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Encouraging and guiding conceptual change

Despite extensive contributions to this field over the last 20 years, the fundamental issue of identifying and enacting effective instructional processes to achieve student mastery of concepts remains an ongoing concern in science education research (Taber, 2011; Treagust & Duit, 2008; Tytler & Prain, 2010; Vosniadou, 2008b). This pedagogical challenge persists for various reasons. Recent claims about the formation of concepts and the nature of conceptual learning from (a) cognitive science perspectives (diSessa, 2008) and (b) semiotic and discursive frameworks (Jewitt, 2008; Lemke, 2004; Mercer, 2008; Prain & Tytler, in press, Tobin, 2008) challenge past accounts of causal mechanisms for this learning. Further, a growing range of contextual factors and cognitive/affective processes has been identified as influencing student learning generally, and science in particular (Barsalou, 2008; Jacobson & Wickman, 2008; Klein, 2006; Wells, 2008). At the same time, science learning outcomes based on conceptual change approaches continue to fall short of systemic expectations (Duit, 2009), suggesting the need for new, or modified, or more widely adapted successful classroom practices.

In this chapter we describe an approach incorporating pragmatist, semiotic, sociocultural, and cognitive science perspectives that addresses each of these concerns by focusing on student engagement in a sequence of representational challenges to support conceptual growth. We consider that this focus on guided development of students’ representational resources and competence provides (a) strong student motivation to reason about science concepts, and (b)
offers a theoretically justifiable and highly practical way to support and direct student conceptual mastery. We view our approach as a form of guided inquiry that is compatible with model-based reasoning orientations, but also provides precise strategies to focus on and support student conceptual learning. We put a case that guided construction of representations productively constrains students’ reasoning and learning of science concepts and processes. Finally, we explore the theoretical implications of this work for the conceptualization of the conceptual change process. First, however, we review other current pedagogical approaches to characterize further what is both complementary and distinctive about our own approach.

**Conceptualizing change mechanisms and processes**

The traditional cognitivist account of concepts as mental models within individual minds (Posner, Strike, Hewson & Gertzog, 1982) led to the view that student conceptual change or growth could occur if teachers problematized students’ initial explanations/ conceptions as a basis for guided inquiry and rational acceptance of target models. However, even these early accounts of concepts recognized that they were more than just mental propositions to be held or changed in the mind. Concepts were also to be understood as “strings, images, episodes, and intellectual and motor skills” (White & Gunstone, 1992, p. 5), suggesting that conceptual understanding also entailed practices, inquiry, applications, and making connections between ideas, artifacts, representations and contexts. There is increasing recognition within conceptual change research of the contextual and sociocultural factors influencing learning. This recognition underpinned early conceptual change schemes (e.g. Cosgrove & Osborne, 1985; Driver & Oldham, 1986) incorporating student questions and open classroom discussion. A growing body of research into classroom practice, sitting broadly within the conceptual change framework,
focuses on discourse and the teacher’s role in managing classroom talk (e.g. Mortimer & Scott, 2003). There have also been calls for more research into classroom talk to support conceptual change (Mercer, 2008).

Various researchers have attempted to integrate conceptual change and sociocultural views. For instance, Vosniadou (2008b) noted that “conceptual change should not be seen as only an individual, internal cognitive process, but as a social activity that takes place in a complex socio-cultural world”. In explaining how her conceptual change perspective differed from cultural studies views, Vosniadou (2008a) claimed that mental models and model-based reasoning were crucial to explaining the creation of artifacts and the capacity of humans to develop and modify theories about the natural world. In this way, “a globe as a cultural artifact is nothing more than a reified mental model of the earth viewed from a certain perspective” (Vosniadou, 2008a, p. 281). Our own approach focuses explicitly on the symbolic and material artifacts and representations through which scientific models are generated, justified, refined and communicated by learners.

