Constructing Representations to Learn in Science

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VAUGHAN PRAIN & RUSSELL TYTLER

CHAPTER 1

REPRESENTING AND LEARNING IN SCIENCE

In this book we argue for an approach to representational work in school science learning and teaching that engages participants, is epistemologically sound, aligns with knowledge-building practices in the discipline, and draws on extensive classroom study. We review in this chapter current research agendas around student representational work in science learning, including the assumptions, rationale and research practices of these agendas. We do this (a) to clarify precisely what we see as the diversity of current mainstream thinking and practices around representational activity, and (b) to articulate what is distinctive about our own contribution, noting the traditions, influences and prior research we draw on. We begin by noting the current dominant role of image generation and analysis in much contemporary science, and its implications for science in schools.

MAKING SCIENCE VISUAL

Increasingly, scientists produce new knowledge in many domains through generating and analyzing the content of images, with fields such as biochemistry and astronomy "image obsessed" (Elkins, 2011, p. 149). This reasoning through visual representations can entail highly complex processes of image enhancement and reduction, and highlights the extent to which current science research extends a tradition of integrating linguistic and mathematical resources with increasingly sophisticated use of visual tools.

Fourier Transform Infrared (FTIR) microscopy is currently used for much biomedical research, as in the images below of chemical maps for healthy cultured adenocarcinoma gut (AGS) cells (see Figure 1.1, and cover of this book). When combined with a synchrotron source, this microscopy allows for the fast analysis and mapping of cells and tissues at high spatial resolutions (between 3–5 microns). The distribution of biological components such as proteins and lipids can then be easily visualized by creating informative false colour chemical maps by integrating the area under peaks of interest: IR absorbance peaks are indicative of specific molecular components and the area under an absorbance peak is proportional to the concentration of that component. This method is commonly used to compare for example normal and diseased tissues, or healthy cells and those treated with a drug, to identify chemical differences between the samples. These image production

R. Tytler, V. Prain, P. Hubber and B. Waldrip (Eds.), Constructing Representations to Learn in Science, 1–14.

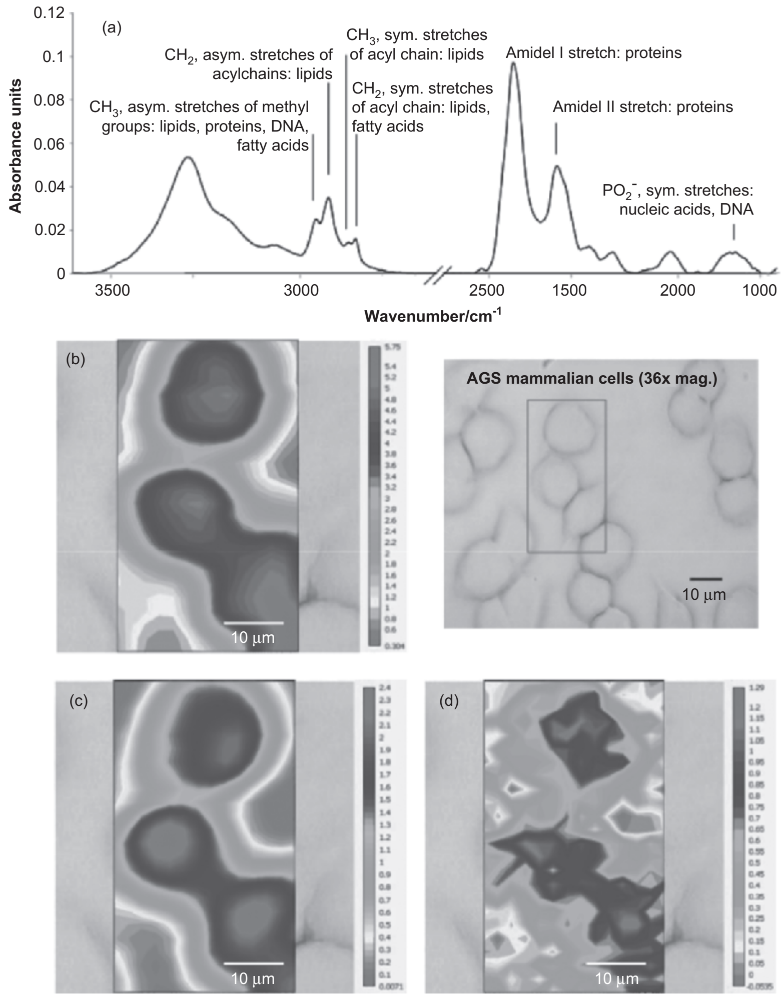


Figure 1.1. Synchrotron images of chemical maps for AGS cells.

and enhancement practices, alongside multi-dimensional simulations, sophisticated model building, and complex data analysis and representation techniques, are an increasing feature of contemporary science practice, driven by the digital revolution.

As noted by Latour (1986, p. 3), more than 25 years ago, the broad emergence of scientific thought depended on developing effective representational tools or "inscriptions" that could be combined, superimposed, turned into figures, interpreted in writing, and reproduced. He claimed that changes over time to procedures for writing and imaging altered the ways scientists argued, proved their case, and believed in their results, and therefore both facilitated and explained new cognitive capacities in this domain. For Latour, this practice of reasoning through visualizing and inscribing (both prospectively and as a record of ideas), of disciplining the mind through engaging with material and symbolic instruments, was crucial to understanding science's origins and special characteristics.

These changes to how scientists generate, validate, and disseminate new knowledge, and to our understandings of the role of representational tools in building knowledge, are now matched by science educators' interest in the role of representations and the act of representing in learning science. There is growing recognition that students need to learn how to interpret and construct representations of scientific concepts, processes, claims and findings, where representing entails both the processes of coming to know in this subject as well as what is known. Researchers have focused on various implications of this perspective. Some have re-characterised science as the acquisition of a particular disciplinary literacy (Linder, Ostman & Wickman, 2007; Moje, 2007; Norris & Phillips, 2003; Shanahan & Shanahan, 2008), specifying what should count as science literacy learning. For Norris and Phillips (2003), to really understand science, as opposed to being knowledgeable about science topics, students need to know how to interpret, represent, and assess scientific claims, implying a foundational role for representational work. Researchers from conceptual development perspectives, such as Gilbert, Reiner and Nakhleh (2008, p. 3), have sought to clarify levels of representation around models in science as a basis for investigating effective pedagogies for student acquisition of this representational competence or a capacity for "visualization". Researchers in this broad conceptual change tradition, such as Vosniadou (2008a, 2008b), diSessa (2004), Duit and Treagust (2012), have considered the implications of this representational focus for enabling student conceptual growth. Other researchers, from cognitive science perspectives, such as Ainsworth (2006) have sought to identify affordances in new technologies that could promote this acquisition as students interact with expert representations. Researchers from sociocultural perspectives have focused on the meaning-making practices of scientists and the classroom (Gooding, 2004; Greeno & Hall, 1997; Hubber, Tytler & Haslam, 2010; Tytler & Prain, 2010), while researchers from socio-semiotic perspectives have analyzed the resources of science's multimodal discourse (linguistic, mathematical and visual) to identify the challenges of learning this new literacy (Gee, 2004; Kress & van Leeuwen, 2006; Lemke, 2003). Each orientation foregrounds representational competence as crucial to learning science.

In contributing to this increasing focus on representation, we put a case in this book for a particular approach to guided inquiry in science learning with a strong explicit emphasis on student-generated representational work through sequences of representational challenges accompanied by negotiation and refinement of the produced representation. Figure 1.2 shows the responses of Year 7 students to a challenge to represent in a drawing the forces involved in unscrewing the lid of a container. Students were given a small container with a screw top lid. The video record showed students moving between the drawing, as it was being constructed, and physically manipulating the container.

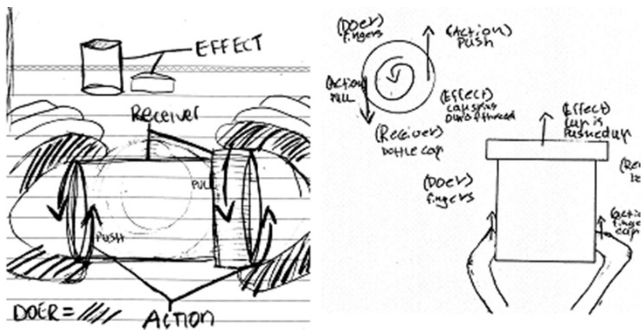


Figure 1.2. Student responses to a challenge to represent the forces involved in opening a screw top container.

We look particularly at learning key foundational concepts in science in the upper years of elementary and junior secondary school. These transitional years of schooling are broadly viewed as critical in developing durable interest and competence in this domain. We claim that our approach is timely and generative because it links current epistemological understandings of science as a specific set of knowledge production practices around representation, with an enabling, workable pedagogy aligned to current understandings of enhanced conditions for student learning. While there is an impressive range of research findings on conditions that enable students to learn from interpreting and interacting with expert representations, research on productive use of students' own representations for learning is less developed, and provides a further rationale and timeliness for this book. We also claim that our approach can contribute to addressing a significant, enduring problem in science education of lack of student engagement with this subject, especially in junior secondary school (see Osborne & Dillon, 2008). Our approach complements Fensham's (2011) recent call for science teachers to understand science literacy as the application of flexible reasoning skills in this domain to meaningful experiences in their lives.

THE PATH TO A REPRESENTATIONAL FOCUS

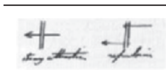
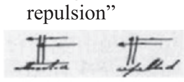
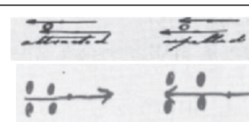
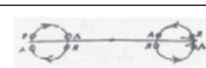
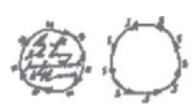
Several research agendas have contributed to the current strong interest in a representational focus in science education, including sociocultural research in science education, conceptual change research, and socio-semiotic research.

Sociocultural Research

Various orientations overlap in this focus on broad cultural, historical, collective influences on the practices of science and on classroom science. These include analyses of historical and current scientific knowledge production processes, studies of classroom-based factors influencing learning including classroom cultures and group activity, and cross-cultural considerations around unequal outcomes for different student cohorts. Each orientation has sought to conceptualize the norms and enablers of scientific activity in terms of contextual influences on patterns of practice, focusing on the particular role of representing in scientific work or in learning science, or in potential and desirable links between both sets of practices. Researchers have sought to build a case that what scientists think, do and disseminate in their professional practice should, where practicable, inform the teaching and learning of science in school. Lemke's (1990) discussion of the key mediating role of talk in learning science is broadly seen as a seminal trailblazer in this field. Here we sketch some more recent themes.

A considerable body of research now confirms the central practice of representational manipulation in generating, integrating and justifying ideas in historical scientific discoveries. 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". Gooding identified a recurring pattern in Faraday's work, of visual reasoning by dimensional enhancement and reduction, that is also exemplified in a number of other scientific breakthroughs. Table 1.1, based on Gooding, shows a series of drawn entries in Faraday's manuscript for 3 September 1821, when he moved from observations of patterns of needle orientation around a wire, through a series of steps involving representational re-description, to an inference for the construction of the first electric motor.

Table 1.1 (Gooding, 2004, p. 16). Visual reasoning by dimensional enhancement and reduction

Reduction of complex phenomena to 2D pattern	Enhancement of pattern to 3D structure	Enhancement structure to 4D process	Inference or material derivation
 "Strong attraction repulsion" 			
			
		 "The N pole being perpendicular to the ring"	 The first electric motor

The pattern involves the reduction of complex, real time phenomena to a patterned abstraction (the pattern of iron filings round a wire), then an enhancement of the image through adding dimensions, in this case first to 3D in the imaging of a magnetic field pattern in space, and next to 4D by imagining a time sequence process model for which the 3D image is but one temporal instant. Alignment of the different phases is a process of consolidation.

Concurring with Gooding's perspective, Latour (1999) persuasively argues that making sense of science involves understanding the processes by which data is transformed into theory through a series of representational "passes". To analyse science theory building, he accompanied two scientists working together on soil profiles in the Amazon basin at the boundary between rainforest and savannah and traced the process by which they converted the raw data into scientific papers. This process involved a series of representational re-descriptions, from the ordered box arrangement in which they assembled their soil samples, through a colour chart and numbering system, and eventually to the table that was the representational form they carried back with them to Paris. Agreeing with this viewpoint on representational reasoning, Klein (2001, p. ix) claimed that representational work and refinement in the historical development of chemical formulae in the early 1800s were constitutive of new symbolic manipulations separate from observable phenomena, and that these representational developments "actively contribute to meaning" rather than merely express already resolved ideas.

Drawing on these sociocultural perspectives of the practices of scientific activity, and following Vygotsky (1978, 1981a, 1981b), we share with researchers such as Moje (2007), Lehrer and Schauble (2006a, 2006b), Duschl (2008) and many others the view that learning science in school should entail a parallel induction into these disciplinary norms. Learners need to understand why and how discipline-specific and generic literacies are used to build and validate scientific knowledge. They need to learn how to switch between verbal, written, visual and mathematical (graphs, tables, equations) and 3D representational modes, and coordinate these to generate, test and justify explanations. They need to participate in authentic activities with these cultural resources/tools to become competent in the diverse reasoning practices in science (Ford & Forman, 2006), as they engage in a learning community where their representations need to be explained, justified, and if necessary modified in the light of informed feedback (Greeno, 2009; Kozma, 2003; Kozma & Russell, 2005). We recognize that there are differences between the goals, knowledge base, resources, methods, and success indicators for participants in research teams and students in classrooms, but claim that classroom teaching and learning practices can parallel the inquiry, representational challenges and processes of the research laboratory. We argue that this parallel effect occurs when students are challenged to visualize, develop, and justify explanations for observed phenomena or patterns, drawing on their conceptual and representational resources, supported by their teacher and peers. The research team is expected to generate new knowledge, and may need to develop new representational forms to achieve this, whereas participants in the classroom are learning how to make convincing knowledge claims in this subject that will be new to them. Both groups are engaged in reasoning with and from new representations. We develop this case for an effective pedagogy for science learning through an orchestrated focus on student-generated representations with the classroom as a learning community, through the chapters of this book and particularly in Chapter 10.

We also recognize that within sociocultural perspectives, some researchers have focused on cross-cultural learning, seeking to identify and build effective pedagogical bridges between the values, interests, discursive practices and representational resources of different student cohorts and science disciplinary literacy learning (Alvermann, 2004; Lee, Luykx, Buxton & Shaver, 2007; Moje, Peek-Brown, Sutherland, Marx, Blumenfeld & Krajcik, 2004). These researchers assume that this learning is enabled when teachers work with students to (a) negotiate between everyday discourse, culture, and values and those of the science community, (b) develop explicit understanding of the rationale for the norms of science knowledge production and communication, and (c) sustain connections between expression and values in both cultures. Moje (2007, p. 30), a strong contributor to this field, points out that this “cultural navigation perspective” on science disciplinary learning poses significant challenges. Researchers have struggled to define how successful learning from this perspective should be understood and assessed, and have also struggled to suggest practical ways in which everyday text production can be linked meaningfully to the literacies of this subject. While our approach has been pursued predominantly with mainstream student cohorts, we argue that its foundational assumptions and practices provide leads on, and can be adapted to, effective teaching and learning approaches with a wider set of cohorts.

Conceptual Change Research

Within this research agenda, concepts have been traditionally understood as mental models in individual minds (Posner, Strike, Hewson & Gertzog, 1982), where student conceptual change or growth can occur if teachers problematize students’ initial explanations/ conceptions as a basis for guided inquiry and rational acceptance of targeted 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, artefacts, representations and contexts. There has been increasing recognition within conceptual change research of the mediating role of language in 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, focused 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 of representational norms and practices. 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 sociocultural 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 artefacts and the capacity of humans to develop and modify theories about the natural world. In this way, "a globe as a cultural artefact is nothing more that 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 artefacts and representations through which scientific models are generated, justified, refined and communicated by learners.

A major strand in theorizing the mechanisms and processes of conceptual change entails research on student model-based reasoning through inquiry (Clement, 2000; Gilbert & Boulter, 2000; Harrison & Treagust, 2000; Justi & Gilbert, 2003; Lehrer & Schauble, 2006a; 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 attention to students' representational resources for meaning-making (Taber, 2011). A growing modeling literature identifies the power of refinement of explanatory models through classroom negotiation to achieve quality learning (Clement & Rea-Ramirez, 2008).

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 sequence of steps in learning science concepts and understanding the explanatory value and function of models in this subject. We argue that these opportunities for students to generate their own representations function as building blocks that productively constrain their reasoning about explanations, models and model construction. We develop this case for the enabling relationship between representations, concepts and models in Chapters 5 and 7. From a cognitive perspective, Bransford and Schwartz (1999) provide some further support for the value of this focus on student-generated representations. They proposed that learning gains and potential for transfer from repeated practice at this process can be understood not just as the transfer of domain knowledge but rather as the development of problem-solving skills that can be applied in new contexts. In Chapter 6 we develop this case further for how students' reasoning skills are developed through guided work with student-generated representations.

Socio-Semiotic Research

This broad range of perspectives focuses on analyses of science text structures as the key to students understanding and reproducing the meaning-making practices of the science community in order to become scientifically literate (Bazerman, 2007; Gee, 2004; Halliday & Martin, 1993; Kress & van Leeuwen, 2006; Martin & Veel, 1998; Unsworth, 2001; Veel, 1996). While predominantly focused on the nature of the learning challenges in science, these researchers also outline various reputedly effective teaching and learning strategies to meet these challenges. Halliday and Martin (1993) asserted that the epistemic distinctiveness of science as a worldview, a body of knowledge, and a form of inquiry with various technical specifications, is indivisible from the development over several centuries of a range of purpose-built features of language use. Through analysis of various historical and contemporary instances of scientific argument and textual examples they argued persuasively that specific grammatical resources of English have been used to construct and represent the specialized knowledge of science, as disseminated in science communities. Similarly, they argued that various genres have been developed to provide appropriate macro-structures to represent scientific reasoning, argument and discourse, and that these linguistic aspects represent the epistemic essence of science as a discipline and field of study.

From this viewpoint, students need to learn the assumptions, rules, and purposes of scientific writing as the basis for understanding what counts as scientific method, explanation, and justification, as well as the underlying history and rationale of this writing. Researchers in this orientation have focused on the discipline-specific structural and functional features of types of science writing (Halliday & Martin, 1993; Unsworth, 2001), their subject-specific vocabulary, and the student knowledge required to understand and reproduce these genres (Martin & Veel, 1998; Unsworth, 2001; Veel, 1996). According to Martin and Veel (1998), and others, students will learn effectively the rules and meanings of these particular language practices through an explicit pedagogy entailing: detailed analysis of linguistic features of textual examples; joint construction of genres with their teacher; and through an extensive teacher focus on key textual function/form relationships and their rationale. This approach assumes that the most effective way for students to learn science through writing is to imitate the semiotic practices of professional scientists, or at least a simplified version of these practices in school science genres. Unsworth (2001) argued that students can learn to write scientifically and incorporate multi-modal resources into their writing through analyzing the schematic structures and grammatical patterns of sample texts, and then reproducing these functions in their own writing.

Empirical research to support and justify this range of strategies has largely taken the form of case studies of reputed desirable or exemplary implementation, or explication of how analyses of form/function structural features of scientific texts provide effective ways to conceptualize and assess this learning (Unsworth, 2001, 2006). However, this approach has tended to characterize the relationship between students' current everyday representational resources and the target competence as conflicted, and has also failed to develop successful pedagogies to support student acquisition of the target competence, other than through explicit teacher instruction. For Martin (1993, p. 168), scientific language is purposefully different from everyday language and "common sense understandings", and therefore students needed to learn the particular genres "in which scientists package this knowledge into text" (p. 167). From this perspective, natural language has inappropriate structures and purposes for representing this knowledge adequately. This denotative view of language in science as the resolved record of knowledge or learning, allied to belief in the stability of genres, provides further justification for what these researchers claim should count as appropriate representations of science learning. This pedagogical stance tends to imply a traditional view that students mainly need to master the reproduction of authoritative representations rather than engage imaginatively and individually with the representational demands of claim-making in science as part of the learning process in this subject. At the same time, the extent to which a metalanguage of form/functions should be learnt by students to help them organize their understanding remains an open question in the agenda of these researchers. Unsworth (2006, p. 72) claims that this metalanguage is valuable for higher-order understanding of tasks in science, but also poses the question of whether there are "any sustainable arguments for a positive relationship between knowledge about language (however understood)" and student success with text interpretation and production.

Our own approach acknowledges that teachers and students need to know the form/function of the conventions in generic and discipline-specific representations. However, as we will argue in more detail in Chapter 5, there are various gains for students when they have to experience first-hand the potential and actual affordances of these modes by using them to construct their own understandings. From this perspective, representations are not simply tools for understanding some higher form of knowledge that avoids representation, what some might claim as the "gist" of concepts or models. Our perspective on learning and knowing follows pragmatist accounts of the situated and contextual nature of problem-solving and knowledge generation (Haack, 2004; Peirce, 1931–58; Wittgenstein, 1972) where understanding an object or concept entails knowing the effects of applying this object or concept to meaningful practical settings. In this way a pragmatist orientation is understood as an empirical systematic method of inquiry that avoids a priori judgments and incorporates a reasoned collective analysis of experience to identify justifiable beliefs, and where representations actively mediate and shape knowing and reasoning. In this, 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 through identification of component parts, causes and effects (Dewey, 1996; Peirce, 1931–58; Wittgenstein, 1972). This implies that classroom teaching and learning processes need to focus on the representational resources used to instantiate scientific concepts and practices. In developing our case further in Chapter 5 we focus on key affordances or enablers of different representational modes to support students' reasoning around models (see Prain & Tytler, 2012).

Influences from Cognitive Science

Our perspective is also informed by 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; Damasio, 1994, 1999; Klein, 2006; Sinatra, 2005; Tytler & Prain, 2010; Wilson, 2002, 2008). Here knowledge is viewed as more implicit, perceptual, concrete, and variable across contexts, rather than as purely propositional, abstract, and decontextualized. This perspective foregrounds various kinds of representation (verbal, visual/spatial, embodied, and mathematical) as critical to learning. As noted by Barsalou (2008), a broad range of recent cognitive science studies and neuroscience research provides compelling evidence that cognition and learning are enabled by perceptual simulations, bodily states, feelings, introspection and situated action. From this perspective, individuals know and learn not just through manipulating stored symbols in memory but through the interplay of mind, body, feelings and environment, supported through re-enactment of these experiences as reflective perceptual simulation. Thinking, reasoning and abstracting are grounded in perception, situated action, motives, embodiment and environmental affordances, rather than in stored resolved symbolic templates. What we can visualize, perceive, rehearse, enact, simulate, feel, want and reflect upon forms the bases of our representations of knowledge and our capacity to symbolize and abstract.

Researchers in classroom studies where students generate their own representations have noted the importance of teacher and student negotiation of the meanings evident in verbal, visual, mathematical and gestural representations in science (Cox, 1999; Greeno & Hall, 1997; Lehrer & Schauble, 2006a, b; Tytler, Peterson & Prain, 2006; Waldrip, Prain & Carolan, 2010). They claim that students benefit 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, 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. Ainsworth, Prain and Tytler (2011) claimed that students' explanatory drawings of aspects of phenomena could support their reasoning as well as develop their understanding of the subject-specific literacies of science. In the next section we present some indicative examples of the representational challenges students responded to in our research.

Examples of representational challenges. Students in a grade 5/6 class, as the final part of a unit on animals in the school-ground which focused on animal diversity, structure and function, were given the challenge of representing the movement of a chosen invertebrate. The teacher emphasized that they needed to think carefully about equipment or materials they would use in their representation. At the start of this lesson, one student, "Ivan" carefully examined representations in his workbook (Figure 1.3) of how an earthworm moved, read his annotations, and discussed them with his partner. Ivan had some rough ideas that he had drawn up on a piece of paper at home.

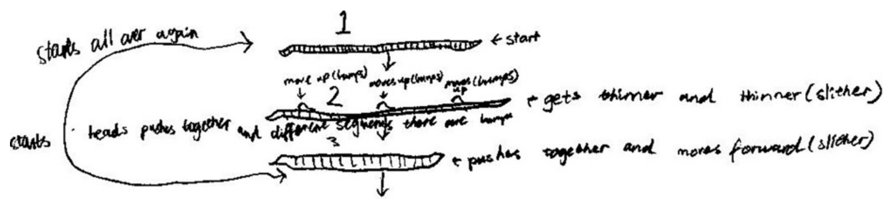


Figure 1.3. Ivan's workbook entry representing the movement of an earthworm.

They then selected meccano pieces, connects, flexi wire and blu tac to build a techno-worm. They wanted their model to represent as accurately as possible the amount of extension and 'retraction' of the earthworm. They drew up a scale on an A3 paper to help them represent the exact extension and retraction as the earthworm moved along a smooth surface.

Ivan then took a piece of flexible wire, measured it, using the scale drawn by them and the two boys proceeded to build up a device to enable them to extend and retract the wire (Figure 1.4).

They described the process of refining their model:

> Well, we just tried something, and then it kind of worked a bit and then we kept on changing until it started to fit. And then it made a bit of more sense, and then we added the wire and blue tack instead of more 'connects' and then it turned out like this [points to model] and now we are making another one with elastic bands.
>
> And we are testing all of the worm measures [points to the scale drawn on paper] to see how big it gets because like when it gets smaller, [moves palms closer together] it shrivels. [Demonstrates the shrivel] like it gets smaller when you push it in , so when you look at it when it is really small [palms

close together] it gets fatter [moves the thumb away from the fore fingers] and then when it is long [hands wide apart] it gets thinner, so that is what happens.

(The model) helped us understand the whole concept of it

Figure 1.4. The 'techno-worm' model of the stretch and retraction of an earthworm.

In this example, we see the multi-modal nature of the students' thinking and reasoning, as they talk, gesture, draw, construct a 3D model, and use artefacts such as the paper to measure objects. In this way the drawing sharpens and challenges their observation, the model forces attention on the material characteristics, and the model construction forces attention on the measurement of retracted/extended length.

In another example, a Year 7 class was asked to use their current understanding of particles to explain why a piece of paper retains its shape when folded. After each student produced an explanatory representation, the class was asked to evaluate the relative persuasiveness of the three examples shown below in Figure 1.5. The middle and right-hand side representations were judged as fulfilling the purpose of the representation. The one on the left was considered not to have achieved its purpose, because it had no structure to sustain shape.

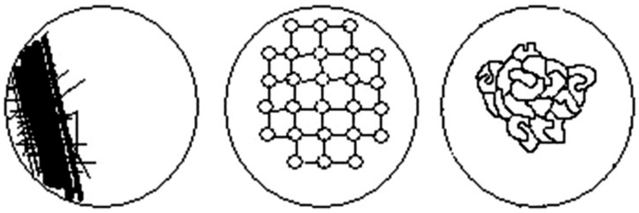


Figure 1.5. Student representations of particle arrangements to explain how paper keeps its shape.

This example points to students' participatory role in knowledge generation and negotiation in a public shared process, where representational work and appraisal functions to (a) enable students to connect referents in the world to representations they can invest with meaning, and (b) anchor the scrutiny and refinement of understanding through productive reasoning processes. From this perspective, learning in science is not just about declarative knowledge in individual minds, but also entails the development of agile problem-solving and reasoning capacities through engagement with the representational resources for meaning- and claim-making in this subject.

In the following chapters we describe how we developed our teaching and learning approach inductively over a number of years. Throughout this process we were interested in building a practice that (a) students and teachers would find engaging because of the roles, tasks and learning in which they could participate, (b) enacted contemporary understandings of the epistemological basis for what should count as knowing in science, and acting scientifically, and (c) aligned with current understandings of scientists' knowledge production and dissemination, and therefore meet broader epistemic requirements.

In this research we have learnt that representations can function in many ways. They can be understood as processes that are speculative, dynamic, and interactive, as well as perceptually-based resources for imagining, visualizing, testing, confirming and reasoning. They can function as claims, or evidence-based causal accounts of phenomena. They can also be products or outcomes of internal mental models, or schemas, or external artefacts of thought. Their affordances function as tools for imagining and coordinating different dimensions, purposes and contexts. Representations are always partial, selective, value-laden, perspectival, and offer abstracted, always constrained accounts of their referents. Learners need to know how to invest them with meaning. In the following chapters we expand this case for their value as reasoning and problem-solving tools, mediators and records of learning, as well as the medium of learning when students have to produce and justify them.

BRUCE WALDRIP & VAUGHAN PRAIN

CHAPTER 2

TEACHERS' INITIAL RESPONSE TO A REPRESENTATIONAL FOCUS

In focusing on the role of representation in learning science, our early studies (2004–2007) sought to identify primary and junior secondary science teachers' beliefs and practices around this aspect of science teaching and learning. We knew that teachers routinely incorporated different representational modes in science topics to motivate students and also expected students to describe, measure, and report findings from inquiries using appropriate scientific language or discourse. However, we were unsure about teachers' understandings, rationales and perceptions of the effectiveness of these practices, as well as their receptiveness to a more intensive representational focus. In this chapter we report on (a) research guiding our early studies in this area, (b) an initial survey of 20 teachers' beliefs and practices around the role of different representations in learning science, (c) four individual case studies of teacher responses to classroom programs that entailed a more explicit focus on the role of representations in learning science, and (d) a framework generated from these studies to guide practice.

RESEARCH GUIDING OUR EARLY STUDIES

There was at that time growing agreement that learning concepts and methods in science entailed understanding and conceptually linking different representational modes (Ainsworth, 1999; Ogborn, Kress, Martins & MacGillicuddy, 1996; Saul, 2004). Students needed to understand different representations of science concepts and processes, translate them into one another, and understand their co-ordinated use in representing scientific explanations. Student learning and engagement was enhanced when students identified links between their own and authorised multiple and multi-modal representations of science concepts and processes (Saul, 2004). 'Multiple representations' refers to the capacity of science discourse to represent the same concepts and processes in different modes, including verbal, graphic and numerical forms. 'Multi-modal' refers to the practice in science discourse of coordinating different modes to represent complex claims and evidence, where textual, mathematical and visual modes are integrated to explain and justify findings.

R. Tytler, V. Prain, P. Hubber and B. Waldrip (Eds.), Constructing Representations to Learn in Science, 15–30.

Students need to learn how to interpret and generate both these aspects of scientific discourse. This focus on student understanding of science as multi-modal reasoning and representation was also consistent with principles of effective pedagogy that emphasise catering for students' individual learning needs and preferences, and students' active engagement with ideas and evidence (Tytler, 2003).

Various studies had focused on student learning through engagement with different representational modes, including in elementary classrooms (Russell and McGuigan, 2001) and in senior secondary physics (Dolin, 2001). Some forms of representation had been researched in depth, (Glynn & Takahashi, 1998), such as the use of analogies for learning science (Coll & Treagust, 2000) and the role of scientific models in this process (Treagust, Chittleborough, & Mamiala, 2002). In the use of multiple representations in learning physics, Dolin (2001) observed that particular representational forms were under-utilised and could be effectively incorporated into classroom practices. Consistent with the view that learning was enhanced through a variety of approaches to the same concept, Nuthall (1999) found that children required three or four experiences of the same concept, through concrete or individual experiences, to establish long term knowledge. In using this general approach with elementary school students, entailing multiple opportunities to engage with the same concept, Russell and McGuigan (2001) argued that learners needed opportunities to generate a variety of representations of a concept, and to recode these representations in different modes, as they refined and made more explicit their understandings. Students and teachers generated various representations of target concepts, and knowledge construction was viewed as the process of making and transforming these different representational modes, as they scaffolded understandings in relation to their perceptions of the real world. This study utilised both multiple representational modes in consolidating conceptual understanding, as well as repetition of the same mode during a topic. Researchers, such as Gobert and Clement (1999, p. 49–50), claimed that some modes were more supportive of student learning than others, noting that students can 'draw to learn' effectively, where the visual media affords 'specific advantages over the textual media'.

