the disciplinary connectedness of science help?

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Most international curricula require students to develop conceptual and procedural understandings along with developing an understanding about the nature of science. Moreover, science education endeavours to produce scientifically literate citizens capable of making informed decisions about the social-scientific issues in their everyday lives; this is indeed the central purpose and aspiration of science education. However, the numbers of students taking science continue to be declining in Australia and New Zealand as well as in many European countries. We propose an as yet unexplored perspective, that of students not seeing the connectedness of the discipline as they grapple to understand the world around them.

This paper takes the view that students need to understand the connectedness within the discipline of science. Moreover, one makes these connections when there is a broad understanding of the discipline. Is it possible that how and what is taught no longer interests those students we would like to see continue in science (Claxton, 2013)? We think conceptual, procedural, and epistemological knowledge is needed, but that it is insufficient for both scientific literacy and for engaging students so that they continue to study science. Evidence suggests that students need to learn science ideas, not just as facts, but to also understand how various science ideas are connected so that they can make sense of their world. We suggest that students need help to make these connections and to understand the connectedness of the discipline. *We need to change not what we teach, but how we teach.*

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INTRODUCTION

Internationally, concerns have been raised about the loss of interest in science and that generally fewer students are taking it as a subject at school. The decline in the number of students in science curriculum areas has continued to be a problem for science education in Australia (Kennedy, Lyons & Quinn, 2014; Lyons & Quinn, 2015), New Zealand (Kennedy, Smith & Sexton, 2015), and in European countries (Osborne & Dillon, 2008). Many reasons for this decline are mooted, including: ineffective or uninspiring science pedagogy (DeWitt, Osborne, Archer, Dillon, Willis & Wong, 2011); irrelevant or unengaging science curriculum (Smith & Gunstone, 2009); changes in attitudes towards science and science careers (Ainley & Ainley, 2011; Osborne et al., 2009); and changes in education structures and policies (Ainley, Kos & Nicholas, 2008). However, some of these have been refuted by Lyons and Quinn (2015), who argue that uninspiring pedagogy is not a recent phenomenon; similarly, context focussed and exam-oriented curricula have been around for more than 20 years. Perhaps it is worthwhile to investigate the relationship between change in attitude towards science and continuing in science. Lyons and Quinn further argue that perhaps there is some connection between policy and curriculum changes and declining science participation rates in Australia.

Science, technology, engineering, and mathematics (STEM) education is the latest focus of schools, as these fields of education are seen as essential for the prosperity of citizens in many societies (Schütte & Köller, 2015). In a growing international market, students opting out of STEM subjects reduces their career options, and also has consequences for their country's prosperity (Schütte & Köller, 2015). In the UK, increased funding for scientific research is considered as a way forward in improving the situation (Torjesen, 2015). Like most countries that share this view, New Zealand aspires for an economic future through scientific innovation (Joyce, 2014; Salmon & Priestley, 2015). However, interest in science drops off as students progress through their schooling and only 5% of students enter tertiary education to study science having enjoyed and engaged in science at school (Kennedy et al., 2015). Half of those students who take science at tertiary level do so because it is a requirement of the qualification they are seeking (Bolstad & Hipkins, 2008; Cooper, Cowie, & Jones, 2010). So New Zealand sees its future in scientific innovation, but it has the challenge of 95% of would-be possible scientists and innovators not enjoying or wanting to engage in science by the time they reach tertiary education. The situation is similar in Australia where concerns have been raised by the Chief Scientist about fewer students choosing to stay in science (Office of the Chief Scientist, 2012).

POSSIBLE REASONS FOR DISENGAGEMENT

Science is a way of understanding and investigating the natural and physical world. Fundamentally, science knowledge is the creation of human imagination and creativity (Al-Abdali & Al-Balushi, 2015; Aydeniz & Bilican, 2014). Science knowledge is about theory and experimentation (Radder, 2009). Osborne (2015) argues "science is fundamentally about ideas. Experiments serve merely to test the many ideas that are the product of the creative imagination of scientists" (p. 16). As a discipline, science requires curiosity and critical thinking (Driver, 1985; Luce & Hsi, 2015; Osborne & Dillon, 2008). Further, Antink-Meyer and Lederman (2015) asserted that both divergent and convergent thinking are essential for creativity. They questioned whether students' science creativity can be supported or enhanced during schooling and found that the inherent complexity of the classroom learning environment and divergent thinking in science are more multifarious than first thought.