Research on student model-based reasoning through inquiry is a major strand in theorizing the mechanisms and processes of conceptual change (Clement, 2000; Gilbert & Boulter, 2000; Harrison & Treagust, 2000; Justi & Gilbert, 2003; Lehrer & Schauble, 2006; Vosniadou, 1994). Advocates of this approach claim that the process of constructing, critiquing, testing and revising models arising from inquiry into science topics is the key mechanism for promoting student conceptual growth. Other approaches broadly within this perspective have focused variously on enabling features of technology-enhanced inquiry (Gerard, Varma, Corliss, & Linn, 2011), model-building through problem-solving tasks (Lee, Jonassen & Teo, 2011), and increased student attention to representational resources for meaning-making (Taber, 2011.
Our own approach is broadly consistent with these strategies, but entails a systematic explicit focus on students being challenged to generate, interpret, refine and justify representations as a key practical step in learning science concepts. In developing our case we focus on key affordances or enablers of different representational modes to support students’ reasoning around models. Our broad orientation continues a pragmatist tradition of inquiry into problems-solving through dialogue, debate and logical proof, where inquiry is focused on resolving practical questions assumed to have identifiable causes (Dewey, 1996; Peirce, 1930-58; Wittgenstein, 1972). Our perspective is also consistent with current cognitive science accounts of thinking and learning processes that stress the role of context, perception, activity, motor actions, identity, feelings, embodiment, analogy, metaphor, and pattern-spotting in cognition (see Barsalou, 2008; Klein, 2006; Sinatra, 2005). Here knowledge is viewed as more implicit, perceptual, concrete, and variable across contexts, rather than as purely propositional, abstract, and decontextualized.

**Semiotic and Sociocultural perspectives on learning**

There is a substantial literature arguing that learning and knowing in science should be seen as a process of enculturation into the discursive practices of science (Lave & Wenger 1991), where these practices are substantially shaped around a set of discipline-specific and generic literacies used in science to build and validate knowledge (Moje, 2007). Learning concepts in science involves students switching between verbal, written, visual and mathematical (graphs, tables, equations) and 3D representational modes, and coordinating these to generate explanations (Greeno & Hall, 1997; Hubber, Tytler & Haslam 2010; Lehrer & Schauble 2006a; Prain, Tytler & Peterson 2009; Waldrip, Prain & Carolan, 2010). From this perspective, students
are expected to generate and coordinate multi-modal representational resources to develop explanations and solve problems. Thus, explicit discussion of the form and function of scientific representations becomes a key aspect of teaching and learning in science (Ainsworth 2006, 2008; Lemke 2004), enabling students to understand the value and use of conventions in this work. Achieving meta-representational competence (DiSessa 2004) as a goal of science education means that students need to understand (a) the key characteristics of effective representational practices, (b) the selective nature of representations, and (c) how they are coordinated to develop persuasive solutions (Gilbert 2005; Kozma & Russell 1997, 2005; Kozma et al. 2000). A growing modeling literature identifies the power of refinement of explanatory models through classroom negotiation to achieve this goal (Clement & Rea-Ramirez 2008).

Further studies have verified the defining, rather than supporting role played by representations in generating knowledge and solving problems (Ainsworth, Prain & Tytler, 2011; Klein, 2001; Tytler, Haslam, Prain & Hubber, 2010). This perspective is consistent with pragmatist accounts of the material nature of knowledge (Peirce 1931/58; Wittgenstein, 1972), and the way representations actively shape knowing and reasoning. This implies that classroom teaching and learning processes need to focus on the representational resources used to instantiate scientific concepts and practices (Moje 2007).

From sociocultural perspectives, learners need to participate in authentic activities with these cultural resources/tools to learn effectively (Cole & Wertsch, 1996; Vygotsky, 1978, 1981a, 1981b). A further literature in science education argues the need for students to actively construct representations in order to become competent in scientific practices and to learn through participating in the reasoning processes of science (Ford & Forman 2006). Sociocultural accounts of the value of this practice focus on the potential for increased student engagement in a
learning community (Greeno, 2009; Kozma & Russell, 2005). From a cognitive perspective, Bransford and Schwartz (1999) sought to re-conceptualize the learning gains and potential for transfer when students generated their own representations. Rather than argue that students developed transferable domain knowledge from this activity, they claimed that student construction of representations led to the development of problem-solving skills that could be applied in new contexts.

Researchers in classroom studies in this area (Cox, 1999; Greeno & Hall, 1997; Lehrer & Schauble 2006a, b; Tytler, Peterson & Prain 2006; Waldrip, Prain & Carolan, 2010) have noted the importance of teacher and student negotiation of the meanings evident in verbal, visual, mathematical and gestural representations in science. They claimed that students benefited from multiple opportunities to explore, engage, elaborate and re-represent ongoing understandings in the same and different representations. Greeno and Hall (1997) argued that different forms of representation supported contrasting understanding of topics, and that students needed to explore the advantages and limitations of particular representations. As noted by Cox (1999) representations can be used as tools for many different forms of reasoning such as for initial, speculative thinking, to record observations, to show a sequence or process in time (see also Ainsworth, Prain & Tytler, 2011), to sort information, or predict outcomes. Students need to learn how to select appropriate representations for addressing particular needs, and be able to judge their effectiveness in achieving particular purposes.