Research in this area also focused variously on students' construction of self-explanation diagrams (Ainsworth & Iacovides, 2005), understanding concepts across multiple representations in different topics (Parnafes, 2005; Tytler, Peterson & Prain, 2006), and the role of visualization in textual interpretation (Florax & Ploetzner, 2005). Rather than emphasize a particular representation or one classroom strategy, our study focused on researching general classroom negotiation of representational understandings as a key to effective learning. Rather than seek to identify or produce an exemplary representation, either authorized or student-generated to promote learning, we were interested in a broader examination of representational processes. The orientation of the study was consistent with research findings by Tytler, Waldrip and Griffiths (2004) that students learnt most effectively in science, and engaged more, where they were challenged to develop meaningful understandings, where individual learning needs and preferences were catered for, where a range of assessment tasks were used, where the nature of science was represented in its social, personal and technological dimensions.

Our study was also guided by Peirce's (1930–58) model of the relationship between concepts and their representation (see Figure 2.1). In this triadic model, distinctions 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 the phenomena to which it refers. This implies that all attempts by learners to understand or explain concepts in science entail representational work in that they have to use their current cognitive and representational resources to make sense of science concepts that are new to them. 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 phenomena. Therefore learning about new concepts cannot be separated from learning both how to represent these concepts and what these representations signify.

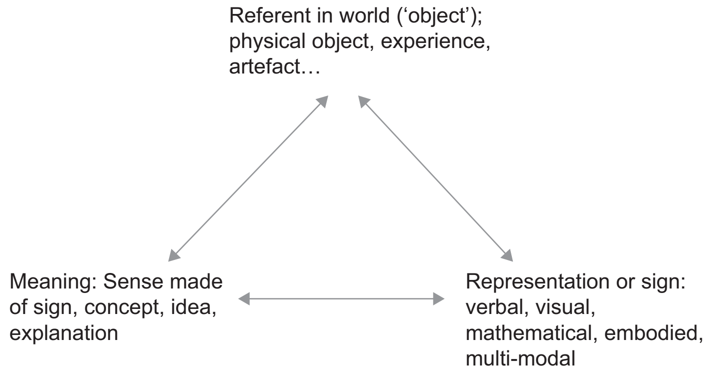


Figure 2.1. Peirce's triadic model of meaning making.

TEACHER SURVEY

The findings from our initial survey of 20 teachers' practices and beliefs in using multimodal representations of science concepts for learning (Prain & Waldrip, 2008) indicated that the teachers:

- tended to focus on resources and students' learning styles rather than on modal diversity, sometimes confusing modes and resources.

- tended to think that learning style differences dictated that many different modes should be used for the same topic on the assumption that particular modes worked better for some students than others.
- viewed modal diversity as necessary for making topics and concepts more tangible, enabling students to "relate resources to their own lives".
- were aware of a variety of possible representational modes.
- tended to use this diversity of modes as resources to promote interest in topics or cater for individual differences in learning styles, rather than as different representations of science methods and concepts.
- used a wide range of modes but did not focus on the specific interpretive demands of individual modes in planning, framing, and conducting diagnostic, formative, or summative assessment.

These findings suggested that there was a need to clarify teacher understanding of the form, function and purpose of representational work in the classroom. While teachers recognized that students found work with representations engaging, and as offering insights into their learning, there was a need to consider (a) the sequencing of the use of representations and re-representations, and (b) the role of representations in developing student reasoning and understanding. Four teachers in the survey then agreed to participate in extended case study research around their classroom representational practices. This case study entailed video-taping of the teacher and students in most lessons, shifting focus between teacher activity and selected student groupwork. The researcher observed lessons and interviewed students about their understanding of the nature of the tasks and concepts. The aim of the research was to identify teacher beliefs and practices as they responded to our request to focus on a representation-intensive approach to learning science. The researchers did not prescribe particular methods or resources but left those decisions to each teacher. We were also interested in the effects on students' engagement and conceptual learning, and capacity to coordinate representations as part of conceptual understanding. But in this chapter we focus mainly on teacher practices and reasoning around this approach.

CASE STUDIES

The first case reports on a primary unit on electricity (with Albert as the teacher), the second on collisions and movement (Raymond). The third and fourth cases describe a secondary technological and multimodal approach to improving student understanding of states of matter (Bob) and forces (Jane) (see Waldrip, Prain & Carolan, 2006). This section analyzes the teachers' responses and perceived challenges to implementing a representation construction approach.

Case One: Electricity (Albert)

These classroom observations (upper primary students) focused mainly on the students' understanding of parallel and series circuits, including how they operated (Prain &

Waldrip, 2006). Consistent with the literature on student alternative conceptions of the nature of electricity (Driver *et al* 1994), the students had various initial views on how electricity functions in relation to light bulbs, such as the idea that the globe consumed all the electrical current. The representational focus emphasized student work on re-representing their emerging understandings across different modes (eg 3D to 2D). We were also interested in whether this re-representational work impacted on learning. Although some students successfully constructed circuits in class, in subsequent interviews there were students who could not reconstruct a physical circuit, or its symbolic re-representation, nor explain their past success without the support of 3D resources, such as batteries and wires. Some students could revise their verbal or enacted representation about an effective circuit in the light of trial and error, and through various experiential prompts. Where a verbal explanation broke down, students would resort to hand gestures. Responses to the task of re-representing a circuit indicated that some alternative conceptions were maintained, despite the 'surface' accuracy of drawings. For instance, some students believed that the wires in a circuit functioned as a hose to transport liquid from the battery, and persisted with this explanation when they produced a new representation of a circuit. They believed that the globe lit when the chemical reacted or the currents 'clashed'. Student capacity to conceptualize effectively was demonstrated through representation coordination.

Albert believed from the outset of the study that student engagement with different modes could result in various dimensions of the concept being highlighted, with contrasting learning outcomes. He viewed each mode as having a distinct and important function in generating understanding. Rather than viewing representations as a mere collection of resources, he asserted that each mode provided a necessary contribution to the teaching and learning process in that engagement with each mode strengthened students' understanding of the underlying concept. He thought that it was important to "*attack the concept from different points*". This approach was achieved by utilising different modes to develop the concept and to address learner differences. He considered that a focus on different modal choices should be connected to an integrated holistic approach to concepts.

While recognizing that a representational-rich environment was highly desirable, he perceived a range of challenges:

- Curriculum time constraints could reduce the variety of modes with which students engaged, and hence limit available time to advance student understanding;
- Student diversity could dictate the type and range of modes used in class, and the need to repeat some modal experiences to consolidate learning;
- He perceived tensions between appropriate repetition of experiences, the timing and duration of exposure to different modes, and maintaining classroom momentum.
- This approach made demands on his scaffolding skills for guiding student understanding of how different representations worked, and this potentially hindered students' construction of their own representations;

Sometimes there were gaps in available representational resources.

Albert indicated that engaging with representational challenges benefited students in the following ways:

- Opportunities for students to re-represent a concept in different modes provided (a) insights into their meaning-making processes; (b) insights into common and divergent understandings across the student group; (c) opportunities to observe the relationship between students' emerging representational resources and their current understanding of the concept and (d) insight into the challenge for students in engaging with effective representation of their emerging science ideas;
- Student were more engaged in tasks and enjoyed multiple exposure to diverse modes; and
- There were many opportunities for the teacher to monitor students' past, current, and potential learning.

Albert considered assessment integral to teaching and learning, with discussion, non-verbal observation, and requests for verbal explanation seen as important methods of science assessment. He recognized evidence of engagement as a major indicator that students were learning, but cautioned that student enthusiasm can be misleading. He considered that traditional forms of assessment, such as post-topic tests, were inadequate for making reliable judgements about the level and extent of student learning. He pointed out that assessment should focus on the mastery of the concept, not mastery of the mode. He acknowledged that it was possible that the teacher might evaluate attractiveness of a presentation and ignore the substance. Teachers might focus on the aesthetics or conventions of a representation to the detriment of concept mastery.

Case Two: Collisions (Raymond)

Classroom observations of this topic were conducted over 8 weeks with a composite class of 30 students (upper elementary students), focusing mainly on their understandings of different representations of science concepts relating to collisions and vehicle safety (Prain & Waldrip, 2006). Initially, students designed and built a model vehicle to test the effect of collision on the occupant. The focus of this class was for the students to design and test their ideas and to compare their findings with the rest of the class. They discussed how to make a model of the occupant that would provide adequate testing of different collision conditions after the teacher stressed the need for this kind of testing. After students had collected their data, they pooled their results through whole-class discussion, and then constructed a graph to display results. They were asked to draw a line of best fit through each set of data. Finally, they were asked to comment in writing on what each data set was representing and which data set indicated the optimal situation for accident survival or minimal injury. Raymond thought that public justification of student representations through discussion served as a clearinghouse for ideas and was valuable in modifying and eliciting student understanding. Initially, some students appeared to be slightly surprised when they were asked to interpret their results for implications for real-life car travel. Some students quickly saw implications for vehicle accidents and safety. The students were required to comment on the essential vehicle features for minimal injury. They were required to comment on the comparability of their results with some published results relating to injury prevention in vehicle collision. Students further consolidated understandings through a whole-class discussion that focused on demonstrated and possible scenarios. However, some students saw the various tasks, including modifications, as disconnected events, while others saw how their results related to vehicle safety. Raymond considered that this focus enabled students to understand other representations of this issue, and the relevance of aggregating class data and representations to refining topic understanding.

Raymond described his main focus in primary science teaching as inquiry-based. He did not perceive explicit representation-focused learning as a process with highly structured procedures, but rather as a necessary aspect of a highly integrated approach. For him, the main value in using different representational forms was in developing students' deeper understanding. For example, students were expected to compare data from the experiment on collisions with official government figures. He also viewed students' work on data as an opportunity for them to see new data patterns in graphical representations. He implied that creating a connection with student lives and interests using appropriate modes would provide a more effective scaffolding to enhance concept understanding. He considered that claims and evidence were crucial facets to every science representation. He acknowledged that reflection and re-evaluation were important to generate greater understanding. He accepted that learners needed opportunities to revisit ideas, but this repetition needed to include small variations so that the activities did not become monotonous. He saw the need for student discussion and reflection, both guided by the teacher and peer-based.

Raymond recognized some challenges to using this broad approach:

- Students varied considerably in their capacity to interpret and construct different representational modes;
- It was important to vary the modes to address this student diversity, but he also claimed that there were learning gains when students were expected to engage with modal variety;
- Some students struggled to develop perceptual mapping between observed effects of the material tools and explanations; and
- Translation of key meanings across modes was easier for some students than others.

Raymond considered that a representational approach needed to incorporate the following aspects:

- Particular modes could stimulate some students to more extended thinking, such as use of a video camera in slow motion to examine collision effects;

- Rich understandings could be developed through a narrow range of selected modes rather than modal or resource diversity for its own sake;
- Students' interests needed to be catered for by linking science to their outside school experiences;
- Everyday materials were viewed as more meaningful for students than commercial products;
- Assessment must be an integral component of teaching and learning. He saw that assessment needed to reflect what the students were actually saying and doing in particular contexts. It needed to also take account of students' understanding of the conventions of different representations; and
- Summative assessment in schools often did not measure the extent and depth of learning. He felt that this breadth was best measured using a range of modes of representations. He implied that the planning process needed to consider incorporation of multi-modal representations rather than see them as separate discrete activities.

Case Three: States of Matter (Bob)

This secondary unit (lower secondary students) spanned approximately eleven lessons (Waldrip, Prain & Carolan, 2010). Bob's goal for the unit was for students to understand key concepts about the particulate nature of matter in relation to real world physical phenomena. The unit began with a formative assessment of student understanding of the basis of different states. Bob posed the question of what the bubbles in boiling water contain. He provided them with a worksheet prompting them to 'show the smallest parts of water' and 'show the smallest parts of the bubbles in boiling water'. The students explored the properties and nature of each state of matter. Student groups were provided with a phenomenon such as expansion or a change of state to enact by showing changes to the particles. Other groups had to explain the phenomenon that they were enacting and provide reasons for their choice. Students were asked, for example, to predict whether water or cooking oil would have a greater temperature gain when heated concurrently on the same hotplate. Finally, students completed the major assessment task of building 3-D explanations of the three states of matter. These models were photographed and presented including annotation using *Comic Life* software (See Figure 2.2).

The presentations aimed to show the degree of attraction, spacing and movement of particles in each of the three states of matter. The students were also asked to show one change of state with the same resources. In Figure 2.2 a student has attempted to show particle movement by blurring the photograph in the image at the bottom left of the account. While indicating some lack of conceptual clarity around structures of matter, the representation visualizes particle vibration in a creative way aligned to scientific accounts.

Figure 2.2. A Student example of representing spacing, movement and attraction of particles.

Bob felt that this approach raised various challenges:

- The teacher needed to be able to guide students as they progressed from self-generated representational conventions to more authorized ones;
- The teacher needed to support students to develop 3D perspectives from 2D ones, where students were sometimes dependent on the presence of concrete objects for engaging in representational work;
- Students needed to engage in explicit justification and clarification of ideas;
- Both teachers and students needed to realize that no single representation reflected complete understanding; and
- Inadequate representational resources could limit students' understanding of concepts such as the student representing attraction using spacing.

Bob perceived that a representation construction focus could succeed if:

- Teachers provide strong scaffolding for student learning;
- Teachers listened carefully to student explanations to guide future probing of understanding; and
- Students had opportunities to justify the adequacy of their representations as well as judge others' accounts through teacher-guided public negotiation.

Case Four: Forces Unit (Jane)

The unit on forces (lower secondary), lasting six weeks, was taught in the context of an integrated curriculum where teachers were expected to link learning outcomes across the subjects of English, Mathematics, Art and Science. Jane's goals for the unit were that students should develop some scientific understandings of, and key concepts associated with, forces in their everyday world. The major assessment task for the unit entailed students undertaking an engineering project over two double lessons to devise the best system of weight distribution to get a miniature hovercraft to travel the greatest distance. Weight distribution was part of the exercise, but the main idea was for students to understand kinetic energy, and that friction could slow the hovercraft down.

To orient students to the subject of forces, Jane focused on students' current understandings of the verbal representation of forces, leading to standard scientific definitions on this subject. Through guided discussion, and a range of practical experiences, the class was encouraged to view forces as things that can start an object moving, stop an object moving, change direction of the movement of an object, change the shape of an object, or have no visible effect at all. These ideas were reinforced through a variety of demonstrations, experiments, and play. This involved dropping objects of different masses but similar sizes, and moving objects across different surfaces. The students experimented with the idea of friction, such as dragging objects across different surfaces and measuring forces involved in this. Most work was conducted in a sequence involving small groups of students speculating about what forces would affect a particular situation, then conducting an experiment to test their ideas, reconvening to re-represent these understandings, discuss their adequacy, and then conducting further activities to confirm or disconfirm representational adequacy.

Jane felt that a representation construction focus was well fitted to her understanding of the nature of scientific knowledge as a growing, evolving process rather than a set of fixed answers. Consequently, she utilized a range of representational forms, particularly ones that involved technology because of student preference.

Jane perceived that this approach could work if:

- The teacher scaffolded student understanding of terms;
- More time was made available for a representational approach;
- The teacher posed significant representational challenges for students, where they utilized a range of representational forms, including roleplay, media, software, animations;
- Students constructed technological representations to demonstrate their understandings. Jane felt that it was important to use novel forms of technology as well as using everyday materials to construct equipment to illustrate complex science concepts;
- Representational forms were linked with other subjects (eg tables and graphs) to their use in science. She felt that there was a real need for students to understand the form and function of representations; and

- The teacher monitored the impact of a representational approach because it produced a more fine-grained analysis of student learning than did the current testing regime.

DISCUSSION

Analyses of the case studies suggest that the teachers had shared perceptions of the challenges, benefits and conditions for effective implementation of a representation construction approach to teaching. Some of the challenges include the following points:

- All participant teachers recognized that this approach could be initially more time-consuming than their current practices. They also perceived significant gains in the quality and retention of student learning.
- This approach highlights individual students' needs and differences in understandings. This challenges teachers to develop a program to address these needs in terms of sequences of representational refinements without unnecessary duplication.

Lack of adequate representational resources was perceived by some teachers as limiting the development of teaching and learning sequences.

Some teachers recognized that this approach crucially depended on students' ability to link representations with features of the inquiry, including properties of physical objects.

The teachers recognized that this representational approach made new demands on their teaching skills and knowledge, including:

- their skill in teaching form/function relations of different representational modes;
- their ability to identify and make use of appropriate representational resources;
- The capacity to guide students from self-generated representations to authorised ones;
- their skill in moving students from dependence on concrete props to abstracting and symbolizing through representations; and
- their skill in structuring social negotiation of different student claims and justifications.

The representational approach was perceived to benefit teaching and learning in that it:

- Improved student knowledge building;
- resulted in improved student engagement and achievement;
- provided a window into students thinking, thereby providing opportunities for productive diagnostic and formative assessment;
- enriched learning through opportunities for representational diversity and choice;

- provided a meaningful learning experience through potential linkage with everyday experiences; and
- could enable students to learn the form and function of representational conventions in a timely fashion.

All the teachers developed a sense of necessary conditions for the effective use of representational work. These conditions include:

- A strong fit for purpose between the representational mode(s) and the task;
- The need for strong teacher scaffolding;
- The need for teacher guided public negotiation of representational adequacy; and
- The need for students to understand the form and function of representation adequacy and to link them to their understandings.

Teachers considered that students needed to be familiar with the nature of the representational conventions in different modes if they were to succeed in both representing and translating concepts across modes. These teachers' comments suggest that they were aware that representations could differ in their degree of abstractedness from, or visual similarity to the target concept, and that these differences posed further challenges for learners. While their comments did not focus explicitly on these differences within individual representational modes, as discussed by Jewitt and Kress (2003), such differences indicate further complexities in the choice of appropriate modes to enhance learning for students with different capabilities.

For these teachers, their beliefs about, and practices in using, representational options influenced their views on effective assessment. They agreed that a focus on multiple representations provided much richer evidence to assess student learning. Students' use of multiple and multi-modal presentations also raised the issue of distinguishing between the quality of learning evident in students' use of different modalities. Some teachers noted that the representational modes with which students were expected to engage needed to be anchored to meaningful hands-on experiences. These teachers observed that this focus on student assessment through cross-representational understanding posed challenges for both themselves and students. They needed to be clearer about what representational capacities would count as satisfactory learning, and they also needed to provide stronger procedural support for students' engagement with, and construction of, different modes.

Each lesson sequence indicated the complexity of these challenges. Student learning in the electricity topic was strongly influenced by their manipulation of resources, and their degree of success in clarifying these experiences through verbal, 3D and 2D re-representational work. However, student success in making a working 3D model did not necessarily mean they understood the underlying principles of a circuit. This raises the question posed by Gee (1996, p. 138) of distinguishing between acquisition or mastery of a skill, and learning, or 'conscious knowledge'.

While clearly some resources and technology promote mastery skills, and this acquisition can be an important part of developing learning, this mastery in itself does not automatically signify learning in science. The students needed to be able to explain limitations of some of their proposed 2D representations to indicate their understanding of concepts. In learning about force, the students were expected to recognize key ideas across different representational modes, and connect classroom investigations to personal experiences and published material. While some students could make these links and represent their understanding verbally, in graphs, diagrams, written text, and with models, others struggled to move beyond superficial pattern identification across 'disconnected' experiences.

THE IF-SO FRAMEWORK

Drawing on these insights and our research in this area (Carolan, Prain, & Waldrip, 2008), we developed the following framework in topic planning (see I and F below), and teacher and student roles in learning through refining representations during a topic (S and O).

I: identify key concepts. Teachers need to identify key concepts or big ideas of a topic at the planning stage to anticipate which teacher- and student-constructed representations will engage learners, develop their understanding, and count as evidence of learning at the topic's conclusion.

F: focus on form and function. Teachers need to focus explicitly on the function and form (or parts) of different representations.

S: sequence. There needs to be a sequence of representational challenges which elicit student ideas, enable them to explore and explain their ideas, extend these ideas to a range of new situations, and allow opportunities to integrate their representations meaningfully.

S: student representation. Students need to have opportunities to re-represent to extend and demonstrate learning.

S: student interest. Activity sequences need to focus on meaningful learning through taking into account students interests, values and aesthetic preferences, and personal histories.

S: student perceptions. Activity sequences need to have a strong perceptual context to allow students to use perceptual clues to make connections between aspects of the objects and their representation.

O: Ongoing assessment. Teachers should view representational work by students, including verbal accounts of the topic, as a valuable window into students' thinking and evidence of learning. This assessment can be diagnostic, formative or summative.

O: opportunity for negotiation. There needs to be opportunities for negotiation between teachers' and students' representations. Students need to be encouraged to make self-assessments of the adequacy of their representations.

O: On-time. Timely clarification of parts and purposes of different representations How do they compare to "authorized" representational conventions as tools for understanding and communication of that concept/aspect of the domain?

IF-SO Framework Implications for an Effective Teaching Style in Science: The Trialogue

Reflecting on this framework, we felt that Roberts' (1996, p. 423) "trialogue" provided a useful way to conceptualize how and why representations can serve student learning in science, noting the capacity for learners to be active participants in these learning processes. This "trialogue" account meshes teachers' use of representations with students' prior and developing ways of representing. Roberts (1996) proposes a three-way reciprocal linkage between teacher, student and domain. In this model, guided by some suitable scaffolding, students are encouraged to generate their own representations to explain observations and predict future outcomes. They can then compare and reconcile these representations with those of their peers, and with those of their teacher, or those presented by their teacher as current within the science community. The teacher then acts as coach and negotiator of the meanings of these representations and their refinement through a range of representational tasks. The arrow from teacher to student indicates the accepted wisdom of representations, as communicated by the teacher, while the reverse arrow indicates the students' prior or developing representations of the domain (Figure 2.3).

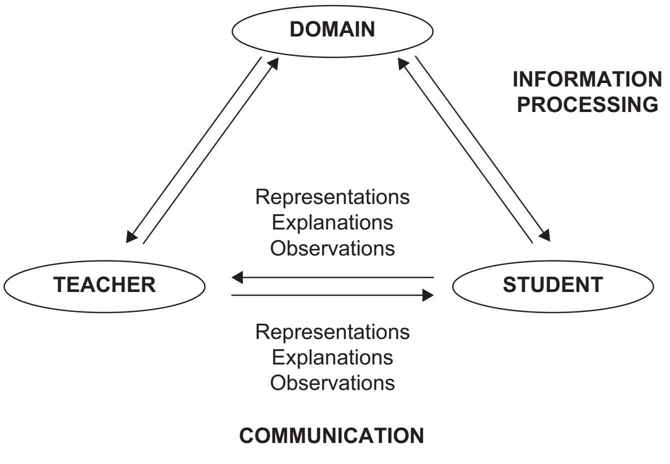


Figure 2.3. Teacher in Trialogue.

The trialogic approach affirms the students' need to generate their own explanations and compare these accounts to others, making the material meaningful to themselves and to others. This approach both recognizes the need for active participation by the learner, and teacher responsibility to coach students about the reasons behind the acceptance of representational modes, forms, conventions and interpretation. As students move into the "community of science" it is crucial for them to be cognizant of and conversant in the languages and practices of this subject.

Combining Peirce's (1931–58) account of the three components of meaning-making (Figure 2.1) with Roberts' (1996) model of pedagogy (Figure 2.3), we represented the pedagogy for a representation construction approach as a set of interlocking triads (Figure 2.4). From this perspective, teaching and learning in science entails various triads incorporating the domain (D), teacher conceptions (TC), teacher representations (TR), student conceptions (SC), and student representations (SR), which are mutually supportive. At all stages in the learning process, the teacher must rely on interpreting students' representations as evidence of their understanding.

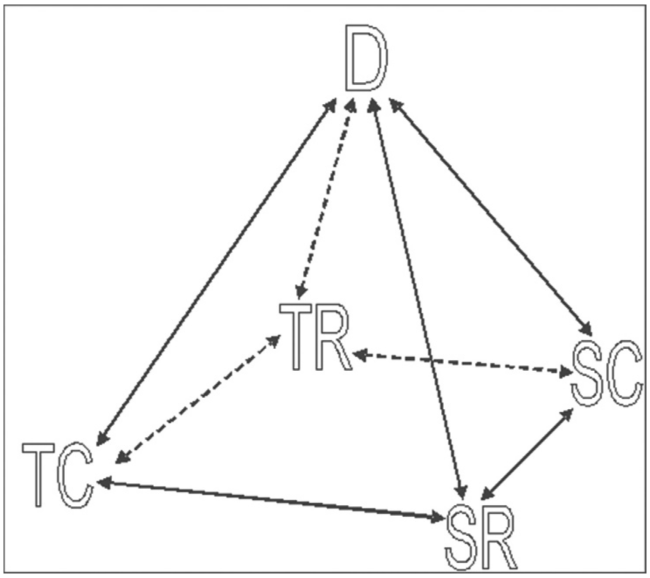


Figure 2.4. Triadic Pedagogical Model.

In the planning phase triad (IF), the teacher chooses the key concepts (TC), the aspects of the domain (D), such as physical objects, experiences, artefacts, situation/context or processes, that will be the focus of the unit, and the types and sequence of representations to use to engage students and develop their understanding (TR). The teacher also needs to consider the purpose of any student representational work. In this approach the teacher guides the students to recognize each representation's key features and, in a 'precious metacognitive lesson' (Roberts, 1996, p. 427), recognize how these features act as knowledge "justifiers" or "definers" in the domain. This style requires the teacher and the student to reason and explain their understanding through negotiation of student-generated and expert-derived representations.

Thus in the sequence of classroom lessons (S and O), different triadic emphases might occur, depending on stages in the topic and student knowledge, interests, and needs. Where key concepts are highly abstract, then students may need guidance in learning how to use accepted conventions to explore relevant ideas. This suggests the value of focusing on the triad of the Domain, Teacher Representations and Student Conceptions (D, TR, SC). Where students can engage initially or further with the topic because of their understanding, the teacher might facilitate student constructions, focusing on the triad of domain, student representations, and student conceptions (D, SR, SC). As stated in the IF-SO framework, students need to have opportunities to create their own representations of the domain to motivate them, develop representational competence, and learn science. The teacher and class then need to assess the convergence or compatibility of these representations with authorized ones, using a different triad (TC, D, SR). The success of this work then frames directions for subsequent lessons, establishing if there is a need for explicit teacher-guided negotiation of students' current representational meanings.

CONCLUSION

Our early research indicated that there was a need to develop and implement programs that aimed to focus on teacher- and student-generated multiple and multi-modal representations of science concepts. Extended case-study research was needed on how students attempt and make sense of this translation work between representational modes, including the specific features students see, and should see, as significant in particular representations. Further research was required on how student-generated representations can be extended, enhanced or contested by the teacher and by student peers to guide students towards more teacher-authorised representation. Teachers needed to be clear about what students' reactions to different modes revealed about their conceptual understanding and learning capacities, and how to enable students to make durable connections across modes. The evidence that students persisted with viewpoints that contradict their observations suggested the need for extensive re-engagements with the same and different modes.

Chapters 3 to 10 describe a variety of aspects of the subsequent research program that pursued these questions. The findings from this program form the backbone of this book.

RUSSELL TYTLER, PETER HUBBER, VAUGHAN PRAIN &
BRUCE WALDRIP

CHAPTER 3

A REPRESENTATION CONSTRUCTION APPROACH

In this chapter we lay out the principles of an approach to teaching and learning science based on student generation, negotiation and refinement of representations in a guided inquiry process. We first tell the story of how we developed this perspective, building on Chapters 1 and 2, and the research approach that led to these principles. The principles of the representation construction approach are described, then exemplified using detailed analysis of parts of classroom learning sequences on force, and substances. We then give examples of teacher responses and beliefs, and finally provide evidence of student conceptual, and meta-representational learning, from this approach.

BACKGROUND TO THE TEACHING AND LEARNING APPROACH

Following the explorations of a pedagogy focused on representations described in chapter 2, a major focus of the *Role of Representation in Learning Science* (RILS) project was to explore more systematically and in more detail a teaching and learning approach based on the central principle of student representation construction, and to investigate the nature and quality of student learning that flowed from this. The project involved refining and extending our previous explorations of such a pedagogy (Carolan, Prain & Waldrip, 2008), and further drawing on and interpreting a diverse literature concerning student knowledge construction and its relation to representation and modeling. This included the extensive conceptual change literature, which we have re-interpreted from a representational perspective (Tytler & Prain, 2010) but on which we explicitly drew for insights into the particular problems evident for students learning key conceptual schema in science.

The literature informing our practice has emphasised the centrality of representations in learning and knowing science, the need to frame learning sequences around the development of students' representational resources, the need to make explicit the form and function of representations, and the need to develop meta-representational competence. Further, we have drawn on a literature that goes

R. Tytler, V. Prain, P. Hubber and B. Waldrip (Eds.), Constructing Representations to Learn in Science, 31–50.

further than emphasising representational interpretation, to advocate representational construction, negotiation and evaluation in authentic settings, in order to more deeply engage students in the knowledge building practices of science. Chapter 2 described the early exploration of these principles in classroom settings (Carolan, Prain & Waldrip, 2008; Waldrip, Carolan & Prain, 2010). Through this work we became convinced of their potential to engage students in quality learning. RILS provided an opportunity to explore more systematically the nature of an approach to teaching and learning that might be built around representation construction, and the resultant quality of student engagement with learning. The RILS project had a number of facets and collaborative work with teachers at multiple sites, but this chapter is based on an in depth exploration where members of the team worked closely with two primary, and three secondary teachers, to explore the approach applied to key science topics that were particularly known to present learning challenges for students. These topics generally consisted of 6–12 lessons.

THE RESEARCH METHODS

Our work involved working closely with teachers to construct units of work jointly around key science topics known to present learning difficulties, developing insights over three topics in each of the primary and secondary classrooms, over three years. The primary school topics were animals in the school ground, energy, and water (changes to matter). The secondary school topics were force and motion, molecular models of substance, and astronomy. Our perspective is that the conceptual challenges in these topics, identified in the conceptual change literature, are fundamentally representational in nature (Tytler & Prain, 2010). The teaching and learning approach involved constructing learning sequences with the teachers around a series of representational challenges that foregrounded assessment of representational adequacy and negotiation, and explicit consideration of the role of representations in learning and knowing. We chose to work with teachers across the middle years (5–9) of schooling, which are recognized as posing particular difficulties for student engagement (Luke et al., 2003), and where interest in science has been demonstrated to markedly decline (Lindahl, 2007; Tytler & Osborne, 2012). The pedagogy is consistent with middle years principles of active engagement and challenge in learning activities, entailing higher order thinking and reasoning. The aim of the research was to:

- iteratively develop over these three years a set of principles of teaching and learning that exemplified our ‘representation construction’ position,
- understand better how this might look in practice,
- investigate the challenges for teachers in adopting this approach, and
- more sharply identify the student learning gains associated with the approach.

For each unit of work, the teachers’ practices, student-teacher interactions, and student activity and discussion were monitored using classroom video capture. This involved two cameras arranged to film the teacher, and a selected group of students for each lesson. Radio microphones were used for teachers and the student group. The video was captured on digital tape and uploaded and compressed, and coded to identify 'quality teaching and learning moments' for later analysis, using Studiocode software (http://studiocodegroup.com/). These teaching and learning sequences were then selectively transcribed and subjected to interpretive analysis to identify the extent to which and in what ways the teaching and learning principles were exemplified, and for evidence of the ways in which the focus on representations supported reasoning and learning. Students were interviewed about their learning and their understandings of the nature of representations in constructing explanations, and teachers about their perceptions of the effectiveness of aspects of the sequence. Student workbooks were collected to provide a continuous record of representational work.

In working with the teachers over three years, we developed a set of teaching and learning principles based on our unfolding experience and on theoretical ideas described above. These were available to teachers, and were the working principles we used to help teachers plan the lesson sequence. They 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 set of teaching and learning principles described in this chapter were hence developed in a hermeneutic cycle involving a conversation between the research literature, the unfolding experience of the researchers in working with teachers and gathering multi-perspectival information on teacher and student learning experiences, a series of workshops in which teachers and researchers reflected on and discussed their observations and experiences, and analysis of a comprehensive data set including the video record of classroom interactions, student artefacts, teacher and student interviews, and student pre- and post-tests. While the broad principles were in place early in the project, the refinement represented here reflects a growing understanding of the key elements and their relative emphasis, the relation between the different principles, and the detailed nature of the teaching practice and the student learning arising from each principle.

The principles of this representation construction approach to teaching and learning are first described in brief, before being illustrated in some detail. As part of this exemplification, we present examples of the challenges faced by teachers in adopting the approach, and illustrate the quality of student learning associated with the principle. Finally, we argue that this approach is a particular form of guided inquiry that shows promise of resolving the tension in science education (Osborne, 2006) between the need to introduce students to the established, canonical forms of science, and the need to engage them in the creative processes by which scientists explore phenomena and build new knowledge.

A REPRESENTATION CONSTRUCTION APPROACH TO TEACHING AND LEARNING IN SCIENCE

The principles underpinning the representation construction pedagogy were developed by the RILS team, based on an iterative process of analysis of jointly constructed teaching sequences and discussion, involving the researchers and teachers.

These principles clearly 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, both involve significant challenges. For students who see knowledge as established facts and processes to be memorized, these principles entail a major shift in perspective. In the remaining part of this paper/chapter we explore what these principles look like on the ground, drawing on two different topics, and the experience of teachers and students in developing this approach.

Compared to the IFSO framework described in Chapter 3 these principles are more detailed and more consciously operationalize the representation construction approach. They are more layered in their treatment of the representation construction tasks, and the nature of judgment of representational adequacy. The changed emphasis reflects the comprehensive data set we generated in working with teachers to address the issues raised in the prior research.

Principles Underpinning a Representation Construction Approach to Teaching and Learning

1. *Teaching sequences are based on sequences of representational challenges:* Students construct 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. Features of this meta-representational discussion include:
   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 critique representations for their clarity, comprehensiveness and explanatory persuasiveness to aim at a resolution, in a guided process.
   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 the coherence and persuasiveness of student representations.
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 are involved in a continuous, embedded process of assessing the adequacy of representations, and their coordination, in explanatory accounts.

The principles are exemplified below. For each principle, we examine the experience of teachers and students and the associated learning outcomes. For this we draw particularly on the teaching and learning sequences in force and motion, and substances, both of which involved students in Year 8 (13 year olds).

Introducing Representations of Force

The first illustrative case is the planning and initial sequence of the forces unit. This was the first unit planned with the secondary teachers. Previous work (Waldrip, Carolan & Prain, 2010) had shown that adopting a 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 discussion of key concepts associated with force. 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 – contact forces, gravity, electrostatic and magnetic force – represented by arrows superimposed on complex and often dramatic photographs of force phenomena. In the book the use of arrows was not justified, but assumed, and the rules relating to the arrow convention were not discussed despite the complexity of some of the force diagrams.

In order to refine the focus of this representational work, the research team collaborated with the teachers to identify the big ideas, or key concepts, of force. Students' alternative conceptions reported in the literature were discussed, including confusion between force and movement in diagrams, conceptions of force as embedded within a body's motion, and confusions about the force-acceleration relations in two dimensional motion, for instance applying to orbiting satellites. The force arrow convention was felt to be central to the representational conventions associated with problem-solving in this area. The initial lessons in the sequence thus focused on the explorations of representations and learning of the scientific conventions of representing forces. As we have described elsewhere (Hubber, Tytler & Haslam, 2010), the idea that force arrows is a negotiable convention, capable of flexible use, and that there is no absolute 'right' or 'wrong' convention to describe force, was an empowering realisation for these teachers. They were surprised that such an apparently resolved representation could be the subject of discussion. Thus, Principle 1a, concerning the identification of key ideas and the associated representational resources, involved in this case an epistemological shift for the teachers, who needed support to think their way into the approach.

Lyn's sequence was broadly representative of the approach of all three teachers, who met regularly to share ideas and experiences and plan. The sequence consisted of a series of challenges (Principle 1) 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 (Principles 1b and 1c). 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. She did this by initially eliciting from the students everyday action words they used, given the task of changing the shape of a lump of plasticine. A brainstormed list of words was quickly constructed and displayed on the board, including *stretch, carve, twist, roll, squeeze, mould* and *poke*. From the initial brainstorm listing Lyn re-represented the list into a tabular form after discussing with the students whether each of the elicited words could be placed into a column labelled 'push' or a column labelled 'pull'. She then introduced the scientific meaning of a force as a push or pull of one object onto another. The terms push and pull operate here as an inter-language (Olander, 2010; Tytler et al., 2012), bridging the gap between everyday words and the formal scientific term.

Lyn used gestures to re-represent the words as they were given by the students. Many of the students also provided a gesture to explicate their meaning further. A noticeable feature of the teachers' and students' communication during this unit was that gestures 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. These point to the embodied nature of the force concept. We see this as a natural form of re-representation in which meaning is established in the public space by a process of representational weaving, in this case between verbal and gestural modes.

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 their actions in changing the shape of the plasticine in paper form. The different representations constructed by the students, some of which are shown in Figure 3.1, were discussed and evaluated within a whole class discussion.

Student 1 Student 2

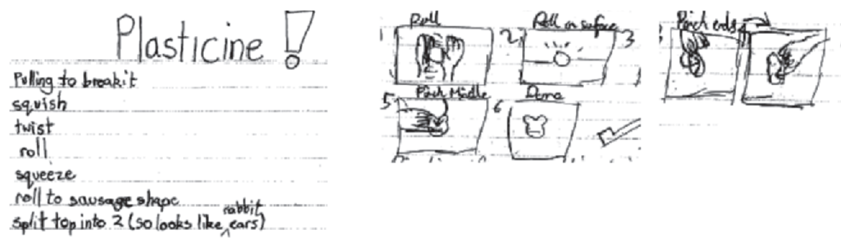


Figure 3.1. Student representations of manipulating plasticine.

One representation, which had a sequenced series of figures with annotation (Figure 3.2 Image A), was unanimously accepted as providing clarity of explanation of the actions that were undertaken:

Lyn: Which one of these representations worked well in explaining what was done?

Student 1: John's because it showed you exactly what to do. Mine could have ended up anything.

Student 2: It was more visual, you can actually see it is easier to actually see what you did. With the other ones you could make it in different ways.

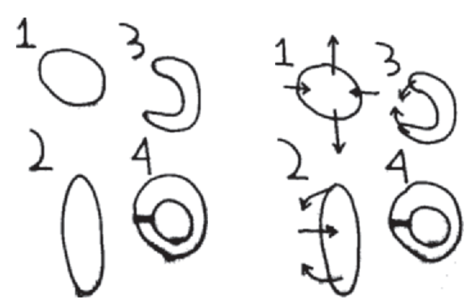


Image A Image B

Figure 3.2. Reproduction of video images of John's representations.

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 3.2 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 3.3 shows three students' responses.

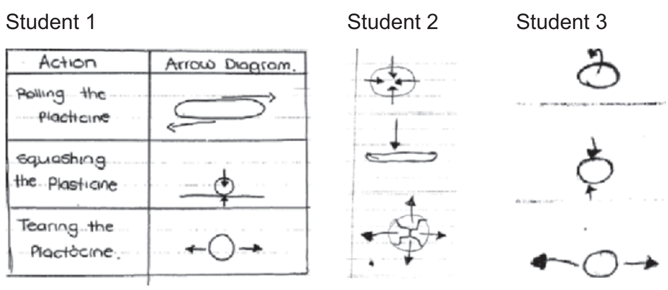


Figure 3.3. Students' use of arrows.

The completion of this task produced different meanings of the use of arrows, which Lyn discussed with her students. Several issues were raised and discussed including:

- Distinguishing between the arrow representation as a force or as a direction of motion;
- Distinguishing between different types of arrows, such as curved or straight, thick or thin, many or few.

Lyn then introduced the scientific convention of representing forces as straight arrows, when the base of the arrow is the application point of the force and the length of the arrow gives an indication of the strength of the force. The students were then encouraged to apply this convention to various everyday situations where forces are applied. 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 3.4).

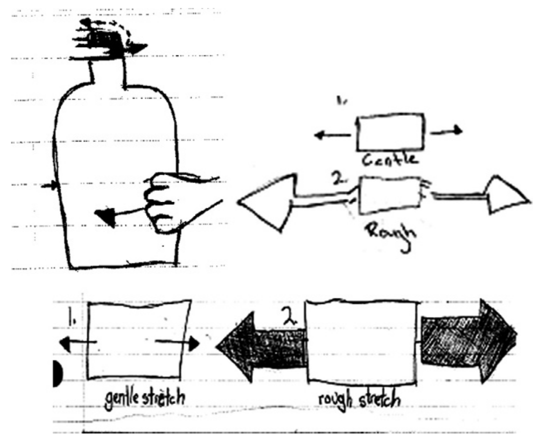


Figure 3.4. Student exploration of the arrow representation of force.

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 (Principle 1). The representation construction task is built on a need to communicate a sequence of shaping forces (Principle 1b), using verbal and visual and gestural modes (Principle 1c) 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 (Principles 2, 2c, 2d). This process of public negotiation in which students agree on effective representations of the shaping process (Principle 2b), leads to an alignment of student and canonical representations (Principle 1d). 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 conceptual change approaches, with 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 on more nebulous 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. Students' ideas about these concepts were elicited through a questionnaire, and the responses helped shape the sequence. Several modes of representations formed the structure of the challenge activities. These included:

- Role-plays with a Swiss ball representing Earth and a soccer ball representing the Moon, and a toy bear 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.
- The use of force and mass measurers to measure the mass and weight of common classroom objects, tabulating the results and determining the mathematical relationship between mass and weight of an object on the Earth's surface.
- 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 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 the motion of objects and the effects of friction. Students were asked to imagine, on a magnified scale, the surface of an object as it slides along a flat surface (Figure 3.5). The students were asked to design, conduct an experiment and write a report on an investigation of factors that affect friction on everyday objects, like sports shoes. Within the investigation reports the students were encouraged to apply multiple representational modes. The audience for the report was someone like a friend who lived in another state and who could repeat the investigation.

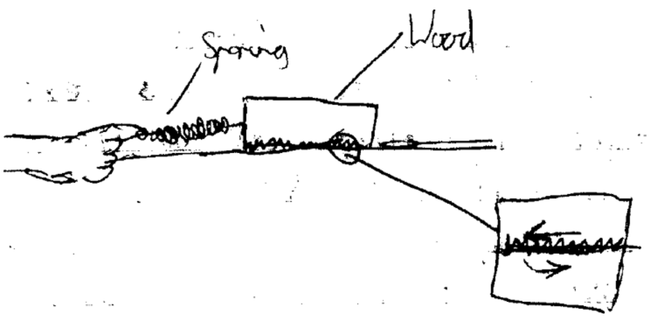


Figure 3.5. Representation of friction.

Friction is thus understood through the coordination of modes (Principle 1c), including arrow representations, detailed microscopic mechanisms, and gestures, aligned with and explanatory of tactile perceptual experiences (Principle 3). Each of these provides a selective, partial view of the phenomenon of friction (referred to in Principle 2a).

There were examples in the sequence where the challenge for students to visually represent enabled a public process of negotiation with the representations mediating a productive exchange. Sally established with the students that when an object is moving on a surface there will be friction that opposes motion and then asked:

Sally: Can you think of an example of why it might not be true?

Student 3: On a skateboard.

Sally: Can you draw it for me? I want to see how you think?

Students 3: [Student drew a pair of wheels] the wheels will be turning that way [indicating by gesture and curved arrows on the wheels]

Sally: if the wheels are moving that way in what direction is the skateboard moving?

Student 3: [Student looks at his diagram, traces out the direction of the wheels and then indicated the direction of the skateboard with a straight arrow] that way? The wheels would be rolling and nothing will be pulling on them.

Sally: So is there any force preventing it from moving?

Student 3: No, the surface is already moving [Student represented by gesture the rolling motion of the surface of the wheel against the ground]

Sally: Let's say you are on the skateboard [Sally modifies the diagram to include a representation of the student] and you are wanting to go in that direction but the skateboard is originally stationary.

Student 3: [looking at the diagram] Oh. Well, your foot would do the pushing for you.

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. This exchange between Sally and the student led to a classroom discussion regarding the reduction of frictional forces related to the nature of sliding surfaces and their area of contact. Different frictional effects were explored with different orientations of the set of interlocked hairbrushes that had acted as a model of the surface contact.

A bridging analogy (Clement, 1993) was used by Lyn to introduce the idea of contact forces. Figure 3.6 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, that help them to coordinate meaning across different aspects of the phenomenon. Each representation offers a selective, partial perspective, and understanding involves the flexible coordination of a view that looks at macroscopic force effects and one that looks at their microscopic causes or correlates. This coordination of the macroscopic and microscopic is currently a challenge of much interest to researchers (Gilbert 2005).

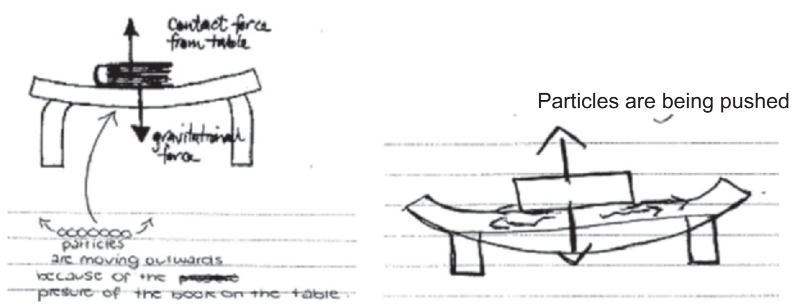


Figure 3.6. Student representation of contact forces.

A Substances Unit for Year 8

After the forces unit, Lyn and Sally were involved in a Year 8 substances unit with a focus on the coordination of molecular models and macroscopic properties of materials. The topics covered atoms, molecules, elements, compounds and mixtures. The research team also worked with a relatively inexperienced biology – chemistry trained teacher, Therese, on a related year 7 10-lesson unit introducing the particle model and coordinating this with states and properties of matter.

In both sets of sequences student representation construction was a central feature. In an exercise involving the categorisation of different substances in the year 7 sequence, class discussion on the lack of clarity of the distinction led to students suggesting a Venn diagram representation that admitted cross-over categories of solids, liquids and gases. The teacher also discussed a 'continuum representation' which students engaged with. The resulting board work is shown in Figure 3.7.

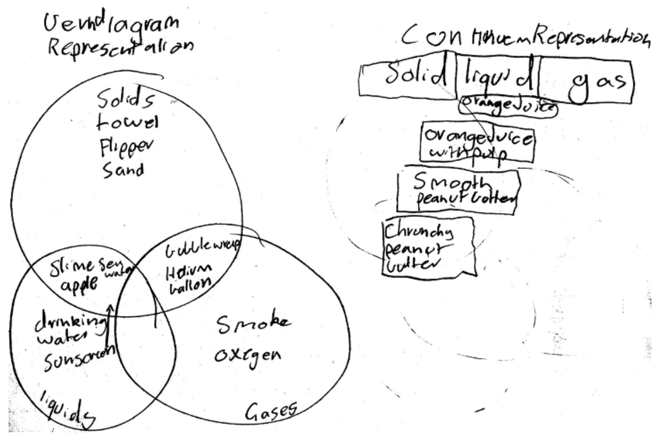


Figure 3.7. Representations of materials as combinations of solid, liquid and gas.

Here, as with the forces unit, one can see the response of students to a representational need and the richness of discussion in the public space of the classroom. The agency granted to students is also apparent. The limitations of the representation were also acknowledged, when a student asked where bubble wrap should be put, and the teacher responded: "in this case this is where the representation doesn't fit?"

In a sequence of representational challenges intended to move students to an alignment of particle ideas with macroscopic properties of materials, students drew imagined particle arrangements to explain the property. Figure 3.8 shows the basic worksheet challenge for the property of paper holding its shape, and three student responses, drawn on the board, which were discussed for their adequacy. The instructions were to draw a representation using particle ideas, which only needs to explain the property that is being described. For the first challenge the three responses are all adequate since they allow breaking up of the structure. For the second challenge the first response was judged inadequate since it has no structure to sustain shape.

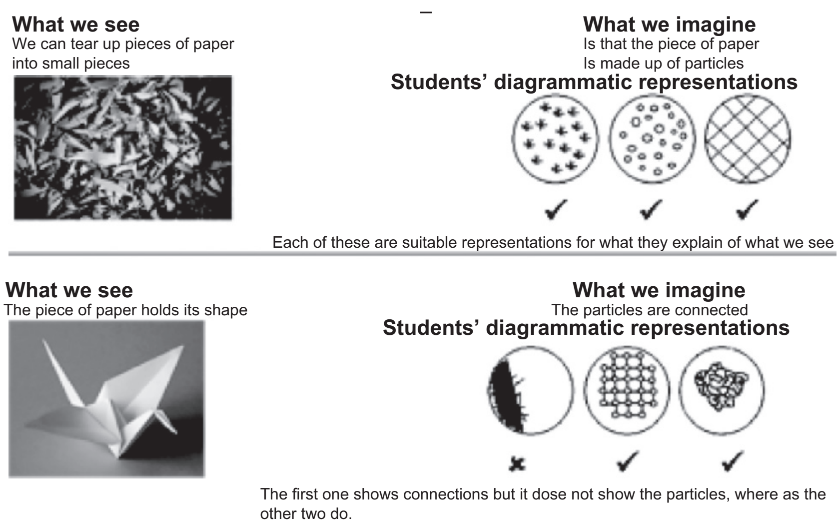


Figure 3.8. Student drawings of 'what we imagine' to explain properties of matter.

In groups students were given a stick of chalk, lump of plasticine and a plastic spoon, and challenged to draw a super magnified view of a sample of the substance that makes up each object to show a particular physical property of the object. The particular property was their choice and so they needed to annotate their representation to explain this. Note that the idea that representations are selective in their intent, and partial, is embedded in the nature of this challenge (Principle 2a). The representational/ perceptual mapping (Principle 3) is very clear here also. Figure 3.9 shows responses to challenges to 'imagine' particles that explain the stretchiness of a rubber band.

Figure 3.10 shows two responses to a challenge to represent dry ice sublimating. The responses in these figures demonstrate the variation and the quality of student work, and the lively engagement of students with the task.

These tasks, as for the force sequence involving public discussion of the adequacy of representations, provide insight into student thinking such that formative assessment is embedded naturally into the teaching and learning process (Principle 4). The process of negotiation of representations and alignment with canonical representations requires teachers to constantly monitor student products. In the dry ice example of Figure 3.10 for instance, important features at issue are the breaking of bonds in sublimation, and the increase in inter- particle distance and particle movement. As Therese said:

> There was more class discussion in this teaching sequence as there were a lot of open-ended questions set out to the students. I wanted to hear the majority

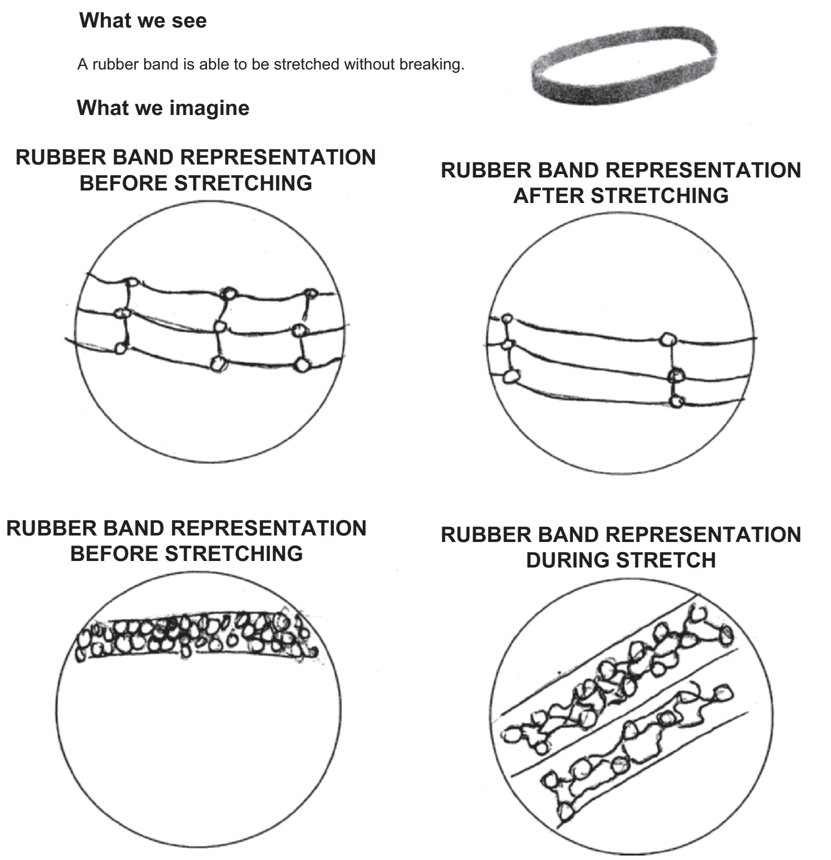


Figure 3.9. Representing particle arrangements for a rubber band.

> of the class' thoughts before moving on to a new stage in the sequence. They all felt a part of the group if they got to share what they thought (Therese, interview)
>
> **Researcher:** You often had students evaluating each other's representations.
>
> **Teacher:** To open up different ideas. This gave insight into their thinking and how they interpreted my teaching so this gave constant feedback on their understandings
>
> ...what you're seeing with representation is that you're seeing what's in their brain, not what they're regurgitating. (Lyn)

The question of assessment will be taken up in more detail in Chapter 9. Over the project, there were two innovations in summative assessment developed by the

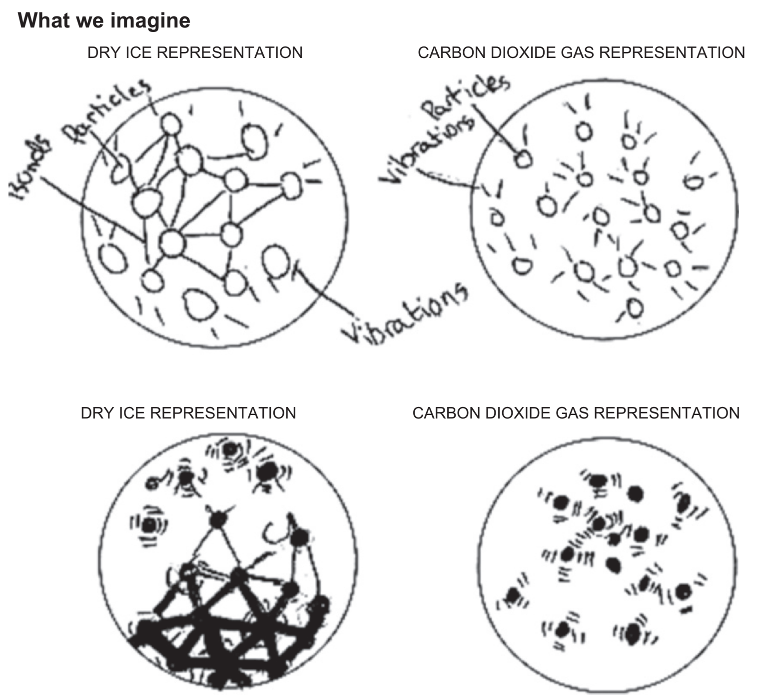


Figure 3.10. Representing dry ice and carbon dioxide using particle ideas.

team. One was that items encouraging or requiring students to represent multi-representationally and multi-modally, were included in tests. This might simply involve a change in language from 'explain' to 'represent to explain', with the provision of space and the absence of lines. These items however pose difficulties in interpreting reliably the extent of understanding. The other was that items were developed that explicitly tested students' meta-representational competence (Principle 2). Figure 3.11 is an example of one such item focusing on students' understanding of the selective and partial nature of models.

IMPACT OF THE APPROACH ON STUDENT LEARNING

In taking a conceptual focus to topic planning the teachers saw themselves as being able to move away from the textbook framing their pedagogical approach. This meant less coverage of content, but provided a more purposeful and a deeper approach to learning. Lyn commented:

> Before we crammed it all in and didn't know what to cut out…we were so pleased to actually pause, particularly in that Forces unit, which was so superficial and done so badly according to the textbook that we were using.

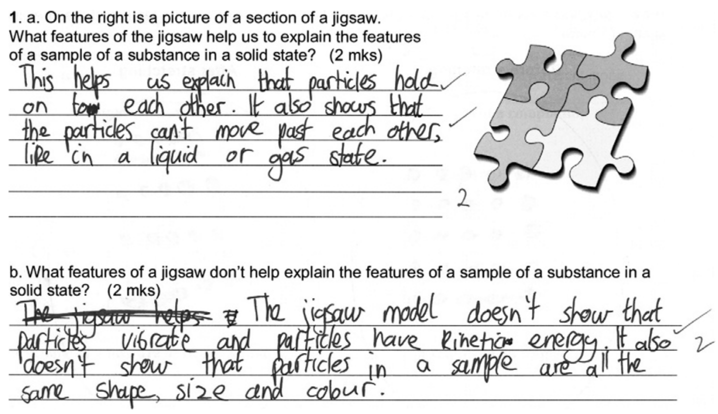


Figure 3.11. Summative assessment item focusing on meta representational competence.

> We were so pleased to go into depth. And it was so lovely to be able to develop ideas with the kids. (Lyn, focus group)

The explicit focus on representations were seen by the teachers as providing a solid grounding for ongoing conceptual work.

> The thing I like about using arrows, I felt I was now coming from a base level whereas before when I taught forces, in hindsight, I now realise I was sort of coming in via the second and third floor. By slowing it down, and giving the kids a slower pace, and getting them on board to use the arrows, and thinking about the directions and size, it sets up the rest of the unit and gives them a really good structure to the concept. So that they can actually start to think in terms of something that is quite concrete for them. (Lyn, focus group)

> When we did use the previous unit plan, I noticed that it was very text book based plus it seemed to pack every topic available into the unit. With a big unit, it was hard to spend the appropriate amount of time teaching the topic. I noticed this year that we were able to choose a couple of topics that blended together well and use the time available to really connect with the students. (Therese, interview)

The teachers were clear that there was more discussion, and deeper learning than had occurred previously in the text book framed units. In reflecting on the impact on student learning the teachers saw benefit in students having the authority to construct their own representations to explain their reasoning.

> Lyn: … what the representation's done is it's changed the conversation from "what" to "how", and therefore they're more doing than thinking and talking.

> Sally: … for me it's changed from "what's happening", to "how would you represent that?" And therefore the students are internalising it and showing it.

> Lyn: … it's a very powerful way of showing understanding and getting the kids to think … it allows kids to be creative in showing their understanding with different representations. And we can all see different ways of doing it.

The quality of student work found in the student artefacts above attests to the learning that took place in these units. Pre and post test comparisons have shown substantial growth in understanding. Table 3.1 shows the improvement in correct responses from pre- to post- test on the multiple choice items in the test.

Table 3.1. Pre- and post- test learning gains for multiple-choice items, in the Year 7 substances unit

7. *Each statement tick the box you feel most fits your understanding of the statement.*	*% correct response*		*Normalised gain index*
Statement	*Pre-test*	*Post-test*	*<g>*
All objects consist of very tiny particles called atoms.	78	90	0.54
A molecule is a tiny particle that consist of more than one atom bonded to each other.	64	90	0.72
When a substance freezes the temperature must always be less than 0 °C.	52	91	0.81
It is possible to heat an object to +1000 °C but it is **not** possible to cool it -1000 °C.	40	93	0.88
When wax melts the molecules that make up the wax change from being hard and firm to being soft and 'gooey'.	11	68	0.64
When a substance condenses it changes from a gas into a liquid.	71	88	0.59
A closed bottle with small amount of water at the bottom is left in the sun. After awhile, when the water has evaporated, the mass of the bottle is now **less** than before.	48	98	0.96
The molecules inside liquids and gases are moving but in solids they are stationary.	19	98	0.98
In the spaces between atoms of an object there is air.	38	93	0.89

In this and an astronomy unit a measure of the improvement in student knowledge over the teaching sequence has been attempted, using a 'normalised gain index', <g>, previously used in other studies using identical multiple choice pre- and post-tests (Hubber 2010). <g> is the ratio of the actual average student gain to the maximum possible average gain: <g> = (post% - pre%) / (100 - pre%), reported by Zeilik, Schau, & Mattern (1999). Gain index values can range from 0 (no gain achieved) to 1 (all possible gain achieved). A respectable mean gain is argued to be 0.3 (Kalkan & Kiroglu, 2007, p. 17). In contrast the mean gain for the 'substances' tests was 0.78, on questions that represented conceptions identified in the literature as problematic.

A similarly impressive result was found for astronomy, for which it was possible to compare gains on identical items used in previous research led studies (Hubber, 2010).

Thus, there is evidence from teachers, from the video and student artefact data, and from pre- and post-tests, that the representation construction approach yields significant learning gains.

The representation construction principles developed in this study have a dual character; as pedagogical principles and as statements about the conditions for quality learning in science. They represent in fact both teacher and student learning, because of the demands of the construction, evaluation and negotiation of representations. Teachers have told us of the clarity they experienced through the process of planning around key concepts and representations, and about the challenge of deeper conversations about the use of these tools to explain or solve problems in science. They talk of greater student engagement with science ideas, a finding that has been explored theoretically by Prain and Tytler (2012), drawing on semiotic, epistemological and epistemic justifications for this representation construction practice. These ideas are described in Chapter 5.

Teachers and students, through this project, grew in their meta-representational understandings, as one might expect from an emphasis on Principle 2, the explicit discussion of representations.

> Sometimes the representation will help us to get to that knowledge. So it is a continuous feed-back; as Sally said, if we try to understand the concepts we have to go to various types of representations …Representations help us get the knowledge, we use the knowledge to help to build our representations (Lyn, focus group).

Teachers increasingly focused on the selective and partial nature of models, and developed in epistemological sophistication of their views. Students were challenged in the substance unit in particular, to evaluate different particle representations, for instance the analogy of popping corn for evaporation ('What's good about the model? What's bad about the model?' As Lyn explained:

> … we're not teaching the particle model as in, this is the model and see how it relates to real life. It's more, this is real life and we have a model and does it actually explain real life, and does it explain this and that? And particularly … how good is the representation?

Sally emphasised how students had adopted a critical perspective on models to the extent that in the following year it was noticeable that they took a critical stance to their text book representations. The relation of models and representations to knowledge was probed in interview. The following exchange was between a researcher and a year 8 student:

> **R:** You have two separate words, one is Understanding and the other one is Representations. [R & U were drawn on the page –Figure 3.12] how do they connect?

> **S:** Through many representations you can come to an understanding [drawing arrows from R to U]. So many representations help you get an understanding
>
> **R:** So do you use representations to show your understanding?
>
> **S:** Representations help you understand but then [now drawing arrows from U to R] through your understanding you can give many representations. So it works both ways.

Figure 3.12. Understanding and representation.

Another student was asked, "Do you need more than one type of representation to understand? She responded:

> I think you need more than one [representation]. Some things get explained better in different ways. Like something just looks better. You can understand more when there are graphs in it. Like other things like diagrams need to have arrows rather than writing to show what happened. Some things need just writing because they are very complicated. You just need to explain them and some things need all of them.

CONCLUSION

Through a three year process of working with teachers to develop and refine the representation construction approach, analyzing video and student artefacts and interview data, and discussions within the research team and with the teachers, we have come to a clearer understanding of the core pedagogical underpinnings of the approach and how these support and shape student learning in science.

The approach is a variant of guided inquiry and is consistent with aspects of conceptual change approaches. We believe however that the explicit focus on representation construction constitutes an innovation in science teaching and learning that can potentially resolve the well recognized contradiction in science education (Osborne 2006) between the need to represent in classroom processes the exploratory and imaginative aspects of science knowledge building practices, and at the same time introduce students to the canonical products of science (Klein & Kirkpatrick 2010). This resolution comes about through the twin focus on representation as a process, and a product. Students in these units were engaged in imaginative production and negotiation of ideas, and achieved significant learning in key ideas as evidenced in their performance on traditional test items, as well as demonstrating capabilities in generating and coordinating representations, and in meta-representational competence.

The principles do not speak strongly to unit structure, but as the analysis shows can be exemplified even in short activity sequences. In a separate analysis, we will look at the structural features of the sequencing of ideas across key topics in primary and secondary schools, to identify patterns they have in common. However, it is clear that the approach admits of considerable variety in this respect.

The approach captured in the principles places significant demands on teachers and on students, and speaks to both student and teacher learning. As they planned and executed learning sequences, teachers were challenged to develop deeper understandings of key science ideas, and challenged pedagogically and epistemologically. They were, however, enthusiastic about the learning outcomes achieved by students and also by the pleasures of deeper engagement in classroom discussion with students and their developing ideas. For students it seemed that the enhanced engagement flowed from the active way in which ideas were introduced and negotiated and linked to science phenomena.

RUSSELL TYTLER, PETER HUBBER & VAUGHAN PRAIN

CHAPTER 4

STRUCTURING LEARNING SEQUENCES

We have argued in this book for an approach to teaching and learning science based on the principle that learning needs to be seen as a process of induction into a set of subject specific disciplinary literacies. Further to this, we have argued that a guided inquiry approach based on the principle of student representation construction provides a powerful response to the problems identified in the literature concerning student learning of key science concepts. This position aligns with Vygotskian notions of mediation of learning through language, conceived of as including the multiple representations through which we know in science, and with pragmatist perspectives on the role of language in learning (Peirce, 1931–58; Wittgenstein, 1972).

The principles underpinning the representation construction approach we described and exemplified in Chapter 3. The key elements of the approach are:

- Representational challenges that involve students constructing their own representations;
- Evaluation, negotiation, and refinement of these representations in class and individual discussion; and
- Explicit discussion of the role of representation in learning and knowing.

Thus, the approach involves a continual back-and-forward between students producing representational responses in small group or individual tasks, and teacher led discussion, in the public arena of the classroom, leading to shared understandings of the appropriateness and efficacy of various representations, and their role. The aim is to build students' representational resources associated with key science concepts, in a way that is more open and epistemologically defensible than is normally the case with transmissive pedagogical approaches.

The representational challenges that are central to the approach are varied, and this variation will be explored in this chapter. However there are two key features of representational challenges that distinguish the approach from other student-focused approaches to school science. We see representational challenges as different to the types of tasks often undertaken that involve replication of ideas or processes in new situations. A representational challenge needs to involve some new coordination or

R. Tytler, V. Prain, P. Hubber and B. Waldrip (Eds.), Constructing Representations to Learn in Science, 51–66.

synthesis of existing representations – a fresh orchestration of elements. In this sense it will involve a claim concerning how a phenomenon should be represented and explained. The other feature is that it has the potential to individuate – the different representations will not converge upon one 'correct' account but will allow for individual variation in describing or explaining. Thus, these challenges align with problem solving/ investigative approaches that offer a variety of solutions. Unlike many open investigations, however, they serve a clearly defined conceptual agenda within the sequences.

Chapter 3 did not focus on the details of how these sequences are structured, how the approach might vary depending on the particular conceptual territory, or the particular purposes and character of the challenges and communal discussions. In working with the small number of teachers, we generated sequences in six conceptual areas – animals in the school-ground, water, energy (primary school sequences), and forces, substances, and astronomy (secondary school sequences). In this chapter we will draw on the video records and planning notes from these sequences to explore variations in the sequencing and purposes of the challenges and the classroom discussions, and the on-the-ground factors that drive these variations.

The aim of the chapter is primarily to lay out, in a practical way, how the pedagogy operates in different conceptual circumstances, as both an elucidation of the principles, and advice for teachers as to how to approach teaching and learning from this perspective.

THE SEQUENCES

Figure 4.1 is a representation of the sequences for the Year 5/6 water unit, for lessons 1, 3 and 5. Aspects of the water unit are discussed in some detail in Chapters 5 and 6. These are chosen to show variation in the structure. This form of representation of the approach emphasizes the movement back and forward between a) challenges – mainly representational but sometimes investigative – in which students generate representations/ideas, and b) class/group discussions led by the teacher in which these ideas are subjected to communal scrutiny. In an important sense, this movement between individual/small group, and communal processes, mirrors knowledge-building practices within science itself.

Each of these lessons shows a similar pattern of alternating challenge and class discussion, but the grain size of the movement between these varies, depending on the nature of the task and the amount of material dealt with in the discussion. In lesson 1 for instance, the discussion around how water might exist in the air was prolonged and included significant student input regarding their experience of humidity, leading to suggestions that water might exist as molecules in the air. Lesson 3 (described in detail in Chapter 5) is unusual for the fast pace with which representational challenges occurred, and the multiple representations used.

The class discussions serve a number of purposes; introducing the challenge for instance, or evaluating student work. The representation in Figure 4.1 does not

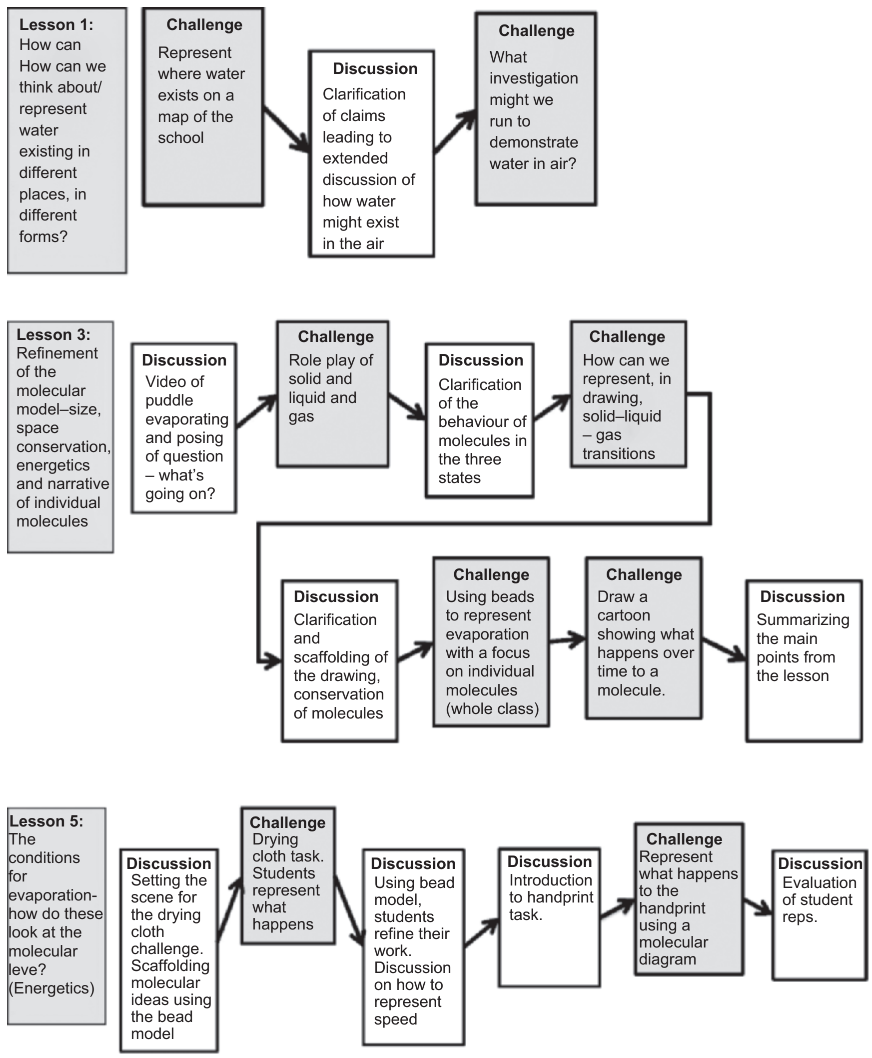


Figure 4.1. The structure of the learning sequences in Lessons 1, 3 and 5 of the water unit (Year 5/6).

include the actions of the teacher in moving round the room while students were working, challenging and scaffolding their work individually or in groups. This often led to brief interruptions to the lesson in which the teacher clarified or pointed out common errors. This monitoring helped in framing the whole class discussions that are represented here. The discussions were not purely verbal, but often included demonstrations (e.g. using the bead model in lesson 5) or the presentation of student work on the board, or teacher exemplifications of the representation. The discussions were thus important in advancing the representational work.

To further investigate the essential nature of the approach, we will explore other sequences in this manner, chosen to illustrate variation. In each case, the unit of analysis is more or less a lesson, but this almost always coincides with a reasonably self-contained idea. The first part of the forces sequence, for instance, consisted of 6 lessons (some 'double' lessons) each focusing on a distinct idea. Each of these ideas can be seen as a code for a set of representational practices, thus:

- What is force? – words for force, the force arrow convention.
- Gravity – how can we represent gravitational force? The distinction between mass and weight.
- Contact forces – how can we represent what is happening at a surface that is pushing up on an object?
- Addition of forces – how can we represent the combined action of forces acting in different directions?
- Force measurement – how can we construct and calibrate a force measurer?
- Friction – how can we represent what happens between two surfaces to impede motion?

Figure 4.2 shows the structure of lessons 1 and 4 of the forces sequence. In these sequences the pace of representation challenge is again quite different, as is the character of the challenge. In Lesson 1, which has been discussed in Chapter 3 and also reported elsewhere (Hubber et al. 2010), the focus of the sequence is to introduce the arrow convention as a key aspect of the discursive practices around force. The class discussions established the words used to talk about force, and the succession of challenges established the need for a convention that clearly communicated the process of molding the plasticine. For the teachers, this sequence was revelatory in that it presented the arrow convention as pragmatically conceived rather than an unproblematic representation of a 'truth' around forces.

This was a first step in their epistemological shift towards a more sociocultural framing of learning and knowing in science, which was important in shaping their management of discussions concerning the adequacy of different representations in describing or explaining aspects of phenomena.

Lesson 4 began with a discussion of students' pre-test responses regarding multiple force situations, and moved into a demonstration sequence in which the stretch of an elastic tape (of the type used for physiotherapy exercises) was used as an indicator of force size. The effect on objects was explored through a role-play with students pulling in different directions and situations. The representational challenge then involved students using these tapes to pull a heavy object at different angles, coordinating what they found with force diagrams representing force arrows in different orientations, and posing the question of how the net force effect related to these. Thus the challenge in this case was not the construction

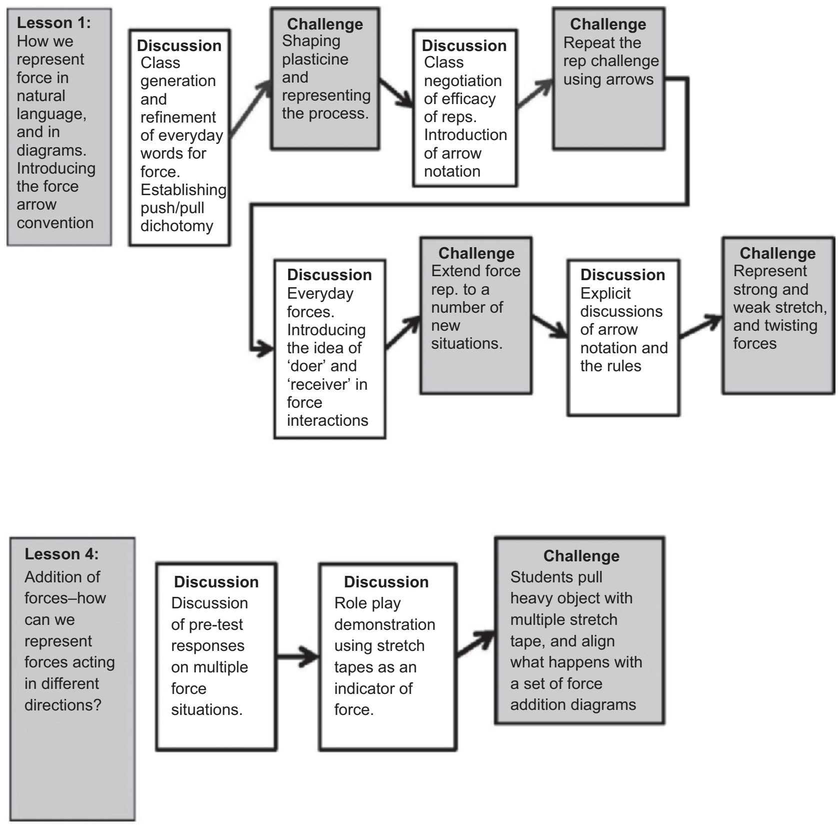


Figure 4.2. The structure of lessons 1 and 4 of the Year 8 forces sequence (Year 8).

of a new representation but rather the coordination / alignment of two existing representations.

In each of these sequences it is clear that the discussion involves significant representational work. In lesson 1, the teacher uses the communal discussion to generate verbal representations as everyday markers of force, gathering the different representations on the board, negotiating their adequacy, and introducing the arrow convention as a suggestion that was then taken up and successively refined. In lesson 4, the pre-test discussion involved representational moves by both teacher and students, and the role-play around the tape artefact introduced a substantial representational resource that was both kinesthetic and visual.

In the astronomy unit there is similar variation, but more sustained use of physical models, role-plays and animations. Figure 4.3 shows three of the 8 lessons in the astronomy sequence. In the introductory discussion the partial nature of the globe as

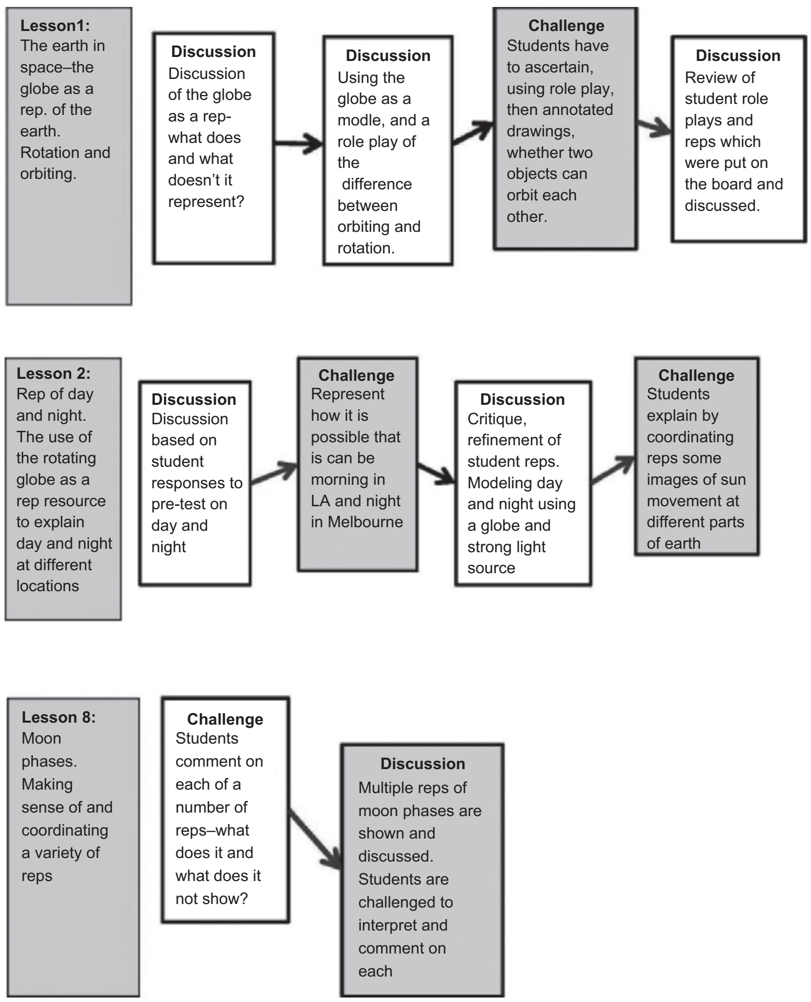


Figure 4.3. The structure of lessons 1, 2 and 8 in an astronomy sequence (Year 8).

a representation of the earth is discussed (see Chapter 7 for details of this sequence). Then a role-play is enacted to explain the relationship in space of the earth to the sun, and the important distinction between orbiting, and rotating. The representational challenge involves a role-play where students imaginatively extend this idea to speculate what two objects orbiting each other might look like. Students then re–represent their solutions in annotated drawings and some solutions are invited onto the board for class discussion. The second lesson starts with a discussion of prior ideas, then students are challenged, without significant scaffolding, to represent how it can be day and night on earth at the same time. Their representations are discussed, before the teacher models day and night with a globe and a strong beam of light. Students are invited and challenged to use this representation to answer questions about the path of the sun in the sky at various points on earth. Finally they are given images of sun movement against a horizon and asked to explain these in terms of the representations they had been introduced to. This was not a straightforward task.

The final lesson, on moon phases, was typical of a number of the astronomy sequences. Here, a range of representations of phases of the moon were presented to students, drawing on animations from the internet, and classic drawings of the lunar cycle pictured as from out in space 'above' the earth. The challenge in this case was dispersed within the introduction and discussion around these models, with students being asked to interpret them and comment on what they did or did not represent, and how they related to each other. This was the basis of a written challenge then set. This way of operating, where the teacher guided a discussion around active modeling which required students to recognize the aspects of each representation that were strongest, was also evident in the lesson structures around 'the seasons' and the 'zodiac' in which students enacted a complex role-play but were continually challenged to answer questions, and stopped to set up more complex situations to discuss (such as coordinating the moon as well as the earth-sun-star systems).

Figure 4.4 shows the structure of three lessons in the 'animals in the school-ground' sequence. Lesson 1 of the 2009 sequence involves observations of a stick insect and raises questions about the characteristics of living things. Lessons 2/3 of the 2007 sequence involved setting up and executing an exploration of a particular habitat. Lessons 6/7 in 2009 involved the setting of a modeling task for animal movement. The first lesson has a dual aim, in pursuing a discussion of the characteristics of living things, and in engaging with the challenge of representing animal movement, using multiple modes. The pattern here is similar to those we have seen in the other sequences. Lessons 2/3 involve a slower pace of discussion and representational challenge, in that the challenge involves a range of representations, including physical artefacts (quadrat) and digital microscopes, and the discussion is substantial. Teachers lead students to think about the relations between animals and a range of features of a habitat, what and how and why they might observe and measure, and the logic of sampling. The final poster presentation involves a multi modal display. The teachers' comments in the discussions cover a range of issues, and are not as explicitly focused as other discussions have been. In this sequence, the focus is more on data generation than on exemplifying an idea. Finally, the animal modeling task is rich and multi faceted, and the teachers have time to engage at some length and depth with individual groups as they perform preliminary sketches, gather materials, and coordinate their different representations of movement. The stories of two of these models are told in Chapter 1 (techno-worm) and Chapter 6 (centipede).

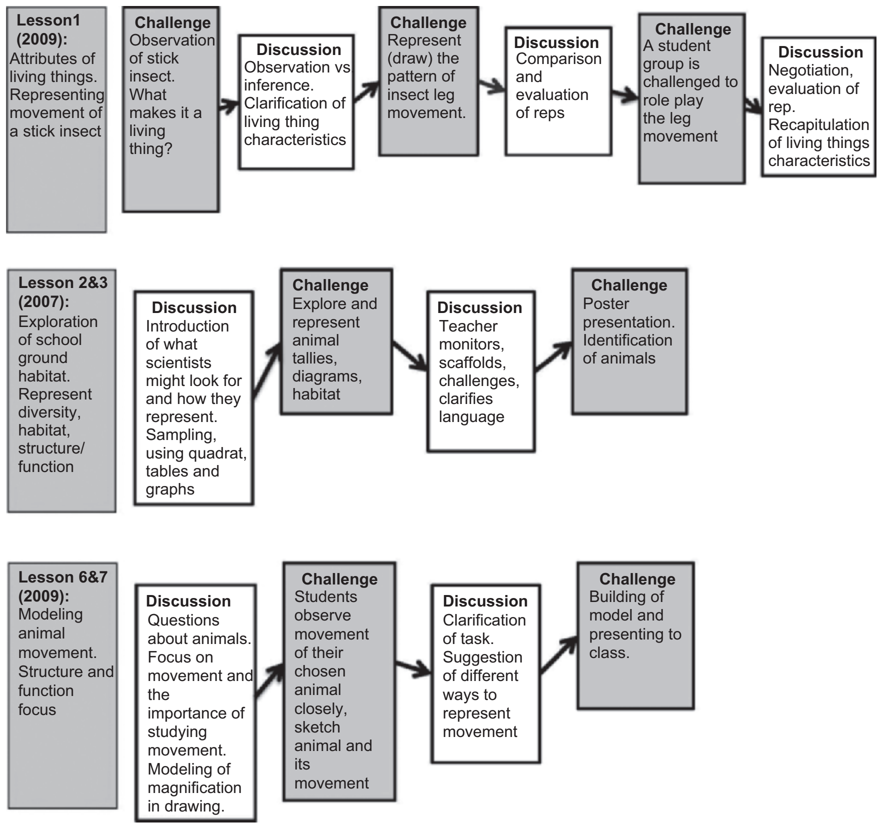


Figure 4.4. The structure of lessons 1, 2/3, and 6/7 of animals in the school-ground sequences (Grades 5/6).

DISCUSSION

These sequences of lessons are the practical expression of the pedagogical principles articulated in Chapter 3. Our intention in laying out details of these sequences is two fold: first, to provide a sense of the 'dance' between the representational challenges and communal classroom discussions that is the core of the approach, and second, to articulate the variation that occurs in this, across and within topics.

The Nature of the Sequences

It is clear from the sequences that there is wide variation in the pattern of challenges and communal discussions, in terms of the complexity of the sequence, the length of each phase, and the nature and specificity of the conceptual focus. In part this relates to where in the sequence the lesson sits. For the forces and the astronomy units, the first lesson involved a complex sequence of challenges in which students were introduced to the core representations underpinning the conceptual territory. In the case of forces, the focus was the arrow convention. In the case of astronomy, the focus was on the nature of physical models and the fundamental relations of earth and space. In the water sequence, Lesson 3 was the most complex lesson, involving the establishment of the core elements of the molecular model. In each of these cases, in later lessons the pace of challenges and discussion slowed down as students explored more elaborated representations of the conceptual territory such as details of the evaporative process, moon phases, or the nature of friction as a force.

The other aspect of these sequences that is noteworthy is that they are shaped by teachers' (and in this case researchers') imaginations in designing productive challenges for a given situation. They are in different degrees imaginative departures from established practice. Some of the lessons, and the representational challenges, are recognizable as incorporating standard 'text book' representations, such as the moon phase diagram or invertebrate drawings. However, in each of these cases the thrust of the challenge, and the associated discussion, focuses on assessing the efficacy and adequacy of the representation in performing its conceptual task. The discussions focus on representations as partial and 'fit for purpose', and on student meta-conceptual understandings of the role of representation in learning and knowing.

The sequences are not uniquely specified solutions to topic specific pedagogical problems, but are shaped by the conceptual context and the knowledge and imagination of the teachers. There will be other ways of coordinating representational challenges and discussion in these topics. One of our tasks, in subsequent research involving working with more teachers on further topics, has been to build a bank of productive challenge activities in a variety of conceptual areas.

Representational Challenge

As we described in the introduction to this chapter, a representational challenge comprises two key elements – it should involve a fresh coordination and synthesis of existing representational resources, rather than being simply replication and extension, and second that it admits of a divergence of solutions rather than being conceived of as a task leading to a predetermined, specific solution. An examination of the variety of representation challenges in these sequences makes it clear that they are quite diverse in nature. The challenges include, for instance:

- An open representation of processes of manipulating plasticine, leading to the use of the arrow representation (see Chapter 3);
- The imaginative representation of what happens at the surface of a table which exerts an upward force (see Chapter 3);

- A role-play exploring what it might mean for two astronomical bodies to orbit each other (see Chapter 7);
- Teacher questioning and student consideration of the partial, selective nature of different representations of moon phases and how they relate to each other;
- The building of an account of a habitat through a variety of representations of animal diversity, biotic and abiotic factors, and animal behavior (Chapter 6); and
- Interpretive molecular model drawings providing an explanatory account of various evaporative phenomena (Chapters 3 and 7).

In each of these, students are challenged to make a reasoned claim about the phenomena. In some cases, these claims concern how best to represent the phenomenon, such as the use of annotated diagrams and arrows to represent force. The reasoning in that case involved selecting and abstracting key features of the moves made in shaping the plasticine, and synthesis of these into a coherent narrative. In other cases such as the role-play of two astronomical bodies orbiting each other, the representations involved interpretation of the rotation and orbital representations and synthesis of these to explore a new possibility. In other cases, such as the upward force from a table, or the molecular model drawings, the representations involved the interpretation and synthesis of previously encountered representations into a coherent explanatory account. The key characteristic of all the challenges is that they went beyond demands for reproduction of known representations, requiring interpretation, synthesis and coordination of representations into new configurations. These are key linguistic markers of higher order thinking, and reasoning. The nature of this reasoning will be elaborated in Chapter 6.

The challenges vary in the extent to which they stand clear of communal classroom processes. In most cases they are group activities leading to individual representational production, and reporting back to the class, or at least to the teacher who circulates and scaffolds the production. In other cases the representation is a group production. In other cases again, the challenge takes place in the public space of the classroom, such as with the moon phase representations involving teacher questioning/ student discussion of how the different representations interrelate. In these cases the public discussion and assessment of adequacy of representations, and the representation production itself, are intertwined in time as representational ideas and judgments are co-constructed in the public space, and discussed and evaluated by the teacher and peers.

One of the voiced concerns with this representation construction approach is that student representations will be so varied that the task of refining them towards scientific conventions becomes impractical if not impossible. We can see from these cases, however, that the tasks are in each case carefully framed and managed so that students are focused in productive directions. Through prior representational work they are given the resources that enable them to productively select, appraise, coordinate and synthesise to construct effective representations of new phenomena. This prior work includes clarifying the nature of the problem and establishing a representational need, and introducing representational resources (force words, reminding students of the usefulness of graphs, introducing an 'anchoring analogy') that enable a productive focus in the challenge. The approach is not based on random, imaginative generation of ideas, but is focused in the same way that work in science is focused, making use of prior resources to imaginatively generate new representations to solve problems in context.

The Class Discussions

As with the challenges, the nature of the class discussions varied. A common approach was to have individual students or groups offer responses to the challenge, either verbally, on the whiteboard, or by displaying work they had done, and then compare, contrast and discuss the adequacy of each. In other cases, as described above, the discussion and the representation production were interleaved.

The length and complexity of the discussion varied considerably. Some of the discussions were quite short, dealing with a specific representational task. Some were longer and more complex, as with the discussion in lesson 1 of the water sequence, on the presence of water in the air, leading to particle suggestions subsequently taken up by the teachers.

Discussions preceded and introduced representational challenges, providing a context and the representational resources appropriate to the task, such as in the first lesson of the animals sequence. In discussions that followed and built on representational challenges, the teacher played an active role in questioning, shaping and assessing student representations. In most cases the challenge, and the discussion, was shaped explicitly to move students towards developing canonical resources, such as the arrow convention for force, bond representations for substance, or graphical representations of animal populations and diversity in a habitat. The representational conversations did not, however, converge on one 'true' outcome. The representations in all cases were framed as pragmatically effective solutions to a representational need that had been established leading to the challenge. This becomes clear if one looks at the variety of representational 'solutions' that are considered adequate and explanatory, in these classroom conversations.

This variation in student representations, distinct from the presumptions of convergence underpinning traditional science pedagogical practice, shows the approach to be profoundly generative of student reasoning and learning. It implies a rich invitation to participate in science knowledge building, and a deeper conception of science understandings built around a rich repertoire of physical and conceptual artefacts used to generate and clarify meaning. The communal nature of the classroom discussions is powerful for building shared understanding across individual differences. The process is not dissimilar to the communicative approach of Mortimer and Scott (2003), involving a movement between dialogic and authoritative discourse. In this case, however, the discourse is more widely conceived, with negotiation of multi-modal representations going beyond the original conception based around classroom talk. The process involves also a continual movement between individual, group, and public spaces.

Representational work underpins these public discussions at a fundamental level – they involve construction, negotiation and assessment of representations. They do not sit aside from the representational challenge as a process of advancement of ideas separate from the representational task. Even in lesson 1 of the water sequence the teacher and students negotiated verbal and analogic representations of water in the air. In the introductory force sequence the representational work was explicitly framed around assessments of the adequacy of different representational accounts. The discussions cannot be interpreted as focusing on essential, verbally expressed ideas that break clear of the representational work performed in the challenges. Rather, the discussions were concerned with representational refinement to enhance students' representational resources. They were thus brought closer to appreciating canonical science representations as effective responses to the task of making sense of the world.

Cazden (1981) made the point that performance always precedes competence, and we can see this clearly in these sequences. Students generate representations that are emergent, approximate and often speculative. They are being asked to perform before they are truly competent in generating the representation. The core feature of the approach – the public negotiation and refinement of representations towards canonical versions - utilises student representational performances and through these negotiative discussions moves them towards competence.

The Principles Underpinning the Approach

The discussion above has highlighted the variation in the nature of the representational challenge sequences and their relation to the whole class introduction / negotiation / refinement process. The variation reflects teacher judgments concerning the key representational resources needed for learning and reasoning in the topic. For the force sequence the arrow representation formed the basis of the initial sequence. For the substances topic, representing the bonding features pertinent to particular macroscopic properties was a key focus for the initial sequence. In astronomy, by contrast, the challenges involved the coordination of well established representations – diagrams, role-plays, physical models – that support understanding of astronomical spatial arrangements and movements and how these relate to perspectives from earth observers. In the case of exploration of a habitat, the resources that were focused on were sampling artefacts and other more generic representations including lists, tables and graphs.

In each case it was important to establish the representational resources needed to understand and work with the 'big ideas' of the topic, such the nature of forces, astronomical spatial relations, or the nature of the molecular model in relation to evaporation. The nature of the challenge sequence needed to establish and refine these resources varied by topic. For astronomy, where the models are specific and detailed and difficult to break down into simple component representations, the challenge did not require students to generate these ‘from scratch’ but rather to interpret and coordinate existing representations. Within a topic the representational challenges tended to move from complex sequences introducing the discursive elements of the scientific view (the initial sequences on force focusing on arrows, the third ‘water’ lesson moving through a variety of representations of the molecular model) to more simply structured sequences where students explored in more depth the interpretation, coordination and extension of these now established discursive elements.

Many of these later lessons consisted of an extended challenge task followed by extended discussion that involved negotiation and reworking of the constructed representations. These lessons were more complex at the individual teacher-student interaction level, as teachers moved round the classroom during the challenge phase, noting students’ work and scaffolding either one-to-one or with whole class comments and questions. In these lessons, the student resources being dealt with were often similar to those traditionally used in these topics, but they differed in the epistemological presumptions relating to their status (they are solutions to explanatory needs rather than scientific ‘truths’), in the nature of the task, requiring reasoning and claim making, and in the pedagogical stance required of the teacher.

As well as requiring clarity concerning the conceptual/representational underpinnings comprising the ‘key concepts’ of the topic, the approach requires more complex negotiating skills from teachers as they orchestrate the movement towards productive representational practices. The challenge for the teacher in interpreting and responding to student work is substantial, but the rewards are also considerable. The evidence from these sequences is that students are more engaged with science ideas, and that teachers achieve much greater insight into their understandings and learning needs. For the teachers also it is an educative journey as they are exposed to student thinking around a topic, and themselves engage productively with knowledge that is richer and more generative than is found with traditional pedagogies, given the fine grained representational variation evident in student work.

With regard to the choice of representations to focus on, part of the demand on teachers is to have a clear sense of the ‘fit-for-purpose’ of representations, including where these sit within larger explanatory models. All representational challenges are in some sense steps on the way to building more sophisticated representational resources, raising the question of what sort of representational competence is appropriate for the particular age level? Thus, the representational work in the primary school water unit focused on spatial arrangements of molecules and their speed, and to some extent on the energetics by which evaporation occurred. There was no attempt to tease out the nature of the molecules themselves, or the nature of bonding, but this work could be seen as an important step towards a longer-term engagement with molecular ideas. Judgments were made as to the appropriate level of dealing with the molecular model, for which representations are always selective, partial and approximate. We found, in our work, that teachers become more astute and achieved greater clarity concerning the essential elements of the representations needing to be focused on, and how best to scaffold student work, the second time they taught a topic (see the discussion in Chapter 7 on support of modeling). It is our expectation that as we research further into this approach, we can develop for teachers a sharper set of insights and advice on productive representational challenges for a variety of topics, and how best to manage these.

Explanation, Argumentation, and Knowledge Generation

We argue that student construction of representations that move further than reproduction, involving selection, coordination and synthesis of ideas, can be viewed as the reasoned production of claims about phenomena. For students, this is knowledge generation work, and can be seen, as with new knowledge generation in science, as involving a process of argumentation. The negotiation and refinement of representations, under the challenge of the teacher or fellow students, involves the alignment of representational moves with evidence, either in relation to the nature of phenomena, or to the self consistency and other values associated with meta representational judgments. Explanation, with this approach, mirrors the knowledge generation processes of science. As such, the distinction made by Osborne and Patterson (2011) between explanation as utilizing known science to deal with unproblematic aspects of the world, and argumentation as a problematizing process associated with the generation of new knowledge, can be seen to represent a continuum to the extent different degrees of justification are involved. For this teaching and learning approach the development of explanatory accounts will involve such evidential backing. We would argue, on the principle that effective learning in science should always involve students in knowledge production processes that in some way mirror the epistemic processes of science, that the development of explanation in school science classrooms must always involve to some extent the production of claims with justification.

Perceptual Mapping

One of the principles underpinning the approach is that learning needs to involve a representational/ perceptual mapping process. In looking at the range of representational challenges depicted in Figures 4.1 to 4.4, one can see that the idea of perceptual mapping does not always relate to real world phenomena, but can also include mapping against other representations. Thus, in the astronomy challenges, the perceptions that are mapped against representations relate to the models themselves. Role-plays are often the perceptual entities that are engaged with to generate further representations in a coordination process underpinning meaningful learning. In other cases the perceptual input involves real world objects and processes, such as animals in their habitat, or phenomena involving forces.

In Summary

The sequence structures depicted and analysed in this chapter illustrate the core nature of the representation construction approach, at the same time as demonstrating the variation in types of challenge and communal discussion around representational refinement. While the dialectic process of representation construction / communal negotiation and refinement, is a central feature of the approach, the nature of the challenges, of the discussion, and how they intertwine, varies depending on topic and the particular representational purposes.

The analysis has shown the way teachers move students towards canonical representations, through establishing representational need, and the strategic introduction of representational resources that are then extended and coordinated through the challenge. We have identified the particular challenges for teachers implied by this approach, and the corresponding rewards in student learning and teacher learning also.

In the next chapters we will first construct a theoretical account justifying why this approach leads to quality learning in science, and then extend our claim that this work inevitably involves higher order thinking and reasoning, and that this is centrally connected to quality learning. We will analyse the sense in which representation construction involves reasoning that is different to classic syllogistic reasoning moves.

VAUGHAN PRAIN & RUSSELL TYTLER

CHAPTER 5

LEARNING THROUGH THE AFFORDANCES OF REPRESENTATION CONSTRUCTION

In this chapter we draw upon several theoretical perspectives and past research into language and learning in science, to develop a framework to characterize how and why student engagement in representation construction practices supports learning in science. In developing this framework, we integrate literature on the role of symbolic tools in facilitating learning, and then focus in detail on the particular advantages of representation construction in learning in science. The chapter parallels an argument developed in more detail elsewhere (Prain & Tytler, 2012).

LEARNING THROUGH REPRESENTATION CONSTRUCTION

As argued in previous chapters, there is growing research interest in the value of students being guided to generate their own representations in science to support learning. This is evident in research on learning through drawing in science (Ainsworth, Prain & Tytler, 2011; Ainsworth, Musgrove & Galpin, 2007; Van Meter & Garner, 2005), studies of visual/spatial reasoning (Mathewson, 1999; Tversky, 2005), and templates developed to guide reasoning processes in inquiry (Keys, Hand, Prain & Collins, 1999). Our own research, described in Chapters 2 to 4 of this book, has indicated conceptual gains and high levels of student engagement with learning and reasoning arising from student-constructed representations (Waldrip, Prain & Carolan, 2010; Hubber, Tytler & Haslam, 2010; Hubber, 2010). In Chapters 1 and 3 we argued that there are strong justifications for this representational work.

The essence of this teaching and learning approach, in a process tracked in the earlier chapters of this book, involves teachers supporting students to construct representations of phenomena and refining these through coordinated public discussion of their explanatory adequacy. Students' representations are loosely scripted, and therefore in an important sense non-standard, or "approximations", but during the learning sequence students are led to understand and appreciate canonical scientific representations. We have argued that this approach brings classroom science closer to the knowledge-building practices of science itself.

R. Tytler, V. Prain, P. Hubber and B. Waldrip (Eds.), Constructing Representations to Learn in Science, 67–82.

As an example, we take the representational challenge activity described in Chapter 1, where students constructed a model of the movement of a chosen animal. Two students chose to represent the extension and retraction of an earthworm as it moved, using an abstracted model in which an elastic material was manipulated to quantitatively duplicate the earthworm's movement. Their account showed a complex weaving between observations of the animal, measurements, the drawing, and the model as they tested materials to provide a valid reconstruction of its movement. The core of our argument in this chapter is that in this case of understanding animal movement, each representational mode the students develop offers productive constraint in what they can draw and model as they attend to the demands of the task, the resources available, and the opportunities for observational checking of the animal. The students need to focus selectively on the details of the movement and the underpinning earthworm structures. In this and in other representational challenges students are supported to coordinate semiotic tools such as annotated drawings, physical models and graphs, and material tools such as quadrats or digital microscopes or rulers, to generate specific understandings of aspects of phenomena. Through this work, students engage with authentic scientific knowledge-building practices in developing representations to make claims and develop explanations. We argue, on the basis of our experience of these cases, that reasoning based on representational construction leads to quality learning, and in this chapter we explore just how and why this might be the case. At the heart of our argument is the idea that representational work productively constrains the focus of student meaning-making.

THEORIZING HOW MATERIAL AND SYMBOLIC TOOLS SUPPORT LEARNING IN SCIENCE

A major tradition in educational research over recent years has involved a focus on the role or roles of material and symbolic tools in supporting student learning. This research has been framed broadly within either cognitive or sociocultural accounts of interactions between learners, resources and contexts. Cognitive accounts focus on individual learners' mental strategies in engaging with these tools and ideas, while sociocultural accounts focus on the design features of these tools, and the nature of the practice in using them, that drives collective learning in the classroom. From cognitive perspectives, learners develop mental models, schemas, organizing strategies and frameworks to learn from interacting with these tools (Piaget, 1969; Bruner, 1966). From sociocultural perspectives, these tools are cultural resources, and learners need to participate in authentic activities with these tools to learn effectively (Cole & Wertsch, 1996; Vygotsky, 1978). Vygotsky's (1981b, p. 141) concept of "mediation" has been widely used to characterize the interplay between learners, tools, environment, guidance, and learning. He was particularly interested in the critical role of everyday language as a symbolic tool for learning the languages of science. He also acknowledged that other symbolic tools, such as algebra, writing, diagrams and "all sorts of conventional signs" (Vygotsky, 1981b, p. 137) were critical mediating tools for this learning.

The idea of mediation is our starting point for analysing current theories of the role and processes of symbolic representation in learning science. There is now broad agreement that school science students need to learn how to interpret and construct subject-specific representations of science concepts, methods, and processes. There is extensive research on what and how students learn from interpreting expert representations (Ainsworth, 2006, 2008; Gilbert, 2005), drawing on cognitive perspectives to provide theoretical justifications for why this learning is enabled (Ainsworth, 1999; Mayer, 2003; Paivio, 1986). However, there is a paucity of research into student-constructed representations, or theoretical justification for this approach. One reason for this is the view that the goal of induction into the literacies of science is achieved more efficiently through an explicit focus on conventions rather than through an open-ended constructive process. There are also concerns about the manageability for teachers in encouraging student constructions, particularly when students generate non-standard representations. Indeed, our research has indicated that a focus on student-generated representations makes significant demands on teachers' conceptual understandings and classroom time (Hubber, Tytler & Haslam, 2010).

In our argument we draw on literature dealing with student representational construction, (Bransford & Schwartz, 1999; Cox, 1999; diSessa, 2004; Greeno & Hall, 1997; Kozma, 2003; Kozma & Russell, 2005) and extensive analyses of the student representational work from our research over 7 years on teacher-guided, student-generated representations. From this pulling together of literature and our own experience, we have proposed a framework of Representation Construction Affordances (RCA) to explain how and why students learn from this work (Prain & Tytler, 2012). This framework interconnects three dimensions to explain how and why this representation construction work supports quality student learning. These dimensions are:

- The *semiotic* processes where learning is understood as students developing the capacity to recognize and use key features of generic and science-specific material and symbolic tools to interpret/explain phenomena;
- Meaning-making at the *epistemic* level, where knowledge building in science is understood as the use of a broad range of material and symbolic practices for undertaking and communicating science inquiry, and our argument that these practices should be strongly reflected in classrooms; and
- Meaning-making as an *epistemological* activity, where student reasoning and learning in science can be enhanced by the process of constructing and negotiating their own representations.

The RCA framework integrates these perspectives and resources by conceptualizing them as necessarily interdependent. However, in this chapter we only have space to sketch out the broad terms of our case. In our account, student-generated representations include oral and written language, and mono- and multi-modal texts, artefacts, and mathematical calculations. Specific examples include tables, diagrams, observational and conceptual drawings, graphs, annotated self-explanations, visual summaries, video productions, animations and 3D models. In the chapter we focus predominantly on drawing, as indicative of our case.

Previous accounts of the value of representation construction practice draw mainly on sociocultural perspectives, considering the potential for increased student engagement in a learning community (Greeno, 2009; Kozma & Russell, 2005). There is a lack of more varied and persuasive literature examining the value of this type of representational work. 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. They claimed that student construction of representations led to the development of problem-solving skills that could be applied in new contexts, arguing that in constructing their own representations students were productively constrained in their reasoning by having to focus on key aspects of the problem, select appropriate tools, and apply relevant background knowledge to the problem. The idea that the use of particular material tools productively constrains scientific inquiry is well-recognized (see Pickering, 1995), as is the productive constraint of symbolic tools and processes. Kozma (2003, p. 205) found that expert chemists, in manipulating representations, used the material features within and across different representations to "reason about their research and negotiate shared understandings", and argued that students could develop this capacity through teacher-guided use of interaction with expert representations. Kozma and Russell (2005, p. 129–30) argued that students learn science effectively when they participate in activities "in which representations are used in the formulation and evaluation of conjectures, examples, applications, hypotheses, evidence, conclusions, and arguments".

These general accounts of student learning gains from constructing representations highlight the need for a framework that recognizes the necessary interplay between student capacities and intentions and task and/or tool design features. They also highlight the key role of the learning context — the purposes and procedures of this representational work. However, these questions raise the issue of what particular student capacities are required or supported by this process and what particular supports might enable this work. In making this analysis we need to develop an account of learning in science, and how learning relates to representation production.

Gibson (1979, p. 5; 1986), seeking to move beyond a focus only on an individual's mental processes to explain perception, theorized that individuals interact with the physical environment in terms of "affordances" that support their goals or intentions. Individuals recognize a required potential action that the environment both prompts as well as supports. This account of affordances has been productively used in various domains, especially in computer program design, and problem solving. Seeking to further clarify this construct, Norman (1999, p. 39) considered that all affordances are "perceived" affordances, in that the enabling feature in the environment needs to be noticed to be enabling. He argued that affordances are best understood as physical enablers and constraints. Both Gibson and Norman were more concerned to explain purposeful perception rather than account for exploratory or learnt behaviour with symbolic or material cultural tools. However, we argue that this idea of affordances as enabling constraints can be applied productively to understanding how and why generating representations supports learning in science. We extend the idea of affordances as perceptual interactions with the environment to include learnt behaviours and strategies in the classroom. We argue that particular material and symbolic tools offer specific affordances for students constructing a representation to develop an explanatory account.

LEARNING THROUGH STUDENT-GENERATED REPRESENTATIONS

Our theoretical framework (RCA) integrates semiotic, epistemic, and epistemological perspectives to explain how and why representational construction supports learning in science (see Figure 5.1). In this nested Venn diagram, each dimension is linked by its focus on the way representations productively constrain meaning-making practices in science and in science education. Within each dimension there will be interplay of diverse cultural and cognitive resources students or scientists bring to achieving this meaning-making. The circles move from the general semiotic dimension, acknowledging the role of material and cultural artefacts in learning and knowing, to the particular epistemic processes through which public knowledge is generated and validated in the scientific or classroom community, to the dimension where reasoning through these resources generates individual or group meaning. Each circle indicates the cultural and cognitive resources, as well as the practices and processes that are involved in this work. The nested Venn diagram provides a window into our framework but we acknowledge the figure on its own may not adequately signal its complexity. The diagram is intended to suggest an indicative map. The arrangement of the diagram reflects our major focus on characterizing students' learning processes. If the focus was on science teams, a different representation may be more appropriate.

Semiotic Dimension

The largest circle focuses on the broad material and symbolic cultural tools available for meaning-making generally. These tools include generic as well as domain-specific resources. This characterization is consistent with recent cognitive science, and sociocultural perspectives regarding the centrality of language or languages in mediating learning (Tytler & Prain, 2010). Constructing a representation is constrained productively by its purpose, context, and the various physical and conventional resources available for any particular type of

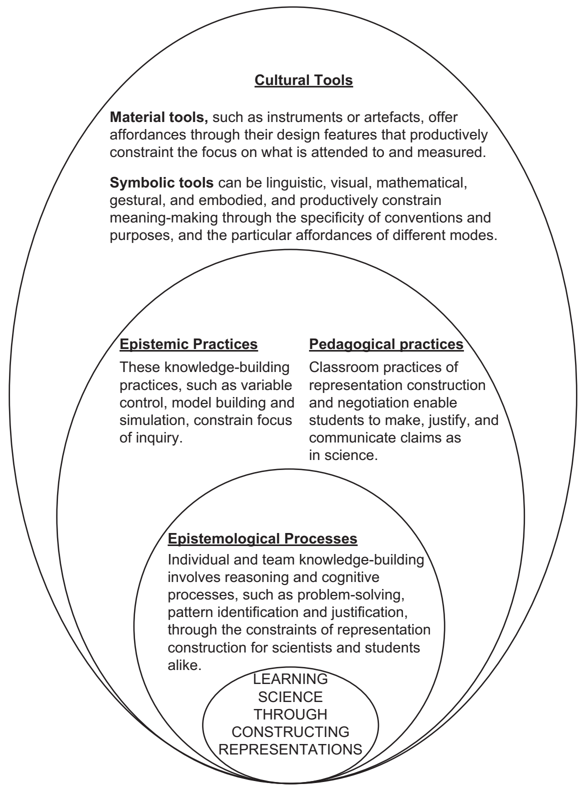


Figure 5.1. The RCA framework for interpreting the power of student representation construction. It consists of three interlocking dimensions: the semiotic, the epistemic and the epistemological.

representation. For instance, when making a drawing of a process, students are constrained by the physical space available, the conventions they can deploy, their form/function limitations, the need to achieve specificity of detail, and the requirement of unambiguous communication. A drawing is forced to be more spatially specific, for instance, than a verbal representation. Properly scaffolded, these constraints can serve to encourage students to engage with the succinctness and adequacy of conventions in constructing explanatory accounts. Trying to represent key features or causal factors in a dynamic system with pen and paper tools poses different challenges from using animation to achieve the same goal. The representation-maker is compelled to be specific in selection of details, to engage with issues of emphasis, layout, adequacy, and fit for purpose in ways that interpreting existing texts do not necessarily 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 a variety of representations, each bringing a complementary perspective.

Representational competence plays a crucial role in developing conceptual learning in science (e.g. Lemke, 2004; diSessa, 2004; Lehrer & Schauble, 2006a). This competence is about knowing how to interpret and construct links between an object, its representation, and its meaning (Lemke, 2003; Peirce, 1931–58). A representation becomes a sign when it signifies something (a key idea or explanation) about the object (or referent) to someone (the learner). Meaning-making practices in school science can be understood in terms of Peirce's (1931–58) triadic account of the components of this meaning-making. In this model, distinctions are made between a representation or sign (for example, arrows in diagrammatic accounts of force), the interpretation or sense made of this sign (the scientific idea of force), and its referent (the phenomena to which both the interpretation and signifier refer, such as the specific operation of force on objects in the world). This implies that for learners to understand or explain concepts in science, they must use their current cognitive and representational resources to learn new concepts at the same time as they are learning how to represent them. Learning concepts in science involves students switching between representational modes (verbal, written, visual and mathematical), and coordinating these to generate explanations. There is a growing recognition that students need to acquire competence in these discursive science practices to achieve science literacy (diSessa, 2004; Gilbert, 2005; Kozma & Russell, 2005; Lemke, 2004). Our own research on student-generated representations (Waldrip, Prain & Carolan, 2010; Hubber, Tytler & Haslam, 2010; Tytler, Haslam, Prain & Hubber, 2009; Tytler & Prain, 2010), and research by others in this area (Cox, 1999; diSessa, 2004; Ford & Forman, 2006; Greeno & Hall, 1997; Lehrer & Schauble, 2006a) suggests that this representational work has the potential to increase students' understanding of the form/function relationships in various representations, enabling students to understand the value and use of conventions in this work.

Epistemic Dimension

The "epistemic practices" circle focuses on the knowledge building and validating and checking processes, as well as communicating practices, that constitute the discipline of science and its literacies (Ford & Forman, 2006; Moje, 2007). There is a growing literature on the role of representation, including visualization, as central to knowledge production practices in science. A considerable body of research confirms the central role of representation in generating, integrating and justifying ideas in historical scientific developments, and thus in contributing to knowledge production. In Chapter 1 we discussed Gooding's (2004, p. 15) highlighting of the central role of representational refinement and improvisation in his account of Faraday's work on conceptualizing the interaction of electricity, magnetism and motion, and Latour's (1999) account of the process by which data is transformed into theory through a series of representational "passes". Nersessian (2008, p. 69), in examining cases of innovation in science using case 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. On the basis of analysis of idea generation in a contemporary scientific laboratory, she supported Hutchins' (1995) notion that 'cognition' and 'culture' should be seen as interrelated in scientific processes, and that problem-solving in scientific and engineering domains should be viewed 'as occurring within complex *cognitive-cultural systems*' (p. 71).

There is growing agreement that classroom practices in science should be organized to practice these representation construction processes to provide an 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 a product focus has been in the ascendency, largely treated separately, and conceptualized as distinct. For instance, 'working scientifically' strands tend to address measurement in science, the nature of investigable questions, and such issues as appropriate design built on levels of sophistication of variables control, without strongly linking these to knowledge generation. The argumentation perspective 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 public justificatory processes through which scientists can claim their work as verified against possible alternative findings, but do not adequately represent the situated, successive cuts and thrusts of data generation and representation that characterize on-the-ground knowledge building and verification. There is need for learning in science classrooms to focus on the processes by which communal knowledge is built, as well as the means by which this knowledge is defended and established.

To adequately capture in classrooms the scientific generation of knowledge, there is a need to foreground representational generation, coordination and transformation rather than mainly focusing on formal aspects of argumentation and 'scientific method'. 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. Student representation construction, in our view, is an approach that enacts new and fresh pedagogies consistent with these recent understandings of the relationships between process, product and language in learning science.

Epistemological Dimension

The "epistemological processes" dimension indicates the diverse range of cognitive processes entailed in reasoning with and through representation construction at an individual or group level. There is growing acceptance that the representational tools of science are crucial resources for speculating, reasoning, constructing and contesting explanations, theory-building, and communicating. For Nersessian (2008, p. 77–78) model-based reasoning by scientists is enabled through the explicit, productive constraints that operate in the way knowledge is represented. These constraints also enable reasoning processes, including making abstractions (limiting the case, or making generalizations), using simulations, evaluating particular cases (identifying the degree of fit, the explanatory power of a case), and judging the coherence of a claim.

This construction and justificatory work can serve a very wide range of reasoning moves and cognitive purposes. 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. Students need to learn how to select or develop appropriate representations to address particular needs, and be able to judge their adequacy for purpose. 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 (such as argumentation) do not.

A strong cognitivist tradition in science education has led to concepts and representations being viewed as separable from one another, with representations held to be subordinate approximations or accompanying pictures of concepts that exist independent of, and prior to, any particular representational instantiation. However, any attempt we might make to explicate a concept in science makes it apparent that the concept can be understood and applied only through a range of associated representational practices and conventions. Thus, to understand chemical bonding requires familiarity with conventions of molecular representation, bonds, and electron energy and orbital representations. To use this concept to develop an interpretation or explanation in any particular context requires flexible coordination of these representations, possibly together with the generation of a range of non-canonical representations such as gestures, annotations and verbal descriptions.

Lemke (2004) and others have noted that although the same idea in science can be represented variously, no shared scientific idea exists separate from its representation. Any explanatory account of ideas in science can only be communicated in different or new representations. Thus, the production of shared scientific meanings and reasoning cannot transcend representations, together with their productive constraints. Meanings in science are always represented meanings. As noted by Kozma and Russell (2005, p. 129), "the meaning of a representation is not embedded in the representation itself but is assigned to the representation through its use in practice". We have argued elsewhere (Tytler & Prain, 2010) that this insight tends to recast conceptual learning in science as fundamentally about the coordination and facilitation of different, multi-modal representations. This implies that 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.

A LESSON ON EVAPORATION: ILLUSTRATING THE RCA FRAMEWORK

To explore the ways in which representational challenges can open up reasoning and learning opportunities, through this notion of productive constraint, we will describe the interactions in a lesson from the Grade 5/6 (age 10/11) water sequence involving a series of representational challenges designed to establish a molecular model of the process of evaporation. This analysis has been previously presented in some detail (Prain & Tytler, 2012). The lesson description below summarizes the events in the third lesson in a sequence of seven, on evaporation. Each lesson posed a challenge for students to explore and represent, based on molecular ideas. Prior to this third lesson students had been challenged to explore and represent a variety of places in the school where water is found, in different forms. In the lesson described below, the molecular representation is introduced and refined, after the idea of molecules was introduced by students and discussed in the previous lesson. This aspect of the sequence is discussed in more detail in Chapter 6. The description is structured to show the different representations that are introduced and used at each point, key teacher moves that are made (in brief), and sample student responses and representational moves.

A Sequence of Multi-Modal Representational Challenges

Representation	*Teacher moves, student actions*
Video of puddle evaporating.	T1 summarizes video issue concerning energy required to evaporate the puddle. There is a brief discussion leading to the question: *What is actually going on?*
Role-play	T1: You are all water molecules. I want you to imagine you are water molecules, in the solid state, I want you to move to show me what you would look like. Students discuss movement: *No, each one sort of moves* – [pushes the other student and moves to and fro]
Teacher uses jiggling body to emphasise movement.	T2: They [students] are moving, is that correct? Do molecules in a solid state move? T1: Yes they move.
Use of role-play to have students simulate solid, liquid, gas	T2 leads question-response discussion where he establishes the greater movement in liquids (students model a liquid compared to solid) and increased spacing for gas: *Gas! Show me!* Students move away from group members, scattering around the hall. All continue vibrating
Drawing challenge: show solids liquids, gases.	T2: Have you shown what is the difference between solid water molecules, liquid water molecules, and gaseous water molecules? Did you show that difference**?** You have bodily moved, very well … how would you indicate that in a diagram? Students draw molecules in the solid, liquid and gas states (Figure 5.2)

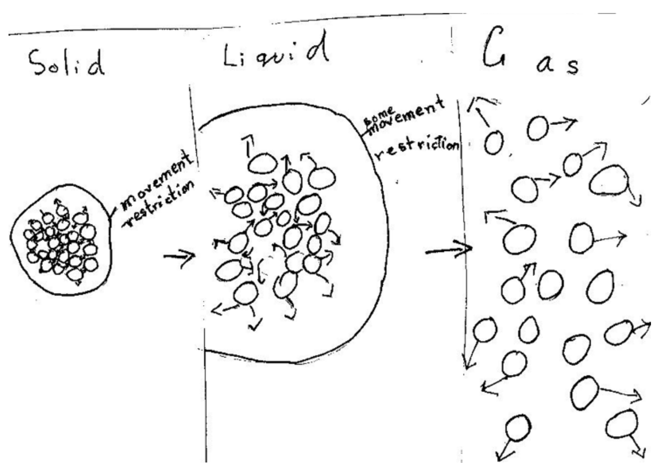


Figure 5.2. Student drawing of molecules in the solid, liquid and gas states.

Representation	*Teacher moves, student actions*
Teacher uses beads now to model a focus on individual molecules responding to an energy source – vibrates them – some spill.	T1: Come back again to that gas molecule …when we had that heat source, that energy coming in is this what happens? A student comes to the container, picks up a bead and moves his hand in a haphazard motion above the head. T1 challenges this by demonstrating dispersal by shaking beads out –models randomness of distribution T1: Which molecules are the first ones to go? Students: Top ones … Ones that had started moving faster … More heated ones … Ones that get more energy
Bead demonstration	T1: In your diagram, there may be need to show a three dimensional diagram or a series of diagrams, think about not just two-dimensional. T1: Okay let us give these molecules, beads, a human form [picks up a bead and points to it]. Here is George, he is here vibrating in water as a solid, then there is more energy he moves more in a liquid state, and then here is Molly …
Drawing challenge T1 models storied drawing on board	T1: Tell me a story about one water molecule, about what happens to it. Let's do it in four frames. Remember, label, say why is he here, what does he actually need? Students work on their diagram narrative (Figure 5.3)

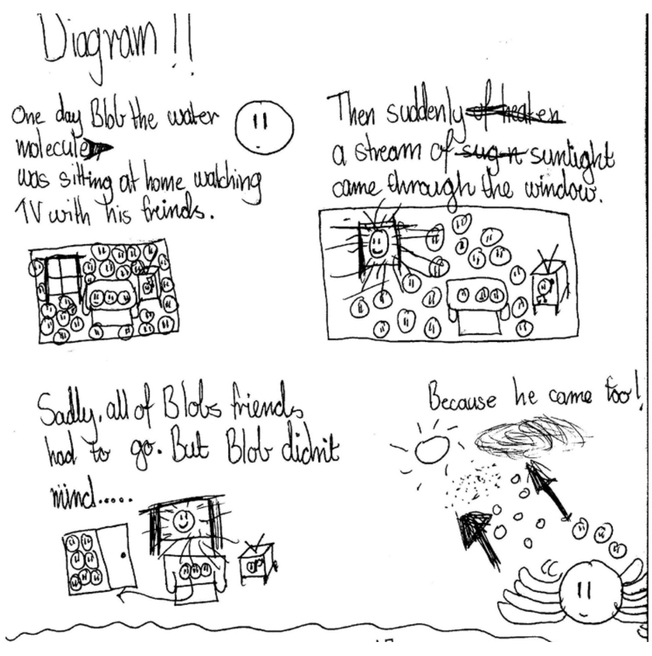


Figure 5.3. A student narrative diagram showing an individual molecule.

The lesson begins with a video presentation of evaporation. The teacher's question 'what is actually going on?'(Move 1) is used to introduce the notion of molecules through a role-play. The teachers (T1, a male, and T2, a female, are co-teaching a composite Grade 5/6 class of 50 children) then use 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 verbal review of the key features of the molecular model.

Features of the sequence illustrate the ways in which representations are critical to learning, reasoning and knowing in science, and the way these relate to the RCA framework of Figure 5.1.

Semiotic dimension: The centrality of semiotic resources, represented in the larger circle of the RCA model, is clearly displayed in the way symbolic and material resources are woven to develop an increasingly complete picture of molecular interpretations of evaporation.

Epistemic dimension: The harnessing of representational resources to make claims and support these in a public process of evaluation and refinement mirrors the epistemic practices of science. The teacher guides the class in extending and exploring different modal representations to model evaporation in a range of contexts.

Epistemological dimension: Students come to know in science through the negotiation and refinement of multi-modal representations, and the integration of these with phenomena, to build personal meaning.

The specific purposes of each representation can be seen to match the affordances it offers. In the analysis we can identify enabling constraint as a productive characteristic of each representational resource – each representation constrains what is focused on and what can be imagined about the process of evaporation. For instance the role-play (moves 2–4) gives a strong embodied sense of the movement of molecules. It focuses attention on spacing and movement by placing constraints on molecular size. 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), when the group of students was confronted with the question of whether they should remain still or move. Their decision to move could be seen as a case of speculative reasoning, perhaps grounded in the embodied nature of the task. In this case as with all these representational challenges, students are driven by the role-play to discern and integrate different aspects 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. They are required to make choices and coordinate and discern the possibilities and challenges posed by the representation. In the drawings (move 5) the visual / spatial choices encouraged students to think about spacing, number, size, and speed, and how to represent these.

In move 7 the bead model acts as both a material tool and a semiotic tool. Insofar as it is introduced by the teacher it is a semiotic tool to be interpreted, but in asking the student to come forward and demonstrate what happens to an individual molecule responding to energy, that student becomes a representation-maker utilizing the material beads. The student is challenged to sort out the possibilities of the representation while enforcing a consistency with what has come before with the role-play. The focus has moved from macro to micro, involving the construction a new explanatory account requiring new representational coordination. The subsequent comment and counter-demonstration by the teacher along with questions about the order in which molecules 'go', constrains thinking by focusing the task on individual molecular-energy interactions. The narrative drawing constrains and focuses attention on the ongoing history of a molecule that is neither created nor destroyed. A key productive constraint of the molecular model is its natural adherence to conservation of matter. The time sequence drawing of the states of matter in move 8 constrains the way the different states can be imagined by forcing attention on coordination of properties (number, size, spacing and arrangement, movement) across the states.

DISCUSSION

In this chapter, and throughout this book, we have argued that there are particular learning gains for students when they construct, negotiate, refine and justify their own representations of scientific processes and concepts. These processes enable students to:

- learn conceptual knowledge through enacting the epistemological practices of the science community, experiencing the challenges of explaining and justifying scientific causal explanations through representations (such as drawings and models);
- learn the nature of scientific inquiry through participating in knowledge-production practices as an authentic induction into those broader practices through which scientists construct representations to generate and justify knowledge claims; and
- learn the literacies of science and their rationale, acknowledging the semiotic aspects of knowledge and communication in science. For us, communication is not simply the final stage in a process after mental work, but rather part of the process of developing representations to produce explanatory/ interpretive accounts, first for the self, then for others.

Our framework conceptualizes these semiotic, epistemic, and epistemological practices and resources as overlapping and intersecting through guided student representation construction work. In this way we seek to explain why this representational practice engenders quality learning.

As discussed in Chapter 1, our theoretical framework is distinct from current socio-semiotic accounts of learning in science (e.g. Martin, 1993; Unsworth, 2001; Veel, 1996). We advocate open-ended exploratory student representation construction rather than highlight directed teaching practices, and identify particular affordances, or productive constraints, entailed in representation construction. The semiotic resources, epistemic practices, and epistemological processes in our model are conceptualized in Vygotskyan terms as external cultural resources that learners draw on as they represent/develop their understandings. Learners are cast in the model as active interrogators of their own representations, and their growing command of these resources involves perceiving opportunities for new connections, imaginative syntheses, and unpredictable solutions.

To explain our experience of significant, quality learning in the water and other units in the RILS project, and the apparent capacity of students to transfer learning to new situations, we draw on the ideas of Schwartz and Bransford (1998) who argued that the learning advantage afforded by active generation of representation comes from students practising discernment of the features and structures of the 'problem space'. That is, that in grappling with the need to represent to interpret and explain phenomena, students come to differentiate key aspects and possible points of attack. Thus, in generating and negotiating different aspects of drawings and role-play representations of evaporation, students' attention was drawn, to some extent systematically, to critical features of the molecular model such as size, distribution and speed, spacing, interaction with energy and with each other, and conservation, and to the relation of these with evaporative phenomena. The alternative conceptions literature has identified all these as representing significant conceptual difficulties for students. We now see them more clearly as representational in nature. In Schwartz and Bransford's terms, this process of exploration supports discernment of both the relevant features of evaporation that need explanation, and the relevant features of the representations needed to make sense of evaporative processes.

It is interesting to compare the representation production work of students in the evaporation lesson described above with Kozma and Russell's (1997) 'curriculum of core representational competence'. This was developed, based on a comparison of expert and novice use of representations to solve problems in chemistry. They identified, as characteristics of this competence:

- The ability to identify and analyze features of a particular representation and patterns of features and use them as evidence to support claims or to explain, draw inferences, and make predictions;
- The ability to transform one representation into another, to map features of one onto those of another, and to explain the relationship;
- The ability to generate or select an appropriate representation or set of representations to explain or warrant claims;
- The ability to explain why a particular representation or set of representations is more appropriate for a particular purpose than alternative representations; and
- The ability to describe how different representations might say the same thing in different ways and how one representation might say something that cannot be said with another.

While these were based on adult chemistry expertise, all these features were arguably present to some degree in the primary school evaporation sequence, and in RILS classrooms more generally. We suggest that students, in generating and then assessing the adequacy of a range of interacting representations of water molecules in evaporative situations, were engaged in precisely the sort of flexible representational moves that draw on the particular affordances and constraints of representations, that allow high level problem solving in science.

In this book we focus on the practice of constructing representations across a range of contexts, levels and topics to support student engagement and learning in science. We have proposed in this chapter, and elsewhere (Prain & Tytler, 2012), a framework intended to make sense of why representational construction within a guided inquiry framework offers particular affordances for student learning of both the concepts of science and of scientific knowledge-building practices. The framework integrates epistemic, epistemological and semiotic perspectives to propose new insights into the nature of quality learning in science. In so doing, we propose and justify an approach to teaching and learning in science classrooms that enacts the knowledge production practices of the discipline. We believe this framework provides further insights into the Vygotskyan notion of mediation of cultural tools in learning domain-specific knowledge and practices.

RUSSELL TYTLER, VAUGHAN PRAIN, PETER HUBBER &
FILOCHA HASLAM

CHAPTER 6

REASONING IN SCIENCE THROUGH REPRESENTATION

In this chapter we argue that our analysis of student reasoning through constructing representations points to a range of informal and formal reasoning processes. This suggests the need for researchers and teachers to shift from an exclusive focus on formal syllogistic reasoning as the main or only reasoning resource for science learning. First we review the literature to identify how informal reasoning is described, and relates to reasoning through representation, then examine one case of reasoning during a representational challenge, to argue that reasoning should be thought of as *deliberative thinking that involves choices, leading to a justifiable claim*. Two case studies from RILS units are then used to identify how reasoning through representation can occur at a number of points during a representational challenge, and finally to develop an indicative taxonomy of the different purposes of reasoning as part of the processes of science.

ACCOUNTS OF REASONING IN THE LITERATURE

There has been increasing interest in reasoning in science classrooms as part of moves to promote higher order thinking and 21st Century skills as desirable outcomes of a school education. These skills tend to be characterized by a set of commonly used terms that are often also associated with reasoning. The TIMSS (Trends in International Mathematics and Science Study) characterizes 'reasoning' questions as involving the following processes: analyse/solve problems, integrate/synthesise, hypothesise/predict, design/plan, draw conclusions, generalize, evaluate, justify (TIMSS, 2007). These are broad terms, but useful in mapping the territory. They leave untouched, however, the question of the relative importance to these processes, in science, of formal, and informal modes of reasoning.

In this chapter we argue for an expanded view of reasoning in science beyond the formal, linguistic-based reasoning that tends to dominate research in the area, and the framing of pedagogy, to include a range of informal reasoning modes. We analyse students' thinking associated with representation construction to show how

R. Tytler, V. Prain, P. Hubber and B. Waldrip (Eds.), Constructing Representations to Learn in Science, 83–108.

quality reasoning arises from addressing representational challenges in a number of ways. We examine cases of student reasoning to identify different reasoning processes associated with representation construction. Our concern is to define the characteristics of a pedagogically rich environment that will maximize students' representational resources for reasoning in school science.

Reasoning in science has traditionally been construed as involving relations between ideas and evidence and the ways these are coordinated. Thus, studies in the psychological tradition have been concerned with developmental aspects of the recognition and coordination of ideas with evidence in formal co-variation situations (Koslowski, 1996), and the capacity of children to make this idea-evidence distinction (Sodian, Zaitchik & Carey, 1991). In science education, growth in reasoning capability has been associated with the level of sophistication of epistemological positions (Driver, Leach, Millar, & Scott, 1996; Tytler & Peterson, 2003; 2005). More recently there has been interest in argumentation in school science, as a representation of the core process by which conceptual claims are established in science itself (Osborne, 2010; Simon, Erduran & Osborne, 2006). These perspectives have underpinned analyses of reasoning in classrooms (Furtak, Hardy, & Beinbrech, 2010). In these cognitive traditions, reasoning has largely been characterized in terms of formal, syllogistic reasoning processes (deductive, inductive, abductive) that involve logics based on linguistic entities. This view draws strength from reference to the processes by which ideas in science are justified and debated, and the formal structures of scientific papers. This perspective is also apparently supported by the cognitive literature on decision-making as a two-step process (Mercier & Sperber, 2011), where the first stage of imagining and representing solutions is seen as automated, intuitive, and based on past knowledge and personal preferences, whereas the second phase of assessment/judgment is viewed as analytical, linguistic and evidence-based, and hence more aligned with the formal logical processes outlined in the science education literature on reasoning.

However, we question whether these formal logical processes adequately capture the reasoning processes that underpin quality learning in science, or indeed the reasoning inherent in the epistemic processes of science itself. On the first point, we have argued (Tytler & Prain 2010; Prain & Tytler, 2012) that informal reasoning processes have an important role to play in students' learning of science, particularly highlighting the role of perception, and the central role of language, through metaphor and representation, in deliberative reasoning processes (see also Klein 2006). On the second point, we draw on a tradition of scholarship in studies of scientific reasoning, to argue that in science, informal modes of reasoning are critically important in idea generation and negotiation, associated with the imaginative creation of new modes of representation.

Recent Cognitive Science Accounts of Reasoning and Learning in Science

Recent work in cognitive science has questioned many assumptions about the nature and processes of cognition. Many cognitive scientists have argued that the brain, rather that being a logical sorter of clearly defined data sets, is a highly flexible adaptor to multiple inputs, using many highly contextual and provisional perceptual cues to build understanding in an informal way. Cognitive scientists such as Barsalou (1999, 2003) view thinking and learning as perceptual processing and analogical mapping. Rather than use logical inferential processes to explain new phenomena, learners often use pattern completion based on perceptual recognition and simulation.

Traditional cognitive science tends to view thinking as primarily the logical manipulation of clearly defined symbols, where science explanations are deduced from causal laws applied to particular conditions and events. Knowledge is understood as stored, stable mental constructs, and language, or any other kind of representation, is understood as denoting propositional understandings, thereby functioning as an accompanying picture or "a by-product of thought" (Klein, 2006, p. 149). From more recent perspectives, language, more generally understood as representation, is central to framing thought. This view aligns with sociocultural interpretations of learning and knowing that form the basis of the representation construction approach. In this chapter we will examine this issue closely through analysis of student reasoning through representation construction.

Reif and Larkin (1991, p. 745) critiqued calls to focus on informal reasoning, arguing that the reliance of everyday processes on contextual, informal, associative reasoning and rich local knowledge, rendered them inadequate for learning science, where students are expected to acquire skills in sustained inferential reasoning and abstract manipulation of formal symbols. From this perspective, it might seem that contemporary cognitive scientists have simply given prominence to the "naïve" cognitive processes learners use in their everyday world. However, Reif and Larkin (1991) also noted that effective learning in science is achieved by using both formal and informal reasoning in "complementary ways" (p. 750). In previous work we have argued (Tytler & Prain, 2010), on the basis of longitudinal data on children's explanatory ideas, that perception, language and representation are key constituents of reasoning and learning in science.

In this chapter we present two case studies of representation construction sequences to further explore students' reasoning through representation, to flesh out in more detail how we might think of the different types of reasoning that occur during a unit, how modal affordances operate to shape and support reasoning, and how reasoning through representation construction involves processes that are not adequately captured by formal, syllogistic accounts. We will also explore how the context of the representational challenge can open up a variety of both informal and formal reasoning processes. Part of our aim is to develop an indicative list of reasoning processes that will inform pedagogical thinking.

In undertaking this analysis, we view reasoning largely through a Deweyan/Peircian, pragmatist perspective of applied problem-solving. We use examples of students' working and thinking to establish the close relationship between representations, their referents, and constructed meaning. Through these, reasoning is related to the Peircian triad of meaning making. Our position is that reasoning and knowledge production in science is associated with the fundamentally contextual, use in action of the discursive tools of science, in response to demands of problem-solving and the construction of explanatory accounts. This is the basis for our analysis of two cases, both involving sequences in the primary school.

Informal Reasoning in the Knowledge Production Processes of Science

In Chapter 1 we referred to a growing literature on the role of representation, especially visual representation, as central to generating, coordinating and justifying ideas in scientific knowledge building processes. Gooding's (2004) account of Faraday's notebook work, described in Chapter 1, suggests a strong case that Faraday's development and modification of representations were critical to clarifying and instantiating his theoretical understandings and were part of informal reasoning processes by which new ideas were created. In characterizing the reasoning processes of scientific knowledge building through dimensional shifts in representation, Gooding (2004) described the process of dimensional enhancement and reduction as an inferential process 'whose cognitive character remains opaque' (p. 19). Latour's (1999) analysis of the process by which data is transformed through a series of representational "passes" to build knowledge (see Chapter 1) calls into question the possibility of a sharp and simple delineation between scientific product and the process through which it is developed, such that formal logical processes of justification of claims ultimately are subject to the contingencies of representational transformation processes. Clement (2008) in an analysis of expert problem solving in physics, identified a range of reasoning processes that he characterized as non-formal, used to tackle non-standard problems. These included speculative modeling, analogy, and thought experiments, often in quick succession and in some cases with impressive fluidity.

Thus, we argue that the traditional characterization of reasoning in science as exclusively syllogistic and linguistic in character speaks to those aspects of knowledge building practices that have to do with communal verification and justification of theory, more so than the generative process whereby new knowledge is imaginatively conceived and tested in a complex, grounded evidential trail. We suspect that even with this formal verification process there are more complex logics operating, in conceiving of the intimate connection between theory and evidence, and claims. There is also a place for formal logical thinking within the idea generation process. If we are to more faithfully represent the epistemic practices of science in our classrooms, then these studies such as those of Clement (2008), or Gooding (2004), highlight the need to better capture these informal aspects of reasoning in science. In this chapter we will focus particularly on the role of representation in reasoning about science phenomena, to broaden our perspective on what quality thinking in science looks like.

CHARACTERIZING REASONING

How do we characterize reasoning, in a way that includes but expands on formal reasoning processes? To guide our thinking we examine two cases – construction of a model of the movement of a centipede, and evaporative sequence examples selectively discussed in Chapter 5 – to unpack where reasoning could be said to occur, and how it looks from a pragmatist semiotic perspective of problem-solving in action.

In the centipede construction example, two boys observed centipede movement closely and constructed a jointed model with elastic connections, which enabled them to capture the undulating movement of the animal. As with all representation challenges, this problem is clearly non-routine, challenging students to extend their representational resources to problem-solve. The 3D model demonstrated a close awareness of the nature of the jointed body and the sequence in which the legs moved. Figure 6.1 shows a series of drawings made by Jesse and Paul, of the arrangement of legs on their centipede, along with a close up of the animal cleaning its antenna with its mouthparts. These observations were later reflected in the constructed model, and in the verbal descriptions the boys made to the class.

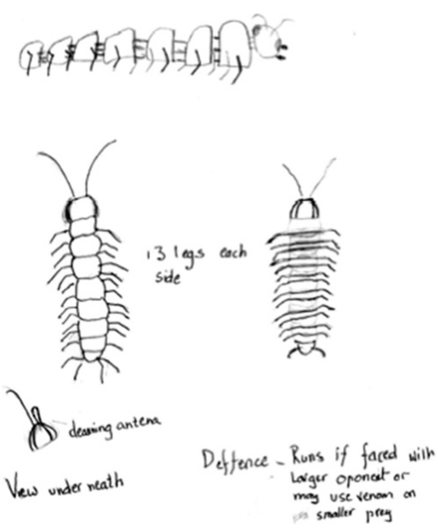


Figure 6.1. Centipede notebook entry.

But what is the nature of the reasoning that occurs during the model construction? In considering the processes by which the boys gained insight into the centipede movement, we would draw attention to:

1. The ways their talk, sketches, and decisions on model design worked together to support them organize their perceptions to ascertain just how the legs and body moved. The construction of drawings involved the analysis of centipede parts and selection of elements important to movement, and abstraction and synthesis of the many details of the centipede's anatomy, in much the same way as Gooding's (2004) description of dimensional reduction (to 2D) and abstraction as the first step in an imaginative visual reasoning process leading to scientific innovation.

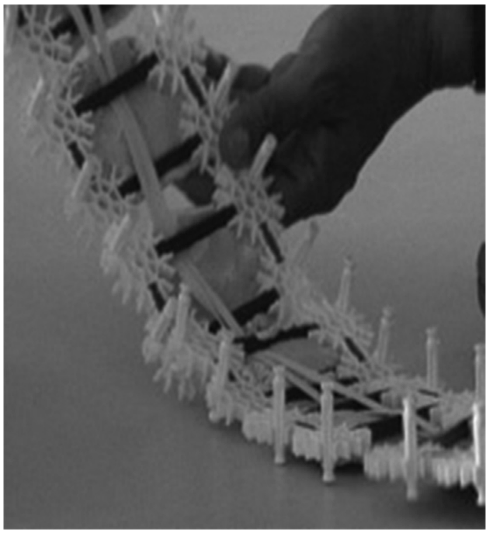


Figure 6.2. Centipede model showing elastic attachment of segments.

2. The way their deepening understanding is built through successive transformations across representations, from labeled drawing, talk, design drawing focusing on the nature of joints, model construction, and embodied characterization, each of which involves analysis and selection and a focusing of attention, and a synthesized abstraction of pertinent features.
3. The specific affordances of the different representation tasks, in constraining and selectively focusing attention. The drawing required specificity in the relation between segments and leg attachments. The design drawing (top of Figure 6.1) forces attention on the characteristics of the joints. The 3D modeling (Figure 6.2) forced attention on the material properties that would allow the movement (e.g. the choice of elastic, with hard sections). The embodied representation (see below), where the boys fell in step with each other, forced attention on details of the undulating movement of successive sections.
4. The coordination of these multiple, selective representations, to construct a coherent narrative of what was happening, constitutive of their understanding.

The 3D model demonstrated a close awareness of the nature of the jointed body and the leg movement sequence. The drawings (Figure 6.1) show the arrangement of legs on their centipede. These observations were later reflected in the constructed model, and in the presentation the boys made to the class:

> Paul moves the model for which individual sections undulate. He gestures, moves the model and adds: "it sort off … so instead of moving in straight lines it moves like a snake.

> Jesse: "Sort off … so instead of moving in straight lines, it moves (he gestures to signify the undulation) so we used elastic so it could move properly (which we took to mean the undulating movement)

The 3D representation operates here as a reasoning and a communication tool, much more than the end-in-itself so often the case with display models constructed in primary school. Again, when presenting to the class, the boys use the model to represent the centipede's movement:

> Jesse: "How we found out, how it moves is (moves the model) it went like (uses right hand to simulate the undulating movement). I also think it did this (moves hands) one set of legs forward and the other" (raises both hands and moves them in a left-right, left –right motion). At this point Jesse moves very close to and just behind Paul, so as to represent the next consecutive segment. Both students then use their hands and their entire body, gesturing and moving in complete sync.

The successive representations constructed by Jesse and Paul actively focused attention on particular aspects of the animal's structures and function related to movement. The fundamental task they were involved in was analyzing and making sense of the patterns of operation of the animal's structures to provide a coherent account of its movement. The nature of the task is understandable in terms of Eberbach and Crowley's (2010) account of the movement from everyday to scientific observation, which involves, among other aspects, the capacity to notice and describe relevant features and ignore irrelevant features using disciplinary structure, to chunk observational information and use smaller search space to notice and group, to record observations using established procedures, to organize and analyse observations, and to reason with observational data and representations. In order to enforce a coherence to their separate representations, the boys needed to reason in the following ways: to organize their observations of centipede structure to be coherent; to organize perceptions of the movement (through visual and embodied means); to reason about joint attachments and their material properties, to organize these observations into a sensible set of interlinked representations telling a story.

The process by which the boys achieved an integrated understanding of centipede movement could be viewed in terms of the Peircian triad (Figure 6.3) in the way each representation was aligned with its referent, meaning particular aspects of centipede structure and function, and its adequacy judged in terms of its capacity to contribute to that understanding. The complete process which involves multiple representations implies a constant circling round the triad to establish a range of perspectives on centipede movement; coordinating ideas about leg and body movement, body structure and characteristics, and an embodied perception of how these fit together to achieve some sense that "the centipede was not passively bending as a result of its anatomy, but it was actively trying to undulate" (Zimmer, 1994). As this circling proceeds, multiple, multi-modal representations are generated the affordances of which are used to make sense of different aspects of the centipede's structure and movement. As the exploration continues, these become available as resources to be coordinated in generating and communicating explanatory accounts.

Nor is this process restricted to a flat structure. In the process of progressive meaning making, symbolic representations become referents in turn, that are re-represented in a spiraling abstraction process. Thus, the integrated, abstracted centipede drawings in Figure 6.1 are referents for the design drawing representation. This in turn becomes transformed as the 3D model further transforms this, and the boys' role-play in turn draws on the model as referent, which 'stands in for' the animal itself. This process of circulating representational re-description (Latour, 1999) enables the construction and communication of the explanatory account of movement drawing on the particular affordances of each mode. The reasoning is distributed across the sequence of visuo/spatial, and verbal representations.

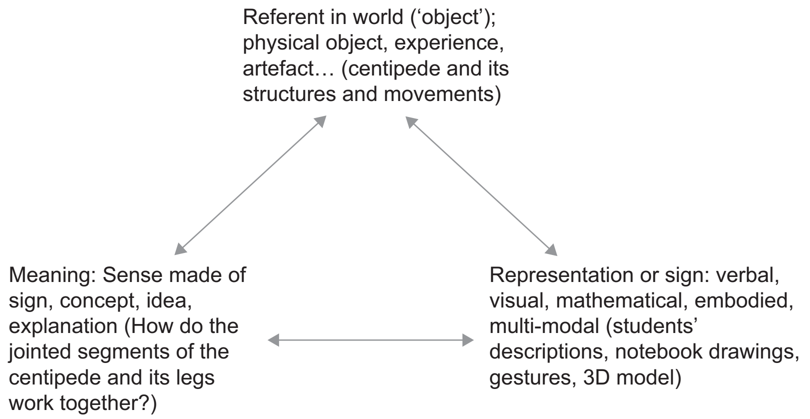


Figure 6.3. Peirce's triadic model of meaning making.

In a similar way to the case of the centipede modeling, the sequence on molecular representations of evaporative phenomena, described in Chapter 5, involves a range of reasoning processes associated with the representation construction. Again, the point was made that the particular affordances of the different modes – diagrams, cartoons, role-plays, 3D models, talk – supported particular aspects of understanding. Each representational challenge, we argue, involves separate reasoning processes and a different conceptual end. Thus, students reason concerning the movement of molecules in a solid, the spatial distribution of molecules in solids and liquids, the spatial patterns of molecules in evaporation, the link between energy inputs and molecular movement and dispersal, and the temporal patterns of change in movement and distribution. This is a different type of reasoning, for a different purpose, compared to the centipede example, in that it concerns relations between different aspects of a molecular interpretation of matter, and the application of this singular representational system to particular contexts.

Clarifying 'Reasoning'

How might we make the case that the construction of an understanding of centipede movement involves instances of reasoning? How might we characterize that reasoning?

We need to acknowledge that the case is somewhat circumstantial, since we do not have access to a running account of students' thinking as they performed the representation construction and the observations and coordination associated with that. We do have evidence of groups of students constantly checking back and forth between animals and their drawings as they refined, asked questions, hypothesized and resolved aspects of structure and function (Tytler, Haslam, Prain & Hubber, 2009). The centipede drawing required close observation and analysis of the animal's structure to ascertain which parts were pertinent to the movement and how they worked together in movement, such that the selection of key features involved in movement was achieved and represented. In the second, design drawing, the key feature of the nature of joints, and their abstracted representation, was the focus. Thus, we argue that the drawings involved close and focused observation and analysis of the animal and its movement, to select and chunk and analyse the perceptual information in a manner that Eberbach and Crowley (2010) characterize as a scientific mode of observation. The act of drawing itself similarly involved selection of what to represent and how, as pertinent to movement, in a process of symbolic abstraction, organization and synthesis of these elements into a coherent visual account.

Gooding (2006) argues that visualization in science (see also Gilbert, 2005) involves objects that:

> Combine visual and non-visual elements because scientific work requires representations that are hybrid (that combine verbal or symbolic expressions with visual and other sensory modalities) and plastic, enabling the meaning of an image, word or symbol to be negotiated and fixed (p. 40).

and that standard accounts of the nature of science that are based on verbal formulations (facts, laws, formulae) that obey semantic rules, and versions of scientific processes that identify cause in terms of the relationship between singular entities, do not capture the nature of new knowledge production. According to Gooding (2006), the more complex thinking based on perceptual, usually visual patterns, draws on two features of human cognition; a) our ability to recognize regularity in visual patterns, and b) our ability to 'integrate different types of sensory information into a single representation' (p. 42).

Through detailed analysis of Michael Faraday's notebook entries, Gooding (2006) demonstrates the intimate relationship between material and symbolic artefacts as the scientist extends and transforms perception using material simulations, symbolic artefacts, in a complex modeling process in which sensory information is integrated into images. This process involves integrating many observations into a few images, envisaging from different viewpoints, combining multi-sensory observations and integrating images into a visuo-temporal explanatory model. (p. 53)

The transformation of sensory perceptions through a series of representations, into an explanatory account of centipede movement, shown in Figures 6.1 and 6.2, echoes the process described by Gooding (2004, 2006) of dimensional reduction and enhancement, as observations are selected and abstracted into 2D models, then 3D and 4D accounts that represent a temporal process underlying the observed phenomena. The explanatory communication again integrates verbal and visual modalities, just as did the process of model generation. According to Gooding (2006, p. 60):

> images are particularly conducive to the essential, dialectical movement between the creative stages of discovery and the deliberative, rational stages in which rules and evaluative criteria are introduced to fix meanings and turn images from interpretations into evidence.

As we have argued in Chapter 5, and elsewhere (Prain & Tytler, 2012) the affordances of the 2D visual mode constrain and channel in a productive way, forcing choices of selection and abstraction to support learning. The drawing is an active agent in developing understanding. We argue that in an important sense, each of these representations can be seen as a reasoned claim (although not in the Toulmin linguistic sense – see Osborne, 2010) in that it involves analysis and selection and choice of abstraction towards an explanatory end. The reasoning is not linguistic or formal, in that it does not contain claims and warrants that are unitary, and that can be stated in logical form. In this case the claims and warrants are distributed across the visuo/spatial representation and accompanying verbal account, and the process of warranting is hidden within the deliberative choices made as students interrogate and select the animal features and synthesise these into a coherent and productive account.

It is possible to argue that if we were to track on a micro-timescale students' reasoning processes as they observed, transformed and generated, checked and surmised and concluded, it might be possible to identify chains of inductive, deductive and especially abductive reasoning underlying the process of idea generation. Following Gooding (2006), however, we argue that the representation construction process involves forms of visual and other reasoning that act in tandem with but are distinct from formal linguistic reasoning, and these need to be acknowledged and characterized if we are to value these processes in science classrooms. Gooding (2006), on the basis of close analysis of Faraday's methods, argues for an active role for visual representations in idea generation:

> Far from being mere illustrations of reasoning that had been accomplished verbally, Faraday's sketches and engravings are integral to his process of investigation. He did not first produce new knowledge and then verbalize or

> image it. Words and images emerged in a context which they jointly helped to generate. Faraday's sensual images express his theoretical aspirations and intentions just as much as the many words that he wrote. (p. 61)

In the centipede and other cases, the construction of these representations involves reasoning aimed at bringing some sort of productive coherence to an apprehension of 'what is going on?' and 'how can we best represent it?

Thus, we argue that:

> Reasoning should be thought of as deliberative thinking that involves choices, leading to a justifiable claim.

In coordinating across representations, reasoning is characterized as the setting up of identifiable and generative relations between entities – either between entities within a complex representational framework such as the different aspects of the particle model, or between aspects of a representation and the properties of the natural world that are being represented.

There are a number of aspects to this view of reasoning that can be identified in the examples above. First, the thinking is deliberative in that it involves a meaningful and justifiable claim, possibly in response to a problem. Second, it involves some sense of bringing together entities or elements into a relation that clarifies. These entities might include aspects of phenomena, or distinct ideas. Third, the entities need to be 'identifiable' implying a need for some degree of clarity, or sharpness, in what is being reasoned about. Finally, reasoning needs to be generative both in its intention, and its effect; it needs to move thinking forward.

In this chapter, we will explore a) the reasoning processes involved in representation construction, at different moments in a learning sequence, with the aim of moving towards an indicative list of these processes, and b) the affordances opened up for reasoning through different modes. We will trace the reasoning processes involved in two cases of Year 5/6 learning sequences; the first being the water sequence partially described in chapter 5, and the second being the animals in the school-ground sequence from whence the centipede example was derived.

In performing the analysis of the cases, we will argue that reasoning is richly supported in the representation construction approach not simply through the act of representing as such, but that a representational challenge will open up reasoning possibilities in the wider activity setting. One might think of three 'moments' surrounding a representational challenge, each of which involves a range of reasoning processes. Figure 6.4 illustrates how this might apply to the centipede example.

Figure 6.4 represents an argument that the representational challenge offers a range of reasoning possibilities and supports. We argue, in line with the sociocultural position that language and representation play an active role in framing thinking; that the act of representation construction itself demands and affords reasoning through the operation of productive constraint. Further to this however, we argue that the task of constructing a representation demands close attention to the natural phenomenon being represented, and that the need to coordinate the referent and representation demands an analysis and synthesis process clarifying the relations between these types of entities. Following the production of representations, the public presentation of these provides an opportunity for questions, challenges, justifications, and further discussion of ideas about invertebrate movement, structure-function relations, and adaptation. In this particular case these conversations were limited to explication of the models and some questions concerning evidence, but it can be readily seen how more formal syllogistic reasoning could arise as teachers probe and extend students' representational ideas.

In characterizing and summarizing these different instances of reasoning we are aware that we have reduced them to linguistic, semantic form, in apparent contradiction of our argument. This is a necessary consequence of the need to codify and structure the reasoning landscape, and it is important to note that underlying each term is a richly multi-modal practice.

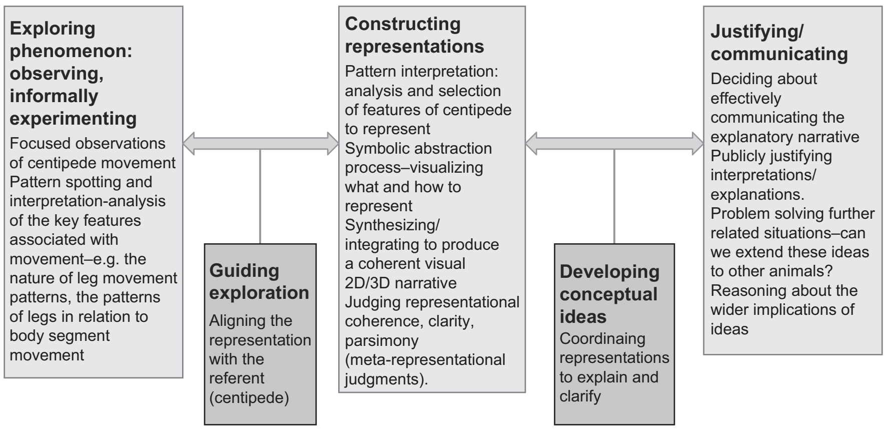


Figure 6.4. Reasoning processes within a representational challenge activity.

CASE 1: A UNIT ON EVAPORATION

This 6 lesson learning sequence for combined 10 and 11 year old classes was co-taught by two teachers, Lauren and Malcolm, who work in adjacent rooms with a retractable dividing wall separating them. The focus of the sequence was on states of water, and particle interpretations of evaporative phenomena.

The sequence started with a representational challenge. Students were given a map of their immediate area of the school and asked to go in pairs, to locate everywhere they think there is water. Malcolm describes the task:

> I want you to record every place where there is water. I want you to **think** how you are going to record here [points to map]. You can do arrows if that

helps you, you can list the places, color in and/or just write down where that water is.

In the discussion, the students volunteer the many places water was found or inferred to be. The representation in this case served as an organizer of students' perceptions and a prompt to their reasoning about the different forms water could take – water in soil, underground water, water in fruit, or the leaves of trees, etc. The class sharing proceeded through talk, with Malcolm listing places on the whiteboard under the headings 'visible' and 'invisible'. The teachers challenged students to justify their assertions with evidence. For instance, when the discussion turned to water that was not visible, students volunteer 'in our bodies … storm water drain' and a student, Sean, says 'water vapour'. Malcolm immediately challenges Sean: 'where is this water vapour?' which leads to an exchange in which Sean says 'like water particles in the air … humidity'. Some other students concur and Malcolm says: 'keep going ... where is this humidity?' Sean continues: 'how much water is in the air. Say if there is 40% humidity there is 40% of water in the air'. Malcolm challenges the class: 'so water in the air? Is there water in the air here (gesticulating to the room)?' He then takes a straw poll of how many students believe this, and when only a minority of students agree, asks 'how can you prove that?'

There follows a sequence where students justify the claim by referring to humidity getting in if the door is open, appealing to the fact the 'weather man' refers to humidity (Malcolm: you can't believe everything you're told), the invisibility being due to the water being microscopic (Malcolm unpacks what this might mean), Catherine's assertion that if you sealed a room for a few days water droplets would appear (the meaning of this was probed) and Charlie's observation: 'In my laundry after I left the drier or something, when I walk in I feel the wall and it's all wet.' The dialogue was gradually steered towards the distinction between water vapour and steam, as between droplets of water, as in clouds, and water as a gas. Later in the lesson, Malcolm comes back to this question and asks students to devise a means of proving 'there is water in the air all around us here right now', and a suggestion to 'leave a bottle of water open and observing the water level go down' is subsequently taken up and refined into an experiment with beakers of water left in different parts of the classroom over a few days, with students predicting the rate of decrease in level.

In the discussion Malcolm continually encourages students to make claims, and challenges them to justify these using a variety of forms of evidence; empirical, social and anecdotal. The reasoning proceeds through partly formed, speculative conceptual claims including appeals to analogy and the proposal of relevant cases (the laundry, the weather report), and judgments about their appropriateness. There are also thought experiments serving as hypotheses (sealing the room and observing droplets). The verbal discursive mode is well suited to such reasoning, being narrative in character.

We can see in this sequence the same pattern of reasoning processes that were described in the centipede example and represented in Figures 6.1 and 6.2.

The representation challenge demanded of students that they focus attention on the possibility of water in all parts of the school ground. The representation construction itself was not particularly generative, but the sharing of student work opened up a range of possibilities of reasoning through classroom talk. Thus, the task was the site for a varied and rich array of reasoning and learning.

The reasoning process shifts when Malcolm introduces a visual representation task. A week after the lesson described above, students note that the water level has gone down in the containers, and Malcolm asks 'where did that water go?' Students agree it has not simply 'disappeared'. One student reintroduces the notion of molecules.

> St-6P: The molecules are like energy… they can't be destroyed or created.
>
> Malcolm: What happens then? We can't create we cannot destroy the molecules, what did we do to them? … you are going to draw them for me. Represent for me in a drawing, in your book in a diagram, draw for me the change, go represent it. …

Figure 6.5 shows one Year 5 student's workbook representations of the change in water level. The one on the left was completed first. The one on the right was an amended one as a consequence of Malcolm's challenge: '*Can you show me both, and show me what is different? What would be the change, how would you represent that?*'

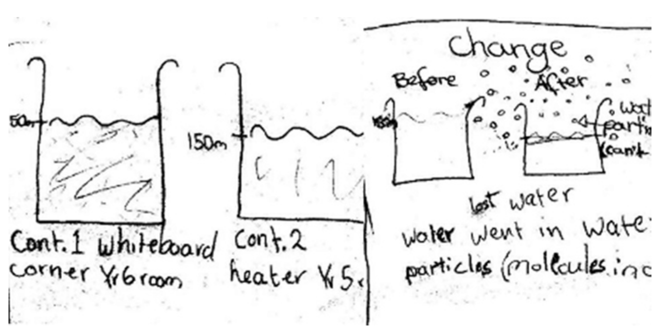


Figure 6.5. Student 5S's representation of change in water level, before and after Malcolm's challenge.

The reasoning involved in the right hand drawing is now different compared to the syllogistic reasoning through talk that dominated the first lesson. The student, in representing what is happening, has had to coordinate the water level drop with a visual 'explanation' of the distribution of water molecules in the air surrounding the container. The affordance of this visual mode in supporting reasoning relates to the need to be explicit about what has changed, and about spacing and distribution and size of molecules. The claims made here cannot be reduced to verbal, syllogistic form. They represent an imagining of the temporal and spatial nature of water molecule redistribution.

The third lesson in this sequence is reported in some detail in Chapter 5. What is remarkable about that lesson is the way the teachers move the students through a series of representations of the molecular basis of evaporation, across different modes (role-play, drawing, 3D model, cartoon sequence), with each mode offering a different but complementary affordance. There are instances of the students being reminded of cross references across the modes, such as using the 3D 'beads in a beaker' representation to comment on the adequacy of students' 2D drawings. The affordances refer in each case precisely to their support of reasoning about the molecular model and its alignment with evaporative phenomena.

Thus, with the role-play of molecules in a solid:

> Malcolm: I want you to imagine you are water molecules, in the solid state, I want you to move to show me what you would look like.

Six students in the videotaped group:

> 5A: hold my hand
>
> 5T why? Because we need some sort of shape and also move.
>
> 6M: No, each one sort of moves – [pushes the other student and moves to and fro]

Thus, the role-play forces students to make reasoned decisions about a range of features of the molecular model; whether they should move, whether they are bonded and fixed in space, how far apart etc., Here we see claim and justification as part of the negotiation surround the representational task. The role-play also reinforces the notion of molecules as fixed in number. In this case, the setting up of 'identifiable and generative relations between entities' that characterizes reasoning involves entities within the molecular model (the adequacy in terms of clarity and coherence etc.), as well as properties of the phenomena (such as the rigidity of a block of ice). The fact that role-play is a public performance also constrains interpretations, as a student in interview explained when asked what helped best in imagining evaporation:

> I probably understood it more with the role-play because we could actually understand by doing what we thought it would be like and if we were doing it wrong we would realise because everyone else would be doing it different.

In the following lesson students were set the task of observing and representing what is going on with an evaporating handprint. The drawings (Figure 6.6 gives three examples) show students making different but defensible decisions about how to represent time sequencing, distribution, and energy inputs. They illustrate imaginative variation in reasoned accounts of a molecular interpretation of this phenomenon, even though they had spent much time in class discussing conventions and refining their capacity to use molecular representations. We would argue this as evidence of student ownership of these reasoned accounts, and of the individual nature of their syntheses of shared representational resources in reasoning their way to a coherent claim concerning how these ideas apply in this context. Their accounts involve the coordination of a number of aspects of the molecular model of evaporation and decisions about how best to communicate these into a visual/spatial narrative. The aspects requiring synthesis include molecular conservation, distribution and movement, energy input, and time sequencing, all tied to features of the phenomenon. The reasoning is not reducible to verbal, syllogistic form, but embodied within the particular visual/spatial aspects of these narratives.

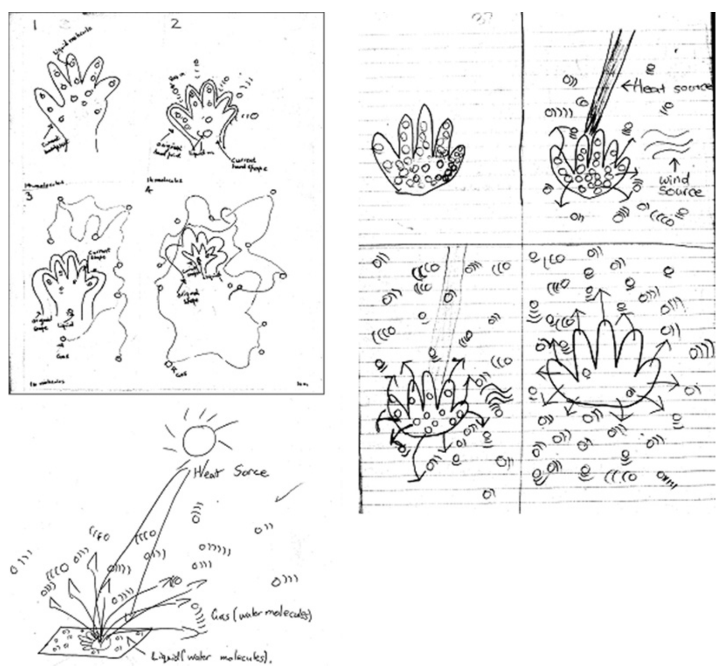


Figure 6.6. Variation in student representations of an evaporating handprint.

In lesson 6, the final lesson before a post-test, students were given the task of constructing an animation of water molecules in a drying cloth. Student 5G explained his animation, shown in part in Figure 6.7:

> Well these are water molecules, when you squeeze it [the cloth], most of them are falling to the ground they are inside the water droplets. Then, some molecules are evaporating, and those are just moving around in the cloth, they don't have enough energy to go out yet.

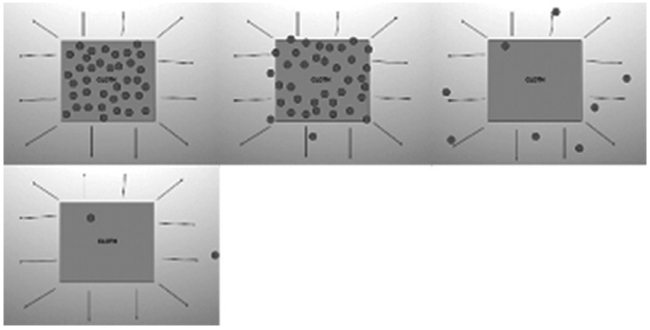


Figure 6.7. Part of student 5G's animation of a drying cloth.

Again, the reasoning involved is constrained by the medium, forcing a consistency of molecular size, a consideration of speed of movement and distribution changes. In this case the student also displays meta-representational insights into the partial nature of the representation, and how it relates to abstract concepts. When challenged to explain if the molecules were really that size:

> I was just focusing on what they do, not representing other things like shape and size, they are very, very tiny. The water that was dropping was still a liquid, then when it was evaporating it was turning into gas.

The quote also illustrates the nature of the reasoned choices student 5G made when constructing the representation. Another student talked of the particular demands on reasoning in constructing visual representations, due to the specificity required of the visual mode:

> It's easier than when you write down words sometimes you wouldn't fully understand what's going on because you might just be remembering what the teacher is saying. When you are doing your diagram you really have to have full understanding of what they were actually telling you, to put it down into a picture.

One of the open questions in the post test asked 'Where do you think the water in the tiny droplets of water in the clouds comes from? Use representations to show how little drops of water form clouds'. Cloud formation had not been discussed in the unit so that this was a new context for students. Figure 6.8 shows a high level response from a grade 6 student that shows detailed spatial/temporal reasoning concerning the process of cloud formation as grouping of droplets. The response represents a detailed claim involving the synthesising of ideas about droplets of water in the air, the nature of clouds, imaginative construction of a reversal of the evaporation process, to form a coherent temporal account. It also involves the alignment of visual and verbal modes. The representational resources the student draws on include varying spatial arrangement of water droplets, motion, and time sequencing. The account is speculative but quite specific in its visualization, and we would argue represents a reasoning process that is informal, emergent, and in Cazden's (1981) terms precedes competence.

It is difficult to know, from Figure 6.8, whether the diagrams precede or follow the text. The question is in one sense important since it bears on the issue of whether the representation construction actively shaped understanding, or simply illustrated a pre-existing mental image. We cannot know in this case, but evidence that the representation construction actively supports reasoning can be found in our previous writing on evaporation, where a student (Karen) was led through the construction and negotiation of a representation of alcohol drops in the room in explaining the smell, to refine her ideas 'on the fly' as the demands of coherence in the representation asserted themselves. (Prain, Tytler & Peterson, 2009).

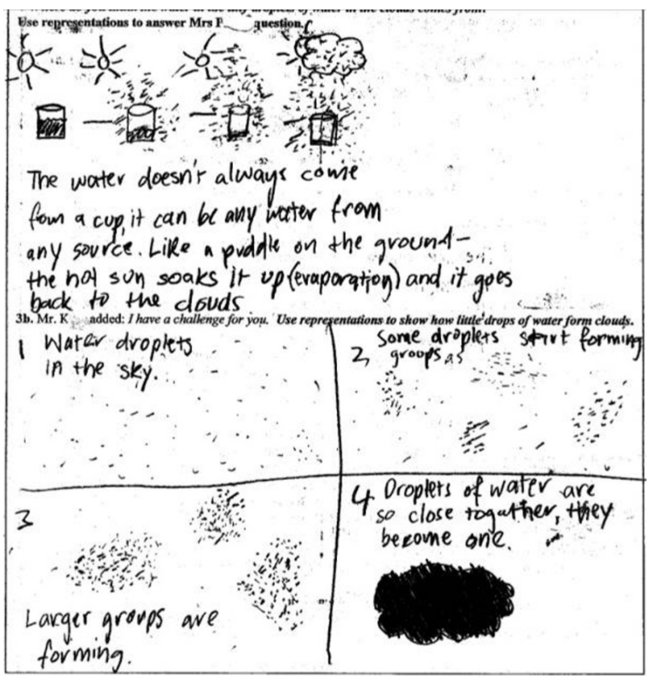


Figure 6.8. Student 6H's response to the post test question "How do little drops of water form clouds".

CASE 2: ANIMALS IN THE SCHOOL-GROUND

The water unit was centrally concerned with building students' representational capacity in relation to molecular interpretations of evaporation, and thus involved a very directed process of theory development and refinement. The 'animals in the school-ground' unit is very different in character, involving explorations of a habitat, animal diversity, and animal behavior. This second case explores reasoning about these rather different scientific ideas.

The animals unit was structured around two distinct sections; one involving an exploration of the diversity of animals in a habitat, and the second involving the exploration of structure and function relationships in a chosen invertebrate, through a modeling process. The first section began with an introduction to the broad task and a discussion of how groups of students might explore what animals are in a specific habitat (each group had a different section of the grounds, for instance under a tree, in a woodpile, round the pond, in an open grass area etc.), and how they would communicate that. After a preliminary investigation and reporting session, Lauren introduced the idea of scientifically studying a habitat, including the need to develop quantitative data through sampling, measurement and representation. Structured discussion led to the question of how they might define the sample space (students suggested: 'mark out the area', 'peg string around it') and the idea of a quadrat was introduced, practically represented by circular hoops in this case. The physical hoop thus served as both a physical, and a conceptual tool to support reasoning about sampling. Xu and Clarke (2012), analyzing classroom interactions from a distributed cognition standpoint, talk of how artefacts can serve both physical and conceptual purposes. After discussion of what students might record concerning their habitat (temperature, aspect, physical items, plants), how they might do this (drawings, tallies, graphs), and the nature of their task (to produce a poster describing their habitat), the students proceeded to investigate.

Figure 6.9 shows sample student notebook sketches of animals, and a tally sheet of animals with illustrations of each. Figure 6.10 is an example of a graph produced

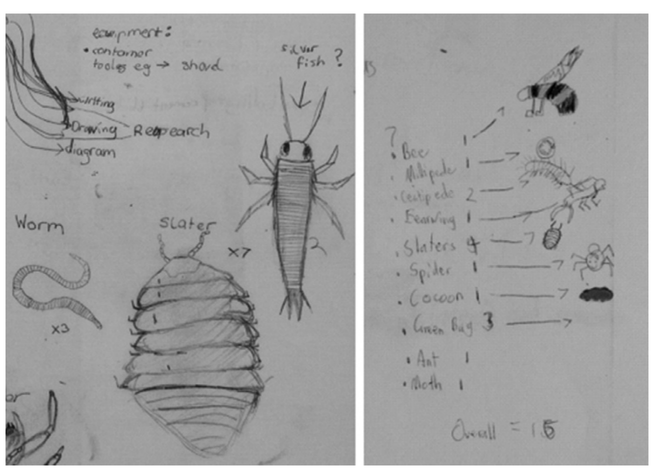


Figure 6.9. Student notebook sketches.

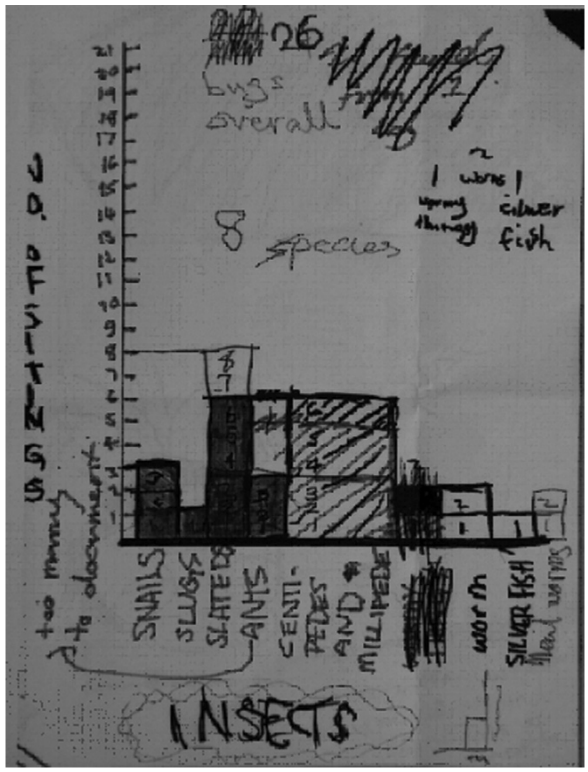


Figure 6.10. Student graphical representation of diversity in a habitat.

to provide a visual representation of the relative numbers of different animals. Re-representing their data on a poster again was the occasion for significant learning. All posters contained many representations. These included annotated drawings of animals and details of their structures (3 dimensional, cross sections, side view, magnification of certain body parts, as in Figures 6.1 and 6.9 above) population graphs, drawing of life cycles, transects, overviews, digital microscope images, and representation of animal behaviours (e.g. defence, or movement).

Greeno and Hall (1997) make the point that representations should not be thought of as 'ends in themselves' but rather they serve as tools for thinking and communicating in science. We argue that these discursive representational practices of science (graphs, tables, drawings, reports, photographs) were critical to each step in the inquiry process: framing the data collection, the interpretation and idea generation, and the communication. We argue (see Chapter 10, and Tytler, Haslam, Prain & Hubber, 2009) that the concept of animal diversity is best thought of in terms of representational practices of the sort engaged with in this unit, rather than as a formal linguistic entity, and that the process of learning about diversity must involve learning to reason with these tools.

The representational challenge (finding and communicating what was in the habitat, and identifying features of the habitat) demanded and supported reasoning at a number of points. As with the water unit, the requirements of the challenge gave rise to reasoned discussion and exploration, separate from the act of representing as such. The initial discussion of how the characteristics of the habitat might be documented, including how we might think of sampling, leading to the quadrat representation, and the role of tallies and graphs, involved significant negotiation of claim and justification. This teacher led discussion involved syllogistic reasoning processes (induction, abduction). The discussion led to the establishment of these representations as supports for thinking and reasoning.

The process of sketching (Figure 6.9) productively constrains observation by inviting close observation of animal features and requiring judgments about what distinctive features to focus on and how best to represent these. These sketches involve analysis of the animals' structures into component parts, selection, and symbolic abstraction and synthesis of the animal's key features. This, and the close observation evident in the drawings, and the employment of scientific conventions such as the scale indication, conform to Eberbach and Crowley's (2010) characterization of high level scientific observation. The tally in Figure 6.9 offers a way of envisaging distinct numbers of different animals, and guides the collection and counting. The construction of the tally clearly involves decisions concerning identification, and choices about where to count – how deeply for instance – and when the tally is complete. As such we would argue the representation operates as both a visual indicator of the concept of diversity in the habitat, and a reasoned claim concerning the sample population. The graph in Figure 6.10 allows direct visual comparison of relative numbers, and involves active choices of features such as scale and order, whether to count centipedes and millipedes together or separately, and how to deal with the large number of ants.

The students in this unit were not given worksheets or templates for recording, and therefore needed to make many choices about what and how to record. The incomplete nature of these workbook representations show them to be 'ideas in progress'. Unlike many school science notebooks, which are constrained by requirements of tidiness and the need for a polished final product, the notebooks for this unit were explicitly used as tools for thinking and preparing for later public communication. Students used the books to jot down ideas and construct preliminary drawings that they later refined in their posters and models. We can therefore justify the characterization of these representations as reasoned claims, in contrast to the more usual mode of school science activity where students simply fill in worksheets and follow instructions. The existence of reasoned choice, selection, and synthesis, implies an element of reasoned justification in the representation construction.

We thus argue that these representations serve as reasoning tools through which the students were guided to produce data, to organize their perceptions of what was in the environment, and to develop their understandings of animal diversity and habitat. We further argue, as we did with the water sequence, that the representation construction challenge is at the centre of a series of activities – exploration, communication, classroom discussion – each of which involves the generation of reasoned claims and justifications.

REASONING THROUGH REPRESENTATION

In this chapter we have argued that:

- representation construction opens up rich opportunities for reasoning in science, not only through the specific act of construction but through a range of exploratory and extension activities that sit naturally within the representation construction pedagogy – including establishment of need, exploration, drawing and modeling, challenge and negotiation, extension of ideas, and communicating.
- the reasoning opened up within these activities cannot be adequately captured by formal accounts that recognize only syllogistic, linguistic processes of deduction, induction, abduction, but includes a range of types of informal reasoning such as analogic and metaphorical reasoning, and reasoning through the construction and negotiated refinement of 2D or 3D representations.
- the construction of a representation is a claim, containing informal elements of justification through the reasoned synthesis of selected, abstracted entities. In drawings and models these claims and justifications are distributed across elements in the representation rather than being expressible in formal syllogistic terms relating single claims to single items of evidence.
- the reasoning within and across representations involves the selection and coordination of entities including aspects of the phenomenon being explored, and aspects of the constructed models.

There were two broad contexts in which reasoning occurred in these sequences: a) to guide exploration through processes such as organizing perceptions, and framing data generation and interpretation, and b) to develop and make sense of conceptual ideas, and apply these to develop explanatory accounts of phenomena in new contexts. Here, we use the case studies to construct an indicative list of some of the processes of reasoning through representation, which occurred within these contexts.

a) Processes of reasoning through representation to guide exploration and investigation, in the sequences described above, included:

Reasoning as the organization of perceptions — drawing and modeling demands a selective focus of attention on key features of phenomena, and their symbolic abstraction in a process of dimensional reduction (Gooding, 2004). This involves breaking a phenomenon into its component parts, analyzing what is important to the question, and synthesizing key aspects to construct an explanatory account.

Reasoning through material and symbolic artefacts to organise data generation — examples of these artefacts include the quadrat which represents an element of a sampling grid, or tally sheets of animals in the habitat which channel attention through offering a frame for data generation and a metaphor for perceiving variety. These require reasoned decisions about where and what and how to count, for instance, involving analysis and integration.

Reasoning to interpret and analyze data — reasoning through the particular affordances of graphs or tables involves decisions about types of graph, representational choices about scale or about how to accommodate diversity in the table construction.

b) Processes of reasoning through representation to develop and make sense of emerging ideas, included:

Reasoning to align representations with phenomena — refining/developing key representational features to align with aspects of the phenomena being represented, such as particle distribution and time sequencing to explain features of evaporative phenomena, or testing and refining a model of animal movement to match observations and measurement. This involves, again, analysis, abstraction and synthesis of features of phenomena.

Reasoning about representational adequacy (diSessa 2004) — for instance in justifying adequacy of a representation in terms of clarity, coherence, and internal consistency, such as when discussing how best to represent molecular speed, in a role-play about particles in a solid, or in justifying to a teacher how a particular model explains aspects of animal movement.

Reasoning to extend representations to problem-solve in new contexts — generating and refining representations, such as speculative representation of what must happen at an air water interface with evaporation, or imaginatively representing cloud formation on the basis of resources developed through explaining evaporative processes.

Engaging in meta-representational reasoning — such as reflecting on the relationships within representational systems and how these operate to explain and communicate.

In reality there is overlap between these reasoning process categories. Nevertheless, as an indicative list, these distinctions reflect the different contexts and purposes of reasoning in the cases described above.

In each sequence the representations were introduced as a response to a need to investigate the particular phenomena ('what's going on with the evaporation of a puddle?', 'how can we make sense of what animals are in a habitat?', 'how can we represent how an animals moves?'). Following this, teachers supported students to develop representational capacities through a series of challenges that involved reasoning about aspects of the representation and how it could be used to better make sense of the phenomenon (what are the features of the molecular model?

What features might we build into our drawings or models to represent movement?) In each case the different representations and modes offered affordances through productively constraining the reasoning in particular ways.

From our basic characterization of reasoning through representation as involving the construction of claims based on the development and synthesis of relations between entities, we see that from a pragmatist, semiotic perspective the reasoning processes opened up by representation construction involve refinement of a mix of relations between aspects of representations and aspects of the phenomena being interpreted. This is a more complex view than that characterizing reasoning in terms of relations between ideas and evidence as distinct entities. In the representation construction itself, we have argued that the claims and justifications can be visual and spatial in nature, distributed across synthesized, abstracted elements, and coordinated to offer a coherent explanatory account.

The analysis has attempted to unpack the multi-faceted representational practices that make for 'ideas' in science, and also the complex and reflexive relationships between representations and 'evidence' that in the pragmatist perspective are part of the Peircian triad describing meaning making. In these learning sequences, students are involved in claim-making and backing with evidence, and can be characterized from an argumentation perspective (Osborne, 2010). However, distinct from pedagogies built around formal argumentation notions, we see that argumentation sits naturally as part of an emergent, situated practice where claims and evidence are used in the service of grounded problem solving (Manz, 2012). Stripped of this context, it struggles to capture the complex and grounded nature of knowledge building in science that invests it with meaning (Ford & Fordham, 2006). This bridging of the dialectic relationship between formal and informal reasoning processes is consistent with pragmatist perspectives on learning that view judgments about emerging representations / ideas as inevitably grounded in practical contexts of use (Peirce, 1931–58).

We hope we have also shed some light on the nature of informal reasoning processes involved in learning science, and the way these relate to more formal, syllogistic and language based justification and validation processes. Much of the reasoning described in the chapter is analogic, perceptual, pattern seeking and identifying, embodied, and emergent in character, yet these processes, with the guidance of the teachers, served to feed into the establishment of canonical discursive practices of science – the molecular model, the characterizations of animal diversity and structure and function – on a solid evidential foundation. As part of this process students developed their meta-representational knowledge. Further, these students had engaged in epistemological discussions involving the notion of successive transformations of representations to develop explanation, consistent with Latour's (1999) notion of chains of representational 'passes' and more complex theory-evidence relations than is generally acknowledged in the reasoning literature. As such, we would argue they had received a more authentic education in the nature of science than is reflected in more formal NOS schemata (see Chapter 10).

Finally, we would point out that in this chapter we have moved between the terms ‘representation’ and ‘model’ without clear distinctions. In fact there is a lot of overlap between these terms, and the literature on modeling in science and model based reasoning is very pertinent to the representation construction approach and the pragmatist perspective on learning and knowing. There are, however, some distinctions. The next chapter will take up this theme, with an account of the use of models, within a representation construction approach, in teaching and learning astronomy, and particle ideas.

PETER HUBBER & RUSSELL TYTLER

CHAPTER 7

MODELS AND LEARNING SCIENCE

Interest in models as a key characteristic of the knowledge construction processes of science, and as a critical feature of quality learning in science, has grown over the last two decades (Gilbert, 2005; Clement & Rea-Ramirez, 2008). Theoretical accounts of model based reasoning in science classrooms (Lehrer & Schauble, 2006) and in science itself (Duschl & Grandy, 2008) have challenged the dominance of syllogistic reasoning processes in writing about science education, and of simplistic accounts of the methods of science. Representation construction and modeling are closely related, and this chapter will draw on sequences from units on astronomy, and ideas about matter, to explore the links between model construction, interpretation and evaluation, and conceptual learning in science. In doing so we will explore the relationship between models, and representations more generally.

The chapter will trace the way the teacher introduces, scaffolds and negotiates student representation/modeling to generate compelling explanations of astronomical phenomena and properties of samples of substance, and how students learn to coordinate these to produce and communicate understandings expressed through a variety of models. Accounts of the astronomy and ideas about matter sequences will show how multiple models are developed and coordinated, and lead to quality learning of concepts related to these topics.

MODELS AND MODELING IN SCIENCE

There is wide agreement that the process of modeling and the models so produced have a central role in modern views of the evolution of science (Cheng & Brown, 2010; Prins, Bulte & Van Driel, 2010) as, according to Crawford and Cullin (2004, p. 1381), "One of the most critical aspects of scientific work is the use of models to explain phenomena in nature. The overall goal of scientific work is to develop an understanding of how various parts of the natural world work. To do this, scientists make observations, identify patterns in data, then develop and test explanations for those patterns. Such explanations are called scientific models (p. 1381)". Gilbert (1991) has suggested it would be helpful to define science as a process of constructing predictive models, as this definition incorporates both the process of science and the

R. Tytler, V. Prain, P. Hubber and B. Waldrip (Eds.), Constructing Representations to Learn in Science, 109–134.

nature of its product. Nersessian (2008, p. 392) adds the view that, "Creating models as systems of inquiry is central in the problem solving practices of scientists".

Despite wide agreement of the central role played by models in the construction of scientific knowledge there is no unique definition of a model (Oh & Oh, 2011). However, Oh and Oh (2011) point out that the term 'representation' is commonly used when defining a model. For example, Nersessian (2008, p. 392) describes a model as, "a representation of a system with interactive parts with representations of those interactions. Models are representations of objects, processes, or events that capture structural, behavioural, or functional relations significant to understanding these interactions". Models are designed with a specific purpose by the modeller (Van der Valk et al., 2007). There can be great variance in the entity, or target, which can be modelled. For example, a globe is a culturally accepted model of the physical object of Earth in space whilst the Big Bang model in astronomy represents an idea about the formation of the universe.

Models differ in terms of content, appearance and function, and can be categorised accordingly; various taxonomies of models have been developed. For example, in one type of classification Black (1962) distinguished between scale models, analogue models, theoretical models and mathematical models. Harrison and Treagust (1996) have added to this list by including chemical formulae, model or standard, and maps and diagrams. A different classification, used by Gilbert (2011, p. 5), includes:

- concrete models (for example, scale models, figurines);
- pictorial/graphic models (for example, blueprints, photographs, diagrams);
- mathematical models (for example, formulae, graphs, topographic maps);
- verbal models (for example, descriptions, scripts, directions);
- simulation models (for example, simulation games, crash test dummies); and
- symbolic models (semiotic models) (for example, words, numbers, mathematics figures).

Models may be concrete, like the Globe as a representation of Earth in space, or abstract, like mathematical models, such as Newton's Law of Gravitation. Whatever the type of model, they all have in common a target system, which is the entity to be represented, a source and a set of correspondence links between certain features, or attributes, of the source and those attributes of the target system under consideration (Norman, 1983).

The process of modeling is, according to Gilbert (1994), "the process by which a model is produced. It involves identifying the need for a model, establishing the purpose that the model is to serve, identifying a suitable source from which it may be derived, and producing the representation" (p. 8). The modeller selects only certain attributes of the target to be represented by similar attributes in the model (Lehrer & Schauble, 2003). The model only exists via the modeller's interpretation of the target and so there is always an element of creativity involved in its design, related to its purpose (van der Valk et al., 2007). From this perspective different models can represent the same target; different models can be constructed to represent different aspects of the same system (Oh & Oh, 2011).

A model cannot represent all attributes of the target otherwise it would be a copy. This perspective leads to a feature of all models in that they have limitations; both the model and target have attributes that do not correspond. A full explanation of a real-world system therefore necessitates multiple models. Given that there are multiple ways of explaining or conceptualizing real-world systems competing or rival models are possible (Grosslight et al., 1991). For example, the nature of light has competing particle and wave models. Both models provide a fuller understanding of the nature of light than either of them singularly can provide. The following quote by Frisch (1972) highlights not only the characteristic of a model as human construction quite separate from the target it purports to represent but the epistemological view that models provide scientists with tools to understand the real world.

> ...we should not ask what light really is. Particles and waves are both constructs of the human mind, designed to help us speak of the behaviour of light in different circumstances. With Bohr we give up the naive concept of reality, the idea that the world is made up of things, waiting for us to discover their nature. The world is made up by us, out of our experiences and the concepts we create to link them together. (p. 105)

Oh and Oh (2011) suggest a reason for the multiplicity of scientific models is that models may be created in multiple forms of representation involving, "any semiotic resources, including linguistic entities, pictures, diagrams, graphs, concrete materials, animations, actions, gestures and their combinations" (p. 1118). Multiple representational formats are used in model-based reasoning. For example, Nersessian (2006) cites the example of Faraday and Maxwell who in reasoning about the electromagnetic field, "constructed visual representations of imaginary physical models, animated imaginatively, from which they derived mathematical representations, theoretical hypotheses, and experimental predictions (p. 700)."

There is a consensus view that the main purposes of modeling in science are to describe, explain and predict aspects of the natural world (Oh & Oh, 2011; Shen & Confrey, 2007). Models also act as a communicative tool in instances where scientists share their understanding with the scientific community and public. Models are seen as a 'bridge' or mediator connecting theory and the natural world (Koponen, 2007; Prins et al., 2010).

There is reasonable but not complete convergence in the literature about what constitutes a model, and the broader perspective on models has them overlapping considerably with 'representations'. We view representations (following Peirce 1930–58 – see Chapters 1 & 2) as signs that stand for something that will be meaningful to someone, and distinguish between a concept, its representation, and phenomena in the world. All models can, from this perspective, be classified as representations. However, not all representations are models. For example, student exploratory talk, gestures, drawings, enactments, and manipulation of artefacts can function as representations of emerging ideas and insights but would not be considered as models. We would view models as being more deliberate, abstracted and resolved, designed explicitly to explain or clarify an aspect of the world, whereas representations are in some cases highly situated and ephemeral (gestures, a metaphor conjured up 'on the spot', a preliminary sketch), serving both as part of the genesis of, and emergent constituents of a model. Representations are the fundamental resources, or tools, through which models are constructed and interpreted, or they can be models themselves.

Therefore, the literature on models and model-based reasoning is highly relevant to our own concerns, and we would aim to contribute to that literature. Maintaining, however, the broader sense of representation is important from our pragmatist semiotic perspective in that these more fluid and ephemeral representations that lie outside the scope of the modeling literature are important aspects of how we come to learn and know in science. We view representations as a very broad range of symbolic and material resources and artefacts for supporting students' reasoning processes, where they can function as both process markers and products of understanding. Maintaining this strong sense of process is central to our view of representations as the central focus in students engaging with the discursive practices of science. The focus on process drives this need to work with a construct that is broader than 'model', which tends to focus attention on the resolved, abstracted products conceived of as the end products of this process.

USES OF MODELS IN THE SCIENCE CLASSROOM

Given that models and the process of modeling are fundamental aspects of science (Schwarz & White, 2005) it becomes important that students learn to use models in classroom activities (Cheng & Brown, 2010; Van der Valk et al., 2007; Lehrer & Schauble, 2003). Jadrich and Bruxvoort (2011) suggest that if students are constructing and evaluating models then they are involved in scientific inquiry. Modeling can assist students to express their understanding of the natural world and to visualize and test their ideas to help them develop higher levels of scientific understanding (Schwarz & White 2005; Schwarz & Gwekwerere, 2007; Passmore et al., 2009). There is wide support for model-based inquiry approaches in the classroom (Jadrich & Bruxvoort, 2011; Schwarz & White, 2005; Lehrer & Schauble, 2003). Modeling is not routinely practiced in schools (Schwarz & Gwekwerere, 2007) and so model-based inquiry approaches require modeling to be practiced by students on a sustained level (Lehrer & Schauble, 2003) and need to take account of the repertoire of models students bring to the classroom (Gobert & Pallant, 2004). Students need to generate their own models which are tested and evaluated alongside the scientific models introduced by the teacher or the textbook. Ramirez et al. (2008) have reported success, in terms of enhanced understanding of science, by students in reasoning with models using a guided inquiry approach.

There is evidence that students may not understand the nature of models and process of modeling even when engaged in creating and revising models (Grosslight et al., 1991) and so it becomes important for students to not only be involved in creating, testing, revising, and using models; they also need to learn about the nature of models (Prins et al., 2009; Gobert & Pallant, 2004). Schwarz and White (2005, p. 167) point out that:

> A model-centered, meta-modeling approach, which emphasizes learning about the nature and purpose of models, also has the benefit of enabling students to develop accurate and productive epistemologies of science. If one defines science as a process of model building, this helps students understand that scientific knowledge is a human construct and that models vary in their ability to approximate, explain, and predict real-world phenomena.

A model-based inquiry approach can assist students to develop a deeper understanding of subject matter and scientific skills, and a strong understanding of the nature of science (Schwarz & Gwekwerere, 2007).

Researching student model-based reasoning through inquiry is a major strand in the conceptual change literature (Clement, 2000; Justi & Gilbert, 2003; Lehrer & Schauble, 2006). Researchers in this area claim that the inquiry process centred on constructing, critiquing, testing and revising models provides a key mechanism for promoting student conceptual growth. Our own approach is broadly consistent with these strategies, but differs in detail with regard to specifics of how the models/representations sit within the pedagogy, and the theoretical and practical end point outcome of the process.

Our approach involves a systematic and explicit focus on students being challenged to generate, interpret, refine and justify representations as a key practical step in learning science concepts. While it differs from modeling approaches where the focus is on interpretation of canonical models, it is broadly consistent with aspects of some model-based reasoning work with a focus on model construction (Justi & Gilbert, 2003; Lehrer & Schauble, 2006; Clement & Rea-Ramirez, 2008). However, even here there are differences related to the theoretical underpinnings of the approach and interpretation of outcomes. Our account focuses 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 problem-solving through dialogue, debate and appeal to evidence, where inquiry is focused on resolving practical, situated questions (Dewey, 1996; Peirce, 1930–58). We focus on representations-in-use that are preliminary and situated, with a focus on the practice rather than a resolved end product. Allied with this, we view the process of representing as an emergent response to the need to explain a selected aspect of a phenomenon, and the representations / models themselves as inherently partial accounts. The task of explaining involves the situated generation, selection and coordination of these resources, often across multiple modes, rather than the building of a coherent mental construct.

The following two sections provide case studies of teaching sequences that exemplified a representation construction approach that introduced students to the scientific models that explain simple astronomical behaviour and basic properties of matter. The RILS teachers Lyn and Sally taught the topic of Astronomy to their Year 8 classes (13 year-old students) whilst Therese taught the topic of Ideas about Matter to her Year 7 class (12 year-old students). The case studies are used to examine the way sequences of models are constructed, interrogated and coordinated to support student reasoning and learning of science concepts, and to develop students' meta representational competence.

CASE OF LYN & SALLY: TEACHING ASTRONOMY

The topic of astronomy was one of three topics that were taught by the two experienced secondary school teachers, Lyn and Sally, as part of the RILS project. The curriculum content of the topic included explanations of astronomical phenomena such as day/night cycle, seasons, phases of the moon, tides and gravity. The astronomy sequence has been chosen as a case in this chapter as it illustrates the ways in which explanatory accounts of day and night, or the seasons, or moon phases, involve the construction and coordination of a range of visual/spatial models of the Earth – Moon – Sun system, each of which is partial, focuses on specific aspects of phenomena, and works to constrain and focus attention on these.

The generation and coordination of even the simplest astronomical models can be problematic for students. For example, Padalker and Ramadas (2008) suggest that whilst most students at junior secondary level understand that we live on a spherical Earth suspended in space, "it is rare that students are able to use this model in interpreting and reasoning about everyday phenomena" (p. 55). Explanations of astronomical phenomena such as the day-night cycle, seasons and phases of the moon require of the learner abilities of spatial visualization, which is the ability to imagine spatial forms and movements, including translation and rotations, and spatial orientation or perspective taking (Hegarty & Waller, 2004). Padalker and Ramadas (2008) add that students also need to coordinate views from locations on Earth and from space. The locations on Earth need to include those in the Northern and Southern hemispheres.

Explanations of the day/night cycle, phases of the moon, seasons and the tides make use of Copernicus' heliocentric model of the solar system that involves a spherical Earth rotating on its axis and revolving around a spherical Sun, and a spherical Moon rotating on its axis and revolving around the Earth. The dynamic system of three celestial objects is held together by gravitational forces. In developing an understanding of this complex model Lyn and Sally constructed a sequence of activities that began with a basic model of Earth as a spherical object in space and then exploring more complex models leading to the Copernicus' heliocentric model of the solar system. An account of these activities is given in the following sections which begin with the introduction of the globe as a model of Earth in space.

Introducing the Globe as a Model of Earth in Space

Lehrer & Schauble (2003) suggest that physical models are fruitful places to begin the modeling game, which is what the teachers employed to begin the lesson sequence. They presented the Year 8 students with a globe as a culturally accepted scientific model which represents Earth as a spherical object in space. The ways in which the globe can be considered a representation of Earth are often not explicitly discussed by teachers. Sally and Lyn began by explicitly discussing the partial nature of representations in the context of eliciting from the students both positive and negative attributes of Earth as being represented by the globe. This was done as a brainstorming exercise.

In Sally's class the students quickly generated the following list of attributes (Table 7.1) which were written on the board.

Table 7.1. Students' responses of positive/negative attributes of the Earth that are shown/not shown by the globe

The Globe shows	*The Globe does not show*
Earth is round	Day & night
Earth has oceans	Gravity
Earth rotates about axis	Weight of Earth
Earth is tilted	Mountains

The students' response that Earth's mountains were not represented by the globe opened up further discussion. Sally made explicit links between different modes of representation in generating the view that because of the very small scaled size of the globe when compared to the size of the Earth the mountains would be represented with negligible height on a globe. She did this by getting the students to explore the globe through sight and touch. This raised an issue of conflicting findings as, by sight, it did not appear that mountains were represented. However, by touch the students could feel slight bumps on the globe in the region of the Himalayas.

The issue of whether the mountains were accurately represented by the height of the bumps was then explored by the class. Sally introduced the mathematical idea of diameter gesturing its meaning on the globe and illustrating this on the board (Figure 7.1). She then explained the scaling process using hand gestures linking the numerical values for the Earth and globe diameters and the height to the highest mountain, Mount Everest, written on the board to the actual globe. The scaled globe height for Mount Everest was given by Sally as 0.01 cm, which the students converted to 0.1 mm. Finally, the students were asked to get out their rulers to then look at them to see what distance 0.1 mm might look like. The question, "*Can the globe represent mountains?*", asked of the class by Sally, was then emphatically answered by the students as "*no*". To create a coherent narrative of her reasoning to establish that Earth's mountains could not be represented in the globe the video record showed Sally moving flexibly between multiple representational modes – gesture, talk, diagram, and 3D model. In regularly questioning the students during this process she ensured that the students were able to follow her reasoning.

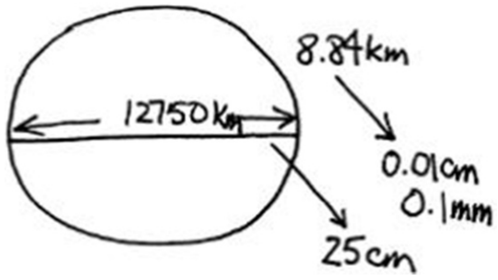


Figure 7.1. Copy of Sally's board work.

Constructing and Testing Dynamic Models of Celestial Objects

A key aspect of the Sun, Earth and Moon model is their relative motion with respect to each other; in particular, the motions described as rotation and revolution. It was these types of motion that were explored by Lyn and Sally's classes following their discussion about the globe as a physical model of the Earth.

Lyn spent some time connecting the everyday language of orbit and spin with revolution and rotation. The meaning to the scientific terms was generated through the use of everyday language. This was done initially by Lyn when she asked the class, "What are some of the movements that you know that the Earth does?". The student responses included, "Spin, revolve, rotate, turn, orbit".

In Sally's class the initial discussion about the types of motion Earth undertakes involved students being requested by Sally to re-represent verbal statements such as 'it turns on its axis' to indicate their understanding by manipulating the globe.

> Sally: Can you show the class what this means with the Globe [student demonstrates with the Globe].

Both teachers gave their students a representational challenge to initially pair up and show, through the physical action of their bodies, the motions of rotation and revolution. The students were able to demonstrate their understanding of these motions through the role-play models they constructed.

From this initial challenge the teachers each set a further challenge for the students that involved them reasoning with their role-play models.

In Sally's class pairs of students were challenged to show if it was possible to revolve around each other. It was evident that the students found this representational challenge a problem in that there wasn't a solution readily apparent to them.

However, the video record showed that through the interplay of discussion and physical movement several pairs of students came to a solution. The students reasoned that in 'running' their role-play models each partner in the pair felt that from their perspective they were revolving around their partner.

In enacting a representation construction approach the student generated models were evaluated by the class who determined if the models satisfied the parameters of the challenge. When one pair of students successfully presented their role-play model as a solution to the challenge Sally then presented them with a further representational challenge. She asked, "*How would you show what you did on the board? I want you to think about different ways of showing a representation of a concept or a phenomenon.*"

The students initially found this representational challenge difficult which they resolved through 'running' their role-play model. The students came up with a diagram (Figure 7.2 left image), drawn by one of the partners, after realising the need to have a central point of revolution. The video record showed the students constantly moving between their role-play model and their diagram discussing how to link corresponding elements of the role-play model and pictorial representation.

Sally then asked the pair to re-represent the diagram showing just the paths of the feet; this is shown by the diagrams on the right in Figure 7.2; one student's representation is shown on top, the other student's representation is shown below. A realisation then came from each student that the feet trace out intersecting circles.

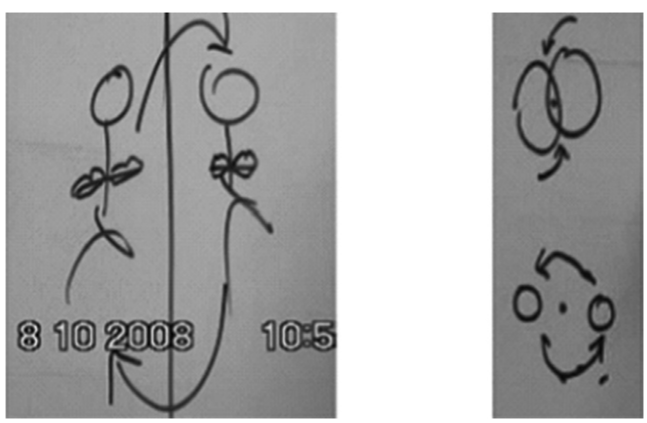


Figure 7.2. Video record of student generated representations of two objects revolving about each other.

This activity led to a discussion, initiated by Sally, about mutually revolving celestial objects found in binary star systems and which exist in the universe. The representational challenge of re-representing the role-play in terms of a 2D drawing enabled the students to gain greater insight into the motion of mutually revolving objects than via the role-play model alone. The visual/spatial record revealed the patterns of movement over time, and the centre of these revolutions.

The modeling process in science involves a two-way mapping exercise between the model and the target. The attributes of the target are mapped onto a suitable model with corresponding attributes. The model is then interrogated to determine if other attributes of the model can be mapped onto the target. In this instance the model is used as a tool to make predictions about aspects of the target.

In this activity Lyn and Sally had students beginning with the role-play model and then explored what attributes of the model might correspond to the target. Lyn's phrase to the students in relation to this activity was, "*Let's do some reverse thinking*". With the guidance of the teachers the students found applications of their models to represent the motion of stars within binary star systems and the revolution/rotation motion of the Moon with respect to the Earth.

Thus, in these activities the role-play model was used as a reasoning tool to enhance student learning. This was evident in the video record, and also in interview with students endorsing the role-plays as providing fresh insights. For example, one student responded: "*I found the orbiting and noticing which wall you were looking at. If the moon was rotating, that helped, because up to that point I didn't think the moon was rotating. If you were looking at different walls then you knew it was rotating*". Rather than just being told that the moon rotates was not enough. The student recognized this through the running of the model. The kinaesthetic experience of the role-play model gave this student the reasoning tool to consolidate the idea of the moon rotating as it orbited.

Models of the Day/Night Diurnal Cycle

Both teachers explored with the students three different representations of Earth's day/night cycle. These included:

1. a globe representing Earth in space and a torch representing the Sun;
2. a time lapse photograph (Figure 7.3) taken over a period of five hours of the setting Sun over Antarctica on the Summer solstice (Southern Hemisphere); and
3. a diagrammatic explanation of day and night for an observer in the Southern Hemisphere (Figure 7.4).

Lyn's approach was to first present the students with a globe which she had attached two small figurines. She explained that one figurine, called Bruce, represented an observer in Melbourne, Australia and the other figurine, called Chuck, which represented an observer in Los Angeles, USA. A strong light source, representing the Sun, emitted light that illuminated the globe. Lyn slowly rotated the globe and in doing so asked the students what Bruce and Chuck were doing in their daily lives for particular orientations of the globe with respect to the light source. For various orientations the students were able to correctly predict plausible actions of Bruce and Chuck. For example, for one orientation "*Bruce is sleeping*" whilst "*Chuck is*

Figure 7.3. Time lapse photograph of the setting/rising Sun over Antarctica (Wayne Papps, photographer Australian Antarctic Division).

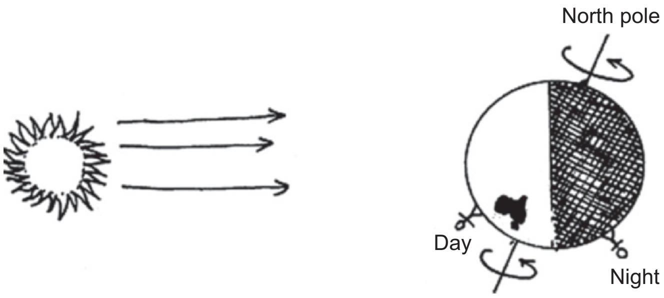


Figure 7.4. A diagrammatic representatin of day and night for an observer in the Southern Hemisphere.

having lunch" or "*Chuck is getting out of bed*" whilst "*Bruce is just going to bed*" for another orientation. The class then evaluated this model when Lyn asked, "*Has this representation explained day and night?*"

Lyn then presented the students with paper copies of the time lapse photograph (Figure 7.3) and the diagrammatic representation of day and night (Figure 7.4). Discussions ensued as to how these representations are linked to the globe/strong light source model and each other. For example, Lyn asked the students to explain using the globe/light source model how the images of the Sun in the time lapse photograph could arise. One student demonstrated his understanding by manipulating the model to indicate that one full rotation of the globe still illuminated the South

Pole end given the tilt of the globe's axis. This activity was an example of explicit mapping across different modes of representations.

In a later lesson Sally showed the students an animation of a rotating Earth being illuminated on one side by a distant Sun. This dynamic representation was critiqued by the class in terms of its affordances and constraints in explaining aspects of the day/night cycle. The students were quick to point out that the representation didn't show the tilt of the Earth with respect to the plane of its orbit around the sun.

Models of Lunar Phenomena

Towards the end of the sequence the teachers allowed the students to choose their own representational forms when attempting the representational challenges. For example, Sally presented the students with a representational challenge, where pairs of students were given 10 minutes to work on a suitable explanation of the key ideas expressed in the following text taken from a website source (Larson, 2008):

> The dark side of the Moon is the hemisphere that is facing away from the SUN and thus is not getting any light. Since the Moon does not have an atmosphere, the dark side of the Moon is very, very, very dark! When we are viewing a new Moon, we are looking at the dark side (which is usually slightly lit by light reflected from the Earth). During a new Moon, the dark side is the same as the near side. When we are viewing a full Moon, the dark side is opposite from us – the dark side is the same as the far side here. In between the new Moon and the full Moon (and back to new again), we are seeing various fractions of the Moon lit by the Sun, and the remaining fractions being the dark side. So, the near side is that side always facing the Earth, the far side is the side always facing away from the Earth. The dark side is the side facing away from the Sun, and the bright side is the side facing towards the Sun.

One pair of students was asked to present their explanation to class. They chose to use a globe to represent the Earth, a torch to represent the Sun and a ping pong ball to represent the Moon. In their explanation they also showed that the Moon was orbiting in a different plane to the Earth to account for the observation that the Moon does not eclipse every half cycle. This conclusion was also reached by another student pair in its deliberations in unpacking the text. This was illustrated in a comment made by one of the students in a post-topic interview.

> …with Harry we were doing the phases of the moon when we drew it (on an orbit diagram) we thought if the moon was here [indicating the location of the full moon] there would have to be an eclipse but if the moon was tilted up in relation to the earth and the sun then this could happen. We understood it a lot better.

To interpret the text related to the dark side of the moon another pair of students constructed an annotated diagram (Figure 7.5). The diagram provides two perspectives, one by an observer looking down from above Earth and the other from an observer located in Australia.

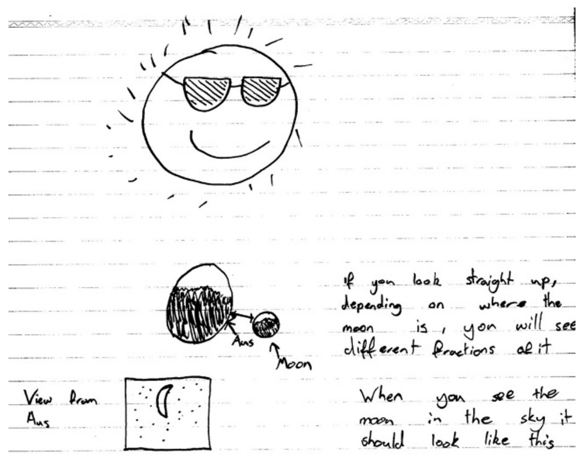


Figure 7.5. Student's re-representations of the dark side of the moon text.

The case study of Lyn and Sally's sequence on the sun-earth-moon system demonstrates a number of aspects of modeling within a representation construction approach, for instance:

- reasoning about astronomical phenomena involved the coordination of a variety of models, each of them providing a selective focus;
- the representational challenges involved students constructing models, extending the use of existing models, coordinating models, and identifying the particular affordances of each;
- the coordination of models involved mapping of attributes across models, and between models and target phenomena; and
- students were engaged in meta-representational thinking about the nature of models and their affordances, modeling, the adequacy of models, and fit for purpose.

The reasoning illustrated in the case can be understood as movement around the Peircian meaning making triad, coordinating multiple models with aspects of lunar/ solar phenomena to generate meaning.

CASE OF THERESE: TEACHING IDEAS ABOUT MATTER

Therese was a secondary school teacher with just three years' experience who taught the topic of Ideas about Matter to her Year 7 students. The curriculum content of the topic involved the states of matter and their properties and introduction to the particle theory. Therese's participation in the RILS project was only in relation to the teaching of this topic. The Ideas about Matter sequence has been chosen as a case in this chapter as it illustrates the ways in which explanations of specific macroscopic behaviour of matter involve the construction of particle-type models of the sub-microscopic domain. In focusing on a particular property of matter the particle-type models are designed with a specific purpose in mind and are therefore partial in nature.

Whilst the particle theory of matter is commonly introduced into the early years of secondary schooling in most countries the research shows poor understanding of the theory among secondary school students (Kind, 2004). Johnson and Papageorgiou (2010) advocate a different teaching approach to the common three states of matter framework when introducing the particle theory whilst Adbo and Taber (2009, p. 758) argue that particle models are often taught "as unproblematic representations of nature, with no explicit acknowledgement that what are being discussed are models. Often the scope, limitations or roles of these models are not presented to learners." This finding supports Lehrer and Schauble's (2003) argument that modeling by students needs to be practiced on a sustained level in the classroom. This was the case in Therese's teaching sequence where students constructed, critiqued and modified models to explain specific macroscopic properties of matter. In addition, Therese chose not to introduce the particle model through the three states of matter. Instead, she gave series of representational challenges with the students constructing models of samples of substances with respect to specific properties of the samples. The particle model is often introduced to students as a set of key elements such as the following set described by the Year 7 students' textbook:

- According to the particle model:
- All substances are made up of tiny particles.
- The particles are attracted towards other surrounding particles.
- The particles are always moving.
- The hotter the substance is, the faster the particles move. (Lofts & Evergreen 2006, p. 86)

Therese chose not to introduce all of these elements when introducing the particle model. Instead, she gave a series of representational challenges where students would engage with one or two of the elements of the particle model at a time. An account of classroom activities is given in the following sections which begin with an exploration of the properties of samples of substances.

Exploration of the Properties of Samples of Substance

Early in the sequence Therese followed up issues that arose during the pre-test. These involved students' alternative conceptions that substances like oxygen or carbon dioxide are always gases. Students also tended to classify matter as solids, liquids and gases without being aware of the possibility of mixtures. Therese negotiated the language of sample, substance and object to clarify distinctions within categories of matter. An object is made of substances and samples of substances can be in different states. The class also negotiated representations of the range of substances and states of matter, including the Venn diagram and continuum representations described in Chapter 3. These approaches drew on the ideas of Johnson and Papageorgiou (2010).

Also, following the pre-test, early lessons in the teaching sequence involved the students exploring the macroscopic properties of different substances. For example, investigating the properties of a rubber band or a stick of chalk and finding that the rubber band was elastic whilst the chalk was brittle.

Introduction of Particles as Constituents of Matter

Particle ideas were introduced to the students to construct their own models to explain specific properties of a sample of a substance. The students were told that scientists, whilst being unable to see inside matter, imagine samples of substances to be composed of tiny particles. A discussion arose as to evidence to support this view with the class concluding this this idea was plausible as any object can be physically destroyed into small and smaller parts. The view that samples of objects could be made up of particles was already evident in the students' prior knowledge. Figure 7.6 is a schematic of the two types of representations drawn by the students in the pre-test when they were asked to draw what they could see if they had a super-magnified view of solid wax.

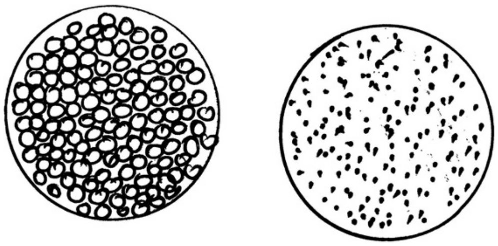


Figure 7.6. Student representations of a super-magnified view of solid wax.

Representing the Macroscopic Property of a Solid to Hold Its Shape

The students were initially set a representational challenge to construct a model, using a pictorial representation of particles, to explain one aspect of a target, which in this case was the property of a piece of paper to hold its shape. After students undertook this task three students were chosen to share their models with the rest of the class after they drew them on the board (Figure 7.7). Each model was evaluated by the class as to whether it served its purpose, that is, to explain using particle ideas how the piece of paper could hold its shape. The class agreed that the middle and right models fulfilled the purpose in that there were particles that were connected. The model on the left was judged to show particles but not connectedness. This model might be construed as representing a microscopic view of the paper, showing fibres, but this was not explored by Therese with the particular student who constructed the model.

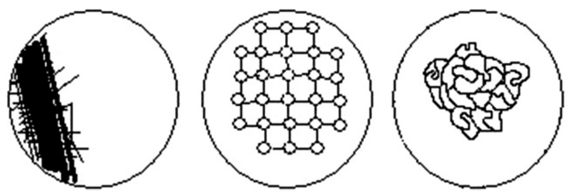


Figure 7.7. Year 7 students' particle models to explain how a piece of paper holds its shape.

The student who constructed the middle model in Figure 7.7 spoke about the links between the particles as being bonds. Therese spoke about how this term was used by scientists when describing the connections between particles. Whilst there wasn't any class discussion as to a preferred way to represent bonds subsequent to the class critique of these three students' models all students began drawing lines between particles in their models when representing bonds.

Again drawing on the key element of the particle model that particles are attracted to surrounding particles another challenge for the students was to draw particle models to explain why a rubber band is able to be stretched without breaking (Figure 3.9 in Chapter 3 provides examples of student models that are scientifically correct). Figure 7.8 below shows another student model, however, this one indicates an alternative conception where the student has indicated that the particles are also stretched.

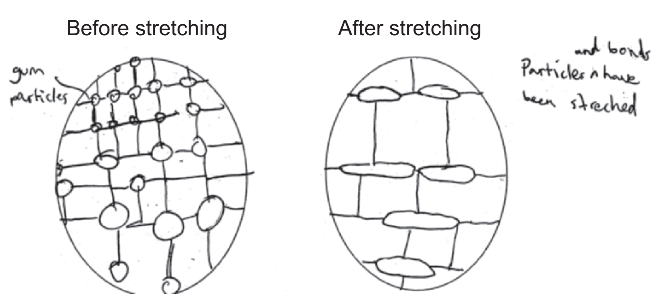


Figure 7.8. Year 7 student's particle model to explain the property of a rubber band to stretch without breaking.

Introduction to the Concept of Temperature from a Particle Perspective

The following activities undertaken by the class revolved around Therese's objective for the students to find meaning for the concept of temperature from a particle model perspective. The pre-test indicated that two alternative conceptions, held by most of the students, needed to be addressed. These were that the temperature of an object could reach less than −1000 °C and molecules inside liquids and gases are moving but in solids they are stationary.

Therese initially presented the students with the scientific fact that the temperature of an object cannot be any less than −273 °C and that temperature is understood by scientists as a measure of the motion energy of the particles that make up the object. As part of a class discussion Therese gave a small group of students the challenge to create a role-play model of a piece of paper showing the property of the paper to hold its shape to be critiqued by the rest of the class. The students grouped together quite closely linking arms to represent bonds.

Therese then asked the students to modify their role-play model to now account for the dual properties of the paper's ability to hold its shape and be at room temperature. The students initially found they couldn't individually move but could do so if they made some space between themselves. The students displayed a vibrating motion, to present the temperature of the paper, whilst holding hands, to represent the ability of the paper to hold its shape. Therese then quizzed the students on the type of motion they were undertaking. This led to a description of the motion as vibration, which Therese confirmed as a word that scientists use for particle motion of samples of substances in the solid state. Therese then asked the whole class to re-represent the role-play model in a pictorial representational mode (Figure 7.9). The particle models in Figure 7.9 show two different ways of representing motion. This raised an issue for the class in terms of communicating ideas though symbols. It was agreed by the class that where symbols may not be commonly understood annotations may be required for the pictorial models. This is seen in the Figure 7.9 models.

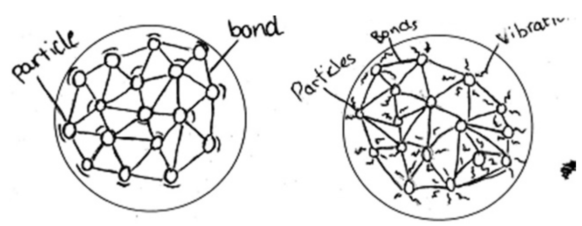


Figure 7.9. Student's particle models to explain the dual properties of a piece of paper holding it shape and be at 23 °C.

Multiple Models to Explain Macