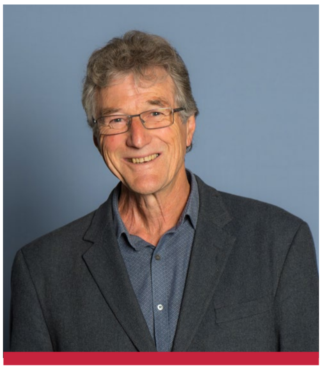
Drawing to learn in STEM



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Russell Tytler is Professor of Science Education at Deakin University. He has been involved over many years with system-wide curriculum development and professional development initiatives. He has researched and written extensively on student and teacher learning in science, and science investigations. His recent research interests include the role of representation in reasoning and learning in science, teacher and school change, international perspectives on science and environmental education, and school–community organisation partnerships. He has undertaken a number of influential studies concerning student engagement with science and mathematics, and STEM policy. Russell has held visiting professor positions in Europe and Asia. He has published more than 100 journal articles, books and book chapters. He is a member of the science expert group for the PISA 2015 assessment.

Abstract

Scientists, mathematicians and engineers draw and model to create knowledge. This presentation will describe a guided inquiry approach to teaching and learning science that involves students actively creating visual and other representations to reason and explain as they explore the material world. The approach has been successfully used in a number of major professional learning initiatives in Victoria and NSW. Evidence will be presented of increased student engagement and quality learning flowing from the approach, which aligns classroom processes more authentically with processes of imaginative scientific discovery. Examples of activities and student drawings and model construction will be used to unpack the relationship between representation, reasoning and learning. Video evidence including that generated in the Science of Learning Research Centre (SLRC) classroom at the University of Melbourne, equipped with sophisticated video capture facilities, will be drawn on to explore ways in which drawing, gesture and talk are coordinated to imaginatively respond to material challenges. The presentation will explore the alignment of these sociocultural analyses to recent findings from neuroscience. Evidence will be presented that the creation of representations is central to quality learning across the STEM disciplines and for interdisciplinary STEM challenges.

The problem of engagement

In Australia and internationally we have seen a considerable amount of concern and policy rhetoric around the engagement of students with school science. This takes a number of forms: a) figures that demonstrate declining participation over two decades in STEM subjects in the senior school years, and in higher education (Office of the Chief Scientist, 2012a, b; Marginson, Tytler, Freeman & Roberts, 2013), b) survey data showing declining attitudes to science over the upper primary and secondary years (Tytler, Osborne et al., 2008), c) data that show attitudes to science negatively correlating with countries' development level (Schreiner & Sjøberg, 2007) such that disenchantment with science is seen to be predominantly a Western phenomenon, d) concerns that Australia's performance in international tests in STEM, as in literacy, is dropping, and e) interview data showing disenchantment with science on the basis of a traditionally transmissive pedagogy, that it does not relate sufficiently to the real world, and that it is difficult (Lyons, 2006; Tytler, 2007).

Osborne and Collins (2001) memorably characterise a major problem with school science as being its superficial coverage of large amounts of content such that 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). Joseph Schwab (1962) argued that school science should increase its focus on what he called the syntactical structure of the discipline rather than its then (and current) preoccupation with the substantive structures of content knowledge; what he famously referred to as a 'rhetoric of conclusions'. In 2006 at the previous ACER conference focusing on science learning, Jonathan Osborne (2006, p. 2) made 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.

A decade further on, this is still largely the case (Goodrum, Druhan & Abbs, 2012), despite growing evidence of the learning payoff of inquiry (Chi, 2009; Furtak et al., 2012). Increasingly there is a curriculum policy emphasis on the development of the 'soft' skills of collaborative problem solving and creativity, and digital literacy. There is a need felt in advanced economies for the education system to produce flexible and innovative individuals. The advancing Asian economies, which have overtaken Australia in international testing regimes, are increasingly emphasising problem solving and inquiry in their curricula (Freeman, Marginson & Tytler, 2015).

The term 'engagement' is often used in relation to these problems, but is used in a variety of ways. Sometimes 'engagement' is used to denote engagement with activity, perhaps busyness. At other times it is related to science as 'fun' (Appelbaum & Clark, 2001). And at other times it is interpreted in relation to the 'relevance' of content, such as approaches that build physics ideas around skateboards or hobbies. In this paper I will argue that we need to see 'engagement' in terms of commitment to substantive learning, as implied by the critiques of Osborne, and Schwab, above. The deeper meaning of engagement, I argue, must relate to thinking and working scientifically, driven by the same curiosity, interest in and passion for ideas that drives scientific knowledge seeking. I will argue that this is the real meaning of inquiry; that it aligns school science classroom practices with the knowledge-building practices of science itself. I will further argue, given new understandings of the nature of science, and recent understandings from classroom studies of how we learn, and what it is to know, that school science as it is traditionally framed and practiced represents a distortion of scientific practices in very specific ways.