**Distinguishing Representations from Models**

Drawing on Peirce’s (1930/58) triadic model of semiotics or meaning-making systems, we view representations as signs that stand for something for an interpreter. Distinctions here are
made between a concept (for example, the scientific idea of force), its representation in a sign or
signifier (arrows in diagrammatic accounts of force), and its referent, or the phenomena to which
both concept and signifier refer (examples of the operation of force on objects in the world).
Learners are expected to recognize the differences between an idea, the different ways this idea
can be represented and used, and the phenomena to which it refers. Coming to know what
‘force’, ‘electricity’ or ‘states of matter’ mean both as concepts and words in science must entail
understanding and using the appropriate representational resources to make cognitive links
between appropriate phenomena and theoretical, scientific accounts of this phenomena.
Therefore learning about new concepts cannot be separated from learning both how to represent
these concepts and what these representations signify in particular contexts for specific purposes.
Demonstrating an understanding of the meaning of the words “sound waves”, for instance,
involves being able to coordinate a range of wave diagrams, time-sequenced representations of
air particle movement, and pressure variation, and to know when, why and how to use these
representations for particular purposes as required in specific contexts.

All models can be classified as representations. However, not all representations are
models. For example, student exploratory talk, gestures, drawings, enactments, and
manipulation of artifacts can function as representations of emerging ideas and insights rather
than as evidence of resolved models. We therefore view representations as a very broad range of
symbolic and material resources and artifacts for supporting students’ reasoning processes,
where they can function as both process markers and products of understanding.
An approach to learning and teaching through representation construction

Associated with theoretical development of pragmatist, semiotic perspective on conceptual change (Tytler, Peterson & Prain 2006; Tytler, Prain & Peterson 2007; Prain, Tytler & Peterson 2009; Tytler & Prain 2010) we worked through a series of research projects with classroom teachers to develop pragmatically a pedagogy that would reflect these unfolding views, culminating in working closely with a small number of teachers over a three year period to develop, refine and evaluate a set of teaching and learning principles. This research involved video capture and analysis of classroom sequences in key science conceptual areas identified in the literature as involving particular challenges. The principles reflect a view of quality learning as induction into the epistemic practices of the science community, with student construction of scientific representations understood as a crucial strategy for acquiring an understanding of the literacies of science as well as their underpinning epistemologies and purposes.

The principles are described below, together with an illustrative case description of a teaching sequence.

1. **Teaching sequences are based on sequences of representational challenges which involve students constructing representations to actively explore and make claims about phenomena**

   a. **Teachers clarify the representational resources underpinning key concepts**: Teachers need to clearly identify big ideas, key concepts and their representations, at the planning stage of a topic in order to guide refinement of representational work.
b. A representational need is established: Students are supported, through exploration, to identify the problematic nature of phenomena and the need for explanatory representation, before the introduction of canonical forms.

c. Students are supported to coordinate representations: Students are challenged and supported to coordinate representations across modes to develop explanations and solve problems.

d. There is a process of alignment of student constructed and canonical representations: There is interplay between teacher-introduced and student-constructed representations where students are challenged and supported to refine, extend and coordinate their understandings.

2. Representations are explicitly discussed: The teacher plays multiple roles, scaffolding the discussion to critique and support student representation construction in a shared classroom process.

a. The selective purpose of any representation: Students need to understand that multiple representations are needed to work with aspects of a concept.

b. Group agreement on generative representations: Students are guided to critique constructed representations, aiming to achieve group resolution.

c. Form and function: There is explicit focus on representational function and form, with timely clarification of parts and their purposes.

d. The adequacy of representations: Students and teachers engage in a process of ongoing assessment of features of representations including coherence, clarity and persuasiveness.
3. **Meaningful learning involves representational/perceptual mapping:** Students experience strong perceptual/experiential contexts, encouraging constant two-way mapping/reasoning between observable features of objects, potential inferences, and representations.

4. **Formative and summative assessment is ongoing:** Students and teachers focus on the adequacy, and coordination of representations.

These principles involve a learning process for teachers as well as students. The clarification of the relation between concepts and representational resources, and the epistemological shift entailed in moving from a view of science knowledge as consisting of resolved, declarative concepts to one in which knowledge is seen as contingent and expressed through representational use, involve significant challenges.

To illustrate the approach we will draw on a previously reported teaching and learning sequence (Hubber, Tytler & Haslam 2010) that focuses on force and motion, involving students in Year 8 (13 year olds).

*Introducing representations of force*

The representational focus places stringent demands on clarifying what knowledge is to be pursued, and what will count as evidence of understanding. The planning process began with the researchers and teachers identifying the big ideas, or key concepts associated with force. Students’ alternative conceptions reported in the literature were discussed, and became key resources for guiding planning decisions.

An examination of the chapter of ‘forces’ in the student textbook, traditionally used to structure this unit, showed a ‘run through’ of many different types of force, represented by
arrows superimposed on complex and often dramatic photographs of force phenomena. The force arrow convention, not discussed as such in the text, was felt to be central to the representational conventions associated with problem-solving in this area, so the initial lessons in the sequence focused on exploring representations of force, leading to the scientific conventions. The idea that a force arrow is a representation convention rather than a resolved and idealized reality was initially challenging for teachers, who needed support to think their way through this approach. This epistemological shift became important, however, in guiding the exploratory and open discussions that occurred throughout the sequence.

Lyn’s sequence was broadly representative of the approach of the three teachers involved in this particular unit, who met regularly to share ideas and experiences and plan. The sequence consisted of a series of challenges in which students constructed representations to clarify force and motion processes, develop explanations, or solve problems. These were often reported on in the public space of the classroom, providing an opportunity for Lyn to question and negotiate the adequacy of the representations and move students towards an appreciation of canonical forms. Lyn began the sequence by developing in students an understanding of the term ‘force’, assisting them to construct meaning for force through their everyday language, and gathering these through the intermediate vocabulary of push or pull.

A noticeable feature of the teachers’ and students’ communication during this unit were the gestures that became an important part of describing and validating what was being represented in words or diagrams. Gestures were used to indicate pushes or pulls or lifting forces, to mime the size of forces, and to indicate direction, and points of application of forces. Following Roth (2000), we see gesture as a natural form of pre-linguistic and re-representational meaning in the public space.
Lyn then explored with the students various ways in which an everyday action or series of actions involving forces could be represented in a two dimensional form on paper. The students were given the one minute task of changing the shape of a handful sized lump of plasticine, and following this task, they were to represent in paper form their actions. The representations constructed by the students, some of which are shown in Figure 29.1, were discussed and evaluated within a whole class discussion.

[Insert Figure 29.1 about here]

One representation, posted on the whiteboard, which had a sequenced series of figures with annotations (Figure 29.2 Image A), was unanimously accepted as providing clarity of explanation of the actions.

[Insert Figure 29.2 about here]

For the next stage of the sequence Lyn introduced diagrams using the scientific convention of representing forces as arrows. She discussed with the students the benefits in adding arrows, to represent pushes and pulls, to John’s drawings to enhance the explanations (Figure 29.2 Image B). The students were then given the task of re-representing their explanations of changing the shape of the plasticine in pictorial form using arrows. Figure 29.3 shows two students’ responses.

[Insert Figure 29.3 about here]

The completion of this task produced different meanings of the use of arrows, leading to a teacher-guided discussion which included distinguishing between the arrow representation as a force or as a direction of motion, and distinguishing between different types of arrows, such as curved or straight, thick or thin, many or few.
This provided the opportunity for Lyn to introduce the scientific convention of representing forces as straight arrows, with the base of the arrow at the application point of the force. The students were then encouraged to apply this convention to various everyday situations. For example, students were each given an empty soft-drink bottle and asked to represent the forces needed to twist off the bottle cap, and asked to use the arrow convention to represent a gentle, and a rough stretch (Figure 29.4).

[Insert Figure 29.4 about here]

This introductory sequence is illustrative of a number of the representation construction principles, particularly how activity sequences are built that involve students constructing rather than practising and interpreting representations. The representation construction task is built on a need to communicate a sequence of shaping forces using verbal and visual and gestural modes, and leads to the canonical arrow form through a process of explicit discussion of representational form and function (Is it clear? Could we reproduce the sequence?), and of the adequacy of student representations. This process of public negotiation in which students agree on effective representations of the shaping process leads to an alignment of student and canonical representations. The teacher, at particular points, introduced arrow notations in response to a felt representational need.

The approach could be seen as a particular form of guided inquiry in which teachers introduce tasks that open up representational needs, and intervene strategically to scaffold students’ development of representational resources. It also has much in common with other conceptual change approaches, including exploration of prior learning, and the development of explanation through exploration and guided discussion. In this particular version however, there is a close focus on representational resources rather than directly on high level concepts, and
there is ample scope for students to be generative and creative within the structured sequence. The end point is not fixed, with students free to produce different versions of the canonical forms.

Concepts about gravity, weight and mass formed the focus of the next stage in the teaching sequence, preceded by probing of students’ prior ideas. Several modes of representations formed the structure of the challenge activities. These included:

- Role-plays with large balls representing the Earth and moon, and a toy animal, simulating the gravitational effects on a person on earth, and on the Moon.
- Comparing everyday language conventions for the term ‘weight’ with the term’s scientific meaning.
- A student-constructed spring force measurer and construction of a graph that connects the extension of the spring to the weight of an object.

Unlike a traditional conceptual change approach, in which activities are designed to directly challenge ‘alternative conceptions’ and establish a scientific perspective through a rational evaluative process, this approach treats understanding as the capacity to utilise the representational conventions of science in thinking and communicating about phenomena, and hence focuses on building up students’ representational resources, and their understanding of the role of representation in learning and knowing.

The next stage of the teaching sequence focused on frictional effects. Students were asked to imagine, on a magnified scale, the surface of an object as it slides along a flat surface (Figure 29.5). Students used multiple representational modes to report on the design and conduct of an investigation into factors that affect friction on everyday objects, like sports shoes.
Friction is thus understood through the coordination of modes, including arrow representations, detailed microscopic mechanisms, and gestures, aligned with and explanatory of tactile perceptual experiences. Each of these provides a selective, partial view of the phenomenon of friction.

The challenge ‘can you draw it for me’, or ‘can you represent that’ became increasingly common for teachers in this study, and accepted and responded to by students.

A bridging analogy (Clement, 1993) was used by Lyn to introduce the idea of contact forces. Figure 29.6 shows two students’ interpretation of that discussion. In classical conceptual change theory, these bridging analogies are seen as props that help span the gap between naïve and scientific conceptions. From a representation construction perspective they are representational resources that are made available to students, which help them to coordinate meaning across different aspects of the phenomenon. Understanding of contact forces involves the flexible coordination of macroscopic and microscopic representations (see Gilbert 2005 on this point) to create a coherent explanatory narrative.

Quality of learning deriving from this approach

In this research we collected substantial informal evidence of quality learning. The teachers noted that their students engaged more in class, discussed at a higher level, and performed better in their work-books (Hubber et al. 2010). Examination of these work-books demonstrated high levels of conceptual thinking, and pre- and post-test results were uniformly encouraging. Analysis of astronomy test results showed stronger outcomes than in previous
studies using comparable methods (Hubber 2010). A significant outcome of the explicit discussion and evaluation of representations was a sharper understanding, for teachers as well as students, of the role of representations / models in knowledge building in science. These findings raise the question: what are the key features of this representation construction approach that lead to quality learning? We can find some leads to this in the research literature.

Productive constraint in representational construction

Constructing a representation is constrained productively by its purpose, context, and the various physical and conventional resources available for any particular type of representation. For instance, when making a drawing of a process, students are constrained by the physical space available, the conventions they can deploy and their form/function limitations, the need to achieve specificity of detail, and the requirement of unambiguous communication. All these constraints have the potential to encourage students to engage with functional concerns with conventions to serve succinctness and adequacy in explanatory accounts. The representation-maker is compelled to be specific in selection of details, to engage with issues of emphasis, layout, adequacy, communicability to self, and fit for purpose in ways that interpreting existing texts do not foreground. Thus, the constraints offered by particular representational modes and tasks enable reasoning and learning precisely because of the specific ways they channel attention, and force choices by the person or group constructing the representation. For example, when making a video explanation of a scientific process, students are productively constrained by the need to synchronize sound, text and image to make their representational case coherent to themselves and others. Students also need to understand the partial nature of representations, where each representation serves to focus attention on a specific aspect of a problem, and that
generating an explanatory account involves coordinating various representations, each bringing a complementary perspective.

Drawing on Gibson's (1979, p. 5) view of "affordances" as productive constraints within the environment that support an individual's intentions, we argue that particular material and symbolic tools offer specific affordances as students construct and refine representations to make and clarify claims about science topics or processes (Prain & Tytler, in press).

*Epistemological dimensions of productive constraint*

There is growing acceptance that the representational tools of science are crucial resources for speculating, reasoning, contesting explanations, theory-building, and communicating to self and others. For Nersessian (2008, p. 77-78) model-based reasoning by scientists is explicitly enabled through the productive constraints that operate in the way knowledge is represented, including spatial, temporal, topological, causal, categorical, logical and mathematical constraints on this representation. These constraints also enable a diverse range of reasoning processes, including making abstractions (limiting the case, making generalizations), using simulations, evaluating particular cases (identifying the extent of fit between representation and purpose, and between representation and features of the phenomena, the explanatory power of a new case), and judging the coherence and adequacy of a claim or claims.

This construction and justificatory work can serve a very wide range of cognitive purposes and reasoning functions. Cox (1999) noted that representations can be used as tools for many different forms of reasoning, such as initial, speculative thinking, as in constructing a diagram or model to imagine how a process might work, or to find a possible explanation, or see
if a verbal explanation makes sense when re-represented in 2D or 3D. They can also be used to record precise observations, to identify the distribution of types, to show a sequence or process in time, to predict outcomes, sort information, and to work out reasons for various effects. Ford & Forman (2006) argued that reasoning in science needs to have a purpose and that active generation and evaluation of representations in pursuit of investigations captures the nature of science knowledge building practices in ways that formal reasoning schema do not. When students focus on the purposes, adequacy, claims, and applications of representations to particular contexts, they are engaging in crucial aspects of learning or coming to know in science, where representational work functions as a tool for knowing and making claims in this field. Also, as noted by Cazden (1981), following Vygotsky (1978), students’ learning capacities are often in advance of their demonstrated developmental level, and students therefore benefit from opportunities to perform representational tasks before they have achieved full competence in these tasks.

An illustrative case of representation affordance to support reasoning

The description below summarises the events in one lesson of a sequence of seven lessons on evaporation, each lesson of which posed a problem for students to explore and represent, based on molecular ideas. Prior to this lesson students had been challenged to demonstrate a variety of places in the school where water is found and to represent water in visible and invisible forms. Students in that lesson speculated on the idea of molecules of water in the air, and the class was challenged to suggest investigations to ‘prove’ that this might be true. In the lesson described, the molecular representation is introduced and refined. The
description in Table 29.1 is structured to show the different *representations* that are introduced in key teacher moves, and sample student responses.

In brief, the lesson begins with a video presentation of puddle evaporation, and the teacher question ‘what is actually going on?’ (Move 1) is used to introduce the notion of molecules through a role play. The teachers (Malcolm and Lauren are co-teaching a composite Grade 5/6 class of 50 children) then take the activities through a sequence of representational moves and challenges to open up, negotiate, and come to some agreement concerning the different molecular representations of the states of matter and the evaporative process. The lesson ends with a review of the key features of the molecular model, expressed verbally.

[Insert Table 29.1 about here]

[Insert Figure 29.7 about here] (close to Table 29.1)

The sequence illustrates the ways in which representations are critical to learning and reasoning and knowing in science. The public and individual coordination of representations in a variety of modes, around the molecular model, is very apparent as the teacher introduces each in turn and challenges students to extend and explore these in developing a molecular explanation of changes to matter in a range of contexts. The centrality of semiotic resources is clearly displayed in students’ reasoning. The pedagogy is built around a process of representational weaving as students are challenged to transform representations across modes, in constructing an increasingly complete picture of the molecular model.

Critically from our perspective, we can identify productive constraint as a characteristic of each representational resource – each representation constrains what can be imagined about the process of evaporation. For instance the role play (moves 2-4) places constraints on molecular size and number, and focuses attention on spacing and movement. In so doing it opens
up possibilities for exploration of the affordances of the representation, which in this case was taken up by the students and teacher (moves 2 and 3). In this sequence the group of students were confronted with the question of how they linked and whether they should remain still or move. Their decision to move could be seen as a case of embodied, speculative reasoning. In this case as with all these representational challenges, students are driven by the role play to discern and integrate different features of the representation. This, in Schwartz and Bransford’s (1998) terms, amounts to the discernment of features of the representational problem space – how might we imagine molecules behaving? In Cazden’s (1981) terms, the students are being required to perform before they are competent. The drawings (move 5) provided a strong visual sense of the difference in spacing for the three states, and forced consideration of molecular size across the three phases. This, with the students’ drawings in move 8, requires them to make choices and coordinate and discern the possibilities and challenges posed by the representation (needing to think about spacing, number, size, speed, time sequencing, and how to represent these).

The focus on individual beads (George and Molly, move 7) and the narrative story line (8) was used to focus on the individual energetics governing evaporation at the molecular level, and a sense of molecules cycling through the states of water. Move 7 shifts the focus from molecular assemblage to individual molecules, forcing new representational coordination requirements and opening up the explanatory landscape. Thus, while students had latitude in constructing their drawings and role plays, the nature of the task and the representation funnelled attention in a productive way. We have discussed elsewhere (Ainsworth, Prain & Tytler 2011) the particular arguments for visual representation as a resource for reasoning, and the variation in student drawings illustrating considered representational choices.
The epistemic case for representation construction as productive constraint in science knowledge building practices

We also claim that the principles guiding our classroom practice are central to the knowledge-building processes of science itself, thus providing a legitimate induction into this domain. The role of representation, including visualization, is understood as central to current knowledge production practices (Gooding, 2004; Latour, 1999). Elkins (2011, p. 149) notes that much research in science is concerned with generating and analysing images, with fields such as biochemistry and astronomy “image obsessed”. A considerable body of research also confirms the central role of representational manipulation in generating, integrating and justifying ideas in historical scientific discoveries, and thus in contributing to this knowledge production. Gooding’s (2004, p. 15) account of Faraday’s work on conceptualizing the interaction of electricity, magnetism and motion highlights the central role of representational refinement and improvisation in developing “plausible explanations or realisations of the observed patterns”. Faraday’s development and modification of representations were critical to clarifying and instantiating his theoretical understandings. 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”, each of which transforms data in a chain linking ideas with evidence, through to publication. Nersessian (2008, p. 69), in examining cases of innovation in science using studies of Faraday and Maxwell and more recent work, argued that model-based reasoning is critically important to the generation of new theory and that the productive interaction of models is the key to this process.
There is also a growing agreement that classroom science should be organized to enact these processes to provide authentic induction into science learning (Duschl & Grandy, 2008). A long tradition in science education has sought to integrate the processes and products of science into a coherent set of science education practices. However, at various times a process or product focus has been in the ascendency, largely treated separately, and conceptualised as distinct. Thus ‘working scientifically’ strands address measurement in science, the nature of investigable questions, and such issues as appropriate design built on levels of sophistication of variables control. The argumentation perspective (Osborne 2010) looks at the way evidence is used to select between alternative positions and how knowledge claims are justified with evidential backings that can withstand alternative positions. These perspectives have tended to explore the crucial justificatory aspects of science knowledge building, the public process by which scientists claim their work as verified against possible alternative findings. While students need to understand this process of public challenge and justification and defence as the way scientific knowledge is established within the community, these processes do not deal with the complex ways in which knowledge is generated in the first place. There is also a need for learning in science to focus on the processes by which knowledge is built.

To capture the scientific generation of knowledge in classrooms, we argue there is a need to foreground representational generation, coordination and transformation rather than mainly focus on formal aspects of ‘scientific method’ and argumentation. Duschl and Grandy (2008) argued that attempts to define a general inductive rule for specifying the scientific method have been a failure and that we must see scientific methods as contextual, local, and contingent. They claim there have been three phases to understanding the nature of science: 1) logical positivism (the received view) that underpins traditional versions of scientific method, 2) paradigm shifts /
conceptual change views that admit social processes, and 3) model-based science with acknowledgement of the centrality of language, representation and communication. We view student representational construction as a way to enact new pedagogies appropriate to these new understandings of the relationships between process, product and language in learning science.

**Perspectives on conceptual change implied by this approach**

This representation construction approach to teaching and learning science offers a promising, coherent pedagogical approach to student conceptual learning / conceptual change. Pedagogically, it sits within the broad spectrum of modeling approaches to conceptual change, but with a major focus on representation construction rather than interpretation. The approach has much in common particularly with the classroom work of Lehrer and Schauble (2006a, b) and Clement and Rea Ramirez (2008), which also feature representational challenge and negotiation.

In practice, we have found that teachers’ initial responses to the approach are very positive, since it aligns well with a view of student activity and engagement as a key to learning. At a deeper level, however, the approach implies, and inspires in teachers, a shift in perspective on the task of learning science, and the nature of what is learnt.

Theoretical developments in the social constructivist tradition (e.g. Driver et al. 1994; Mortimer & Scott 2003) match classroom processes aimed at the development of shared understandings, with a conceptual change perspective on outcomes based in traditional cognitive versions of knowing. While our own work can be seen in this tradition, it raises important questions about learning and knowing in science. The first question concerns the nature of reasoning that students need to engage in to learn science. We have argued that recent work in
cognitive science places much more importance on informal modes of reasoning, in contrasts to
the formal logic that tends to be emphasized in traditional conceptual change accounts of science
learning, and expectations that rational appraisal of inadequate conceptions can drive the
learning process.

The second question concerns the nature of concepts as drivers of learning and knowing
in science. From a socio-cultural, pragmatist semiotic perspective, learning in science is seen as a
process of enculturation into the discursive practices of the scientific community. In this sense,
the focus of learning is primarily on the particular representational practices, and representations,
that are core to developing explanations in any conceptual area. The task then becomes one of
building students’ representational resources with respect to engaging with these practices. From
this perspective, conceptual understanding involves being able to work with and coordinate
representations to develop explanations and solve problems. This contrasts with traditional
verbal definitions of concepts that dominate text-books and curriculum outcome statements. The
question therefore concerns the nature of a ‘concept’. In the conceptual change literature, this
question is far from resolved (Vosniadou, 2008; Taber, 2011).

A pragmatist perspective considers the meaning of terms to be instantiated in cultural
practices, and argues they should not be idealized beyond these practices. In this spirit, we
contend that it is fruitful to think of concepts, which are core entities within the language
practices of experts discussing learning and knowing in science, as privileged linguistic markers
through which conversations in the domain can productively proceed. Thus, while understanding
sound waves implies a capability to select and coordinate a range of verbal, mathematical and
visual representations, the conceptual term is useful for someone who has achieved such a
capability, to converse with others with similar capabilities (‘understanding’) without the need
for further explication (until questions might be raised about instances, in which case the representational system will be called into play to clarify).

Privileging of ‘concepts’ performs a very valuable function in enabling flexible movement around the conceptual space in an area, and acting as a marker in high level discursive practices. Concepts are used as organizing entities to shape learning sequences. The danger is that if we ascribe to a concept an idealized, resolved mental existence (rather than recognize it as standing for a range of representational practices), then we run the danger of misrepresenting the learning task. To ‘achieve’ a concept is a question of the degree of mastery of a range of relevant representational practices. We argue that the learning issues identified so thoroughly in the conceptual change literature are fundamentally representational issues, and the learning task involved in achieving the required shifts needs to be conceived of in terms of building students’ requisite representational resources.

Thus, to the question of ‘what is a concept?’ we would respond, referring to Wittgenstein (1972), that it should be viewed as a language form used by experts for effective communication, referring to a range of discursive (representational) practices that may include formal category lists, verbal strings, arrays of representations including metaphors and analogies and the ways these are selected and coordinated to solve problems, as well as personal aspects such as historical narratives and analogies. From this perspective, concepts have both public and personal aspects. They are not resolved entities despite the tight linguistic forms often used to define them.

The other aspect of this work that provides a significant way forward for science classroom practice is the fresh way it interprets and aligns with the epistemic practices of science. The approach, and the theoretical perspective underpinning it, aligns with significant
contemporary research directions on science epistemic practices that emphasize the contextual and cultural nature of knowledge production (Nersessian 2008; Duschl & Grandy 2008), and the key role of representational practices in generating and justifying theory (Latour 1999; Pickering, 1995). Compared to more idealized versions of the NOS which focus on relations between theory and evidence viewed through a Kuhnian lens of socially determined paradigm shifts, this pragmatist semiotic perspective provides a more grounded education for students in the way it models the chains of representational transformation that characterize theory building from evidence in science, and discussions about the adequacy and the role of models to represent natural phenomena. Thus, there is a natural alignment here between the processes and the conceptual products of science, and classroom practices and practices in science.
References


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