Searching for reasons, is it possible that how and what we teach in science no longer interests those we would like to encourage to continue in science? Internationally, school science aims for students to develop conceptual, procedural, and epistemic understanding (Allchin, 2011; Hodson, 2014; Millar, 2011). Science education in both New Zealand and internationally aims for scientifically literate citizens capable of making informed decisions about the socio-scientific issues in their everyday lives (Ministry of Education, 2007). School science teaching and learning is different to that of practising scientists' science in that for each question scientists want to answer, they have considerable conceptual and procedural understanding (Hodson, 2014; Millar, 2004). In contrast, students are novices learning science ideas and at best are discovering what is already known. Scientific inquiry, as practised in school, is a pedagogic approach used to verify a phenomenon explained by the teacher.

Millar (2014) talks about a science curriculum that is fit for purpose and points out that in the UK 80% of students do not continue with science in senior school. He reminds us that there are three well-established educational purposes for science teaching — economic productivity, social cohesion and inclusion, and personal fulfilment and expression — and argues that the three purposes are interconnected. He states:

> *Young people are different. They are interested in different things, have different aspirations for their lives, learn in different ways. They are also growing up within a society that needs to be grounded in some common understandings and ideals. The science curriculum needs to address both the things that make us different and the things that we need to hold in common. Reconciling the demands of diversity and cohesion will always be a challenge for educators. (p. 19)*

The Twenty First Century Science project in the UK designed and piloted such a programme, but one can only imagine how effective it could have been as policy changes took place before the findings of the pilot could be evaluated (Millar, 2006, 2014).

The ideal curriculum could deliver on all three interconnected purposes of science teaching but it is a challenge to design such a curriculum. Osborne and Dillon (2008) also raise this issue, focussing on the current state of secondary education where an increasing number of students continue to move away from science:

> *The irony of the current situation is that somehow, we have managed to transform a school subject which engages nearly all young people in primary schools, and which many would argue is the crowning intellectual achievement of European society, into one which the majority find alienating by the time they leave school. In such a context, to do nothing is not an option. (p. 27)*

Somehow along the way the needs of 20% of students (the ones who Millar says might carry on with science) have not been met by the *science for all* curriculum, even though it would have been desirable that they had been encouraged to continue in science. Frustrated, or bored, they choose the alternative more attractive options. So, how do we meet the needs of this group so they remain in science? Is it that the students no longer see the disciplinary connectedness of science?

DISCIPLINARY CONNECTEDNESS OF SCIENCE

Disciplinary connectedness here means an understanding of the physical and biological concepts and how they interact with each other. To illustrate, consider the following example using the most common material, air, which is essential for survival of most living things on this planet.

In elementary school, students are taught that we breathe in oxygen and breathe out carbon dioxide and that plants breathe in carbon dioxide and breathe out oxygen. The latter is a misconception that often remains beyond primary school science education. In high school, students learn that air is made up of 78% nitrogen, 21% oxygen, 0.033% carbon dioxide and that the rest is a mixture of other things. They also learn that green plants use carbon dioxide to make food. All these facts are memorised and can be repeated with accuracy by a large number of adults well after their school education.

Recently, we asked prospective science teachers which gas they breathed in. The standard answer was oxygen. We challenged: "What about the 78% of nitrogen in the air, so why did you not mention nitrogen? Is there some way that our nose filters out all else and allows us to breathe in oxygen?" Clearly, they had not thought about it. The next question was "what do we breathe out?" Again, the standard response was carbon dioxide. Further exploration confirmed that this was the general belief. We continued this exploration further by saying "all right then, if we only breathe out carbon dioxide, how come we give mouth-to-mouth resuscitation to save someone's life or blow embers to make fire?" We wondered if they had ever considered that the 0.033% of the carbon dioxide is used by plants for photosynthesis and is responsible for most food on our planet; it was clear that they had not. Finally, it is our contention that 0.033% of carbon dioxide concentration has not as yet reached 0.034% and that its impact on our planet is leading to climate change, but this was all new to our class of would-be science teachers who all have science degrees.

The above example might be a simple one, but this connectedness can be considered at a deeper level across the various sciences. In the middle of the last century, zoology and botany were taught as two distinct sub-disciplines. Students learnt about the taxonomy of plants and animals and their forms and functions. Scientists then looked at the impact of one on the other, with ecology emerging as a field of knowledge, and to understand the interactions between the living things the focus turned to ecosystems. As the discipline grew and scientists looked beyond the biological interactions to the impact of abiotic factors, a bigger and more complex picture of both the physical and chemical factors and the geological and astronomical aspects that influence the natural world became clearer. We were getting somewhere close to having a deeper understanding of the connectedness of all science. School science began teaching about both the natural and the physical world. Making science relevant to students and their particular contexts was promoted next. Alongside this was the growing emphasis on teaching about the nature of science and how scientific knowledge is created. In essence, all of the above have a place; students do need to learn about the natural and physical worlds and to develop epistemological understandings, but they also need to make connections within and between the science disciplines.

One could argue that the curriculum can be taught in ways that help students to understand how science ideas are connected. But when schools and teachers are judged on the results of assessment practices that prioritise fragmentation of knowledge for assessment purposes, it sets up a challenge that is difficult to overcome at a systemic level. Globally, the current focus is on *evidence-based* teaching. The question being raised here is: evidence of what? If it is about evidence of learning, then emerging literature is telling us that increasingly, teaching is being focussed on assessment and students are not able to understand or make connections within the discipline (Tewkesbury, 2017).

Earlier this year, during professional development of science teachers in Malaysia, the usual problems of not having resources, larger classes and examinations were cited as challenges for science teaching. To illustrate what we mean by disciplinary connectedness we chose the context of the human body. We started by saying, "Talk amongst yourselves and tell us, what biology is there in the human body?" There was excited discussion and a long list emerged from cells to organs and organ systems and their functions. Next, we wanted to know what chemistry was involved in the human body. Now the conversation became even more interesting. It did not take a lot of time for teachers to work out that all biological systems are dependent on chemical elements and that all biological functions are controlled by chemical reactions. Lastly, we asked if there was any physics related to the human body. Teachers started with mechanics, joints and levers, and soon were talking about sound, heat and energy. There was a lot of chatter and one teacher said, "Well all the chemical reactions take place at 37°C. Homeostasis is a biological process which makes sure that the heat produced during the biochemical reactions helps to maintain this temperature." One quiet physicist then said, "and it all needs energy". They concluded that the human body was something all students possessed, so what more meaningful context is there for students to want to know and understand science? And, all that was done was asking three questions.

A WAY FORWARD

This paper proposes not a change in the design of the curriculum but rather in the teaching and implementation of it. It is argued that students need to learn about the disciplinary connectedness of science to achieve the goals we set for school science. Assaraf and Orion (2005) talk about systems thinking. One could study systems within the major branches of science (e.g., biological systems or mechanical systems), but do we need students who are able to understand the disciplinary connectedness of science beyond sub-disciplines? Disciplinary connectedness comes from both critical and creative thinking, but more, it requires seeing what someone else has seen, but thinking about it in a different way (Claxton, 2013). We need to consider the ever-increasing fragmentation of science knowledge and its possible impact (on the discipline of science teaching and learning).

Currently, making connections does not have a priority in school science. Current assessment policies in several countries, including New Zealand, offer courses that are assessed by achievement standards. By design, standards are meant to assess what *has been learnt* rather than what *needs to be learnt*. Emerging evidence suggests that science content is being assessed in discreet silos for a set number of credits. Courses can be tailored to offer a smorgasbord of standards. The backwash effect is that assessment prioritises fragmentation of knowledge (Moeed & Hall, 2011; Tewkesbury, 2017) and that disciplinary connectedness is no longer a priority in secondary school science.

If countries want to have creative scientists who draw upon wide-ranging ideas in the science discipline, we need students who will not passively accept the facts that they are taught but who will be curious and ask questions. They will be creative in pulling together what they know and then use their imagination to become lateral thinkers about the wider scientific discipline and the nature of science. Scholars like Lederman and Lederman (2016) and Abd-El Khalick

(2013) highlight the need for students to learn about the very nature of science by asking questions, looking for evidence, being critical of the way in which that knowledge was created, critiquing the robustness of the evidence, and not just analysing but also synthesising existing knowledge to come up with novel solutions, or just be critical consumers of science.

WE NEED TO CHANGE NOT WHAT WE TEACH, BUT HOW WE TEACH

One could argue that in modern times scientists work in multiple disciplinary teams, bringing a broad range of expertise to a research project. The counter argument can be that those who *conceptualise* a multi-disciplinary research project understand the disciplinary connectedness of science, otherwise such projects would not even be started. Returning to school science, if we want students to be creative and innovative scientists, we need those who will not passively accept the facts presented to them or accept the *training to perform in assessment.* One may argue:

> *They will need to get 'right answers' if they are to pass their exams. But the critical thing is how you help them. Do you help them in a way that means they have to remember what it is that you did, or which merely gives them a technique that is triggered by a particular problem? If so, they may not really understand what it is they are doing — and that means they are completely thrown by an apparently trivial change in the way the problem is worded. Nudging, coaxing and encouraging may have better long-term impact than explaining and drilling. (Claxton, Chambers, Powell, & Lucas, 2011, p. 55)*

We want students who are curious, creative, and imaginative in pulling together what they know. In our view, students need to understand the connectedness within and between the disciplines of science and we need to teach in ways that achieve this within policy constraints. As teachers, *how we teach is in our hands.*

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