I will propose a new way of looking at inquiry, taking as a principle that if we are to engage students with thinking/reasoning and working scientifically, we need to align classroom practices more authentically with the knowledge building or epistemic practices of science (Duschl, 2008; Tytler, 2007). I will ask the questions: How is knowledge built in science? What does it mean to know, in science?

How is knowledge built in science?

Increasingly we have come to understand that scientific knowledge is built by more complex processes than straightforward rational and logical reasoning involving hypothesis generation and testing. Developing explanations and theories involves an imaginative and often communal process of creation of models and representations such as diagrams, 3D models and mathematical symbols. These are the tools through which we develop new ways of looking at the world. This is as true for wave representations, for food webs, for the arcane symbolism of particle physics, and for molecular models, as it is for heliocentric solar system models. Increasingly, with vastly increased digital power, the representational resources available to scientists have expanded enormously to include 3D graphs, false colour stellar imaging, and sophisticated simulations. Further, recent work has emphasised the embodied nature of much of our developing understandings. The interplay between experimental exploration and creative generation of multi-modal representations that is central to scientific epistemic processes is what we need to capture in school science classrooms.

David Gooding's (2004) analysis of Faraday's detailed notebooks shows the key role of visual images generated by Faraday as he worked on his ideas concerning field lines and the relationship between magnetism and electric current leading to the first electric motor design. Gooding identified a fundamental pattern of dimensional transformation from 2D to 3D to 4D (including time), back to 2D representations in Faraday's and others' discovery work, and argued that complex informal reasoning through a mix of inscriptions and artefacts was a fundamental but unacknowledged characteristic of scientific discovery. Faraday devised 3D models to illustrate his ideas, which served as dual artefacts and representations in mounting complex arguments (Gooding, 2006). Latour was an early commentator on scientific laboratory work, and the collaborative processes by which science teams generated representations to guide and make sense of data generation. In following two scientists studying the encroachment of agricultural land into the Amazon forest, he charted the representational re-descriptions that occurred, from ordered and labelled soil container arrays, to measurements of soil characteristics, to tables and finally graphs that were transported to Paris in preparation for writing a paper (Latour, 1999). He talks of 'circulating representations', in which understanding the nature of the transformations is key to understanding the relationship between theory and evidence in science.

What does it mean to know in science?

Sociocultural perspectives on learning characterise the process of learning in science, as induction into the multi-modal representational tools through which we understand the world scientifically. We become increasingly competent members of the scientific community of practice (Lave & Wenger, 1991). Lemke (1990), in a seminal paper, showed the importance of classroom talk in framing reasoning and learning, and in a later paper (Lemke, 2004) showed the multiple modalities involved in coming to know science through classroom discourse, inevitably involving text, diagrams, images, 3D models, abstracted symbols and formulae, gesture, and artefact. The growth in importance of scientific literacy places a dual burden on our conception of learning in science. First, it is an argument about the purposes of science in school that it should prepare citizens to be able to engage in public discourse about science. Second, it makes the more fundamental demand that we see learning science as involving induction into scientific disciplinary literacy, which involves command of the multi-modal representational forms used to reason about and explain the world, and specialised production genres that reflect the way science creates and interprets evidence through interactions with natural systems.

We see representations as the reasoning/visualising tools through which both scientific discovery, and learning of science, progress. We see the abstracted concepts around which scientific knowledge is often structured and mapped as fundamentally constituted of representational practices. Thus, a sophisticated concept of animal diversity will involve facility with the use of keys, cladistics maps, comparative labelled diagrams, tally tables and graphs, geographic distribution representations, and so on. This is often represented but rarely recognised in textbooks.

In a series of projects, we have worked with teachers to develop an approach to teaching and learning science that brings together these understandings about the material, multi-modal nature of learning and reasoning with the demand that learning in classrooms needs to proceed through inquiry, involving the use of these representational tools to reason about and explain phenomena.

The core principles of this guided inquiry approach are (Tytler et al., 2013):

1. Students inquire into phenomena and develop explanations through actively constructing and evaluating representations.
2. Teachers guide explicit discussion of representations – their adequacy and their partial nature – such that students develop 'meta-representational competence'.
3. Students are challenged and supported to reason through a process of mapping between representations and perceptual experiences/hands-on exploration.
4. Formative and summative assessment is embedded in the process, as students and teachers focus on the adequacy and coordination of representations.

Because science is so often visual and spatial in nature, drawing is a key activity in this representation construction practice, alongside modelling, role-play, and digital simulation. Figures 1–3 show examples of students' drawings in response to representational challenges. Each challenge was part of a learning sequence in which students' representational resources were systematically developed and explicitly acknowledged.

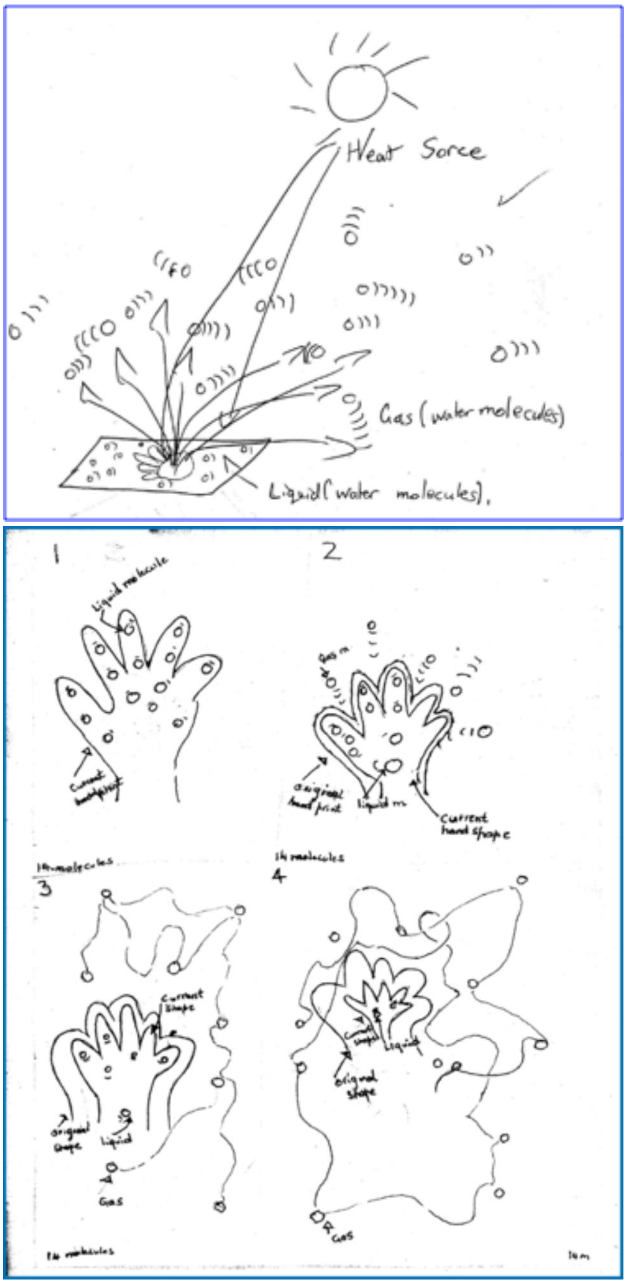

Figure 1 Year 5/6 students' particle representations of a wet handprint on paper evaporating. (Ainsworth, Prain & Tytler, 2011)

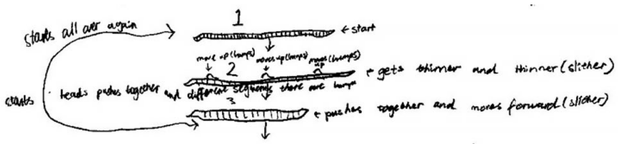

Figure 2 Year 6 students' planning diagram for a model to show how a worm moves (Tytler et al., 2013)

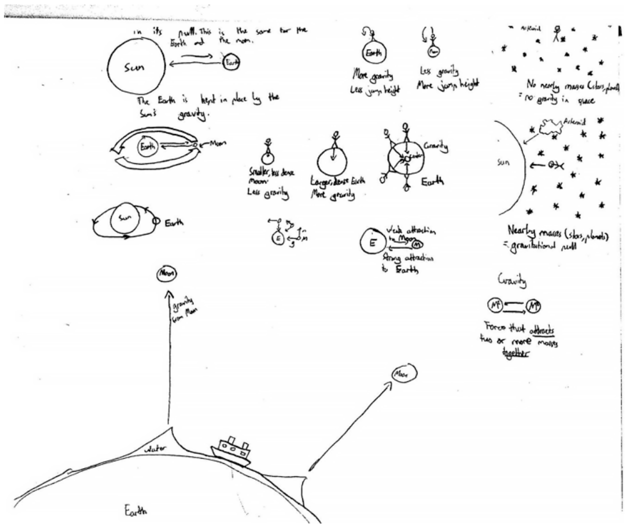

Figure 3 A Year 7 student's exploration of how gravity affects astronomical objects and tides

The effectiveness of drawing and modelling to support rich learning we explain using the notion of affordance as productive constraint. Drawings and models, because of particular visuo-spatial requirements, constrain and guide the learner into seeing phenomena in new ways (Prain & Tytler, 2012). These approaches to representations construction have also been explored in mathematics and in interdisciplinary STEM inquiry, for example in Lehrer's (2009) research with children generating new mathematical forms to investigate growth in plants over time. STEM design tasks are a natural for such representational work.

Studying collaborative reasoning through constructing representations

The Science of Learning Research Centre (SLRC) is a major Australian initiative housed at the University of Queensland, the University of Melbourne, and the Australian Council for Education Research, involving researchers from a variety of universities throughout Australia. A key aim of the Centre is to achieve a productive coordination of understandings about learning from education neuroscience, from psychology, and from in situ classroom studies. A major challenge for the Centre is to translate between sociocultural perspectives on the relation between reasoning, learning, and multi-modal languages and disciplinary practices, described above, and the much more constrained models of learning that have thus far been experimentally investigated in neuroscience.

As part of the SLRC, a Science of Learning (SL) classroom has been set up at the University of Melbourne with state-of-the-art video and audio facilities that can simultaneously capture the talk and work of groups of students engaged in problem-solving tasks. We have thus far captured groups of Year 7 students engaged in representational challenges in the topics of energy and force, levers, plant morphology, and astronomy. For each group of 2, or 4, we have been able to capture their dialogue, their gestures, the artefacts they produce, and to varying degrees a continuous record of their drawing and working with models and digital production. The questions we are investigating include: How do students utilise and coordinate talk, text, artefacts, drawing and embodied modes to collaboratively reason in science? What are the challenges and affordances of transforming and coordinating representations? Under what circumstances is drawing productively engaged with? How do teachers productively support students in inquiry-focused representation construction?

Ethnographic analysis of the video data, supported by StudioCode software, supports the following findings.

- Drawings are a powerful focus for collaborative reasoning and generation of meaning, provided the task is matched to a joint purpose and students are appropriately scaffolded. Drawings often were used to solidify meaning negotiated using talk, gesture, and embodied representation. Students were able to flexibly negotiate drawings, particularly when using a whiteboard that allowed ongoing modifications and joint control.
- The transformation from 3D to 2D representation is challenging, requiring selection of key features and abstraction. For instance, two students achieved sudden insight into why the arctic region can have 24-hour daylight in summer, using a model globe and torch. However, translating this into a 2D drawing proved beyond their resources. Students took a variety of pathways whereby confusion, which is important in inquiry learning, was resolved.
- Conceptual understanding of science concepts involves the capacity to coordinate and re-describe across a variety of representations, which are inherently partial.

Through this and previous research, we argue that to productively engage students in school science, attention needs to focus on the construction and negotiation of representations as disciplinary tools for reasoning and learning, mirroring the way that knowledge is built in science itself.

Implications

In this paper I have argued that inquiry in science classrooms needs to reflect contemporary understandings of the role of representational work in scientific discovery. Traditional versions of inquiry based around hypothesis-method-results-conclusion tend to sidestep the real, and interesting, task of creating explanations in the visuo-spatial forms that provide real insight into phenomena. Experimental results are often taken to speak for themselves without interpretation. Much of traditional investigative designs tend, in the absence of seeking to develop models, to resort to pattern seeking. If we are to develop an engaging invitation for students to take on the challenge of thinking and working scientifically, we need to focus much more strongly on challenging and supporting them to imaginatively construct and explore drawings, models and digital simulations as explanatory resources.

Science curricula, and conceptions of conceptual developmental progression, are traditionally characterised by abstracted concepts expressed in verbal form. However, we would all agree that coming to know involves much more than learning the words denoting concepts. Textbooks reflect this abstracted verbal focus, but concepts are in most cases supported by multiple representations. These, however, are often highly abstracted and simplified, such that the representational practices underpinning them are unacknowledged. Similarly, assessment is often based on the manipulation of high-level abstractions such as formulae or verbal responses, without regard to the visuo-spatial representational practices that are the drivers of reasoning and explanation. We argue that in order to support the agenda described above – where students are challenged to inquire through constructing representations as a core feature of classroom practice – the formal curriculum, resources and assessment need to change to explicitly reflect and acknowledge the primacy of representational work in carrying the burden of reasoning and learning.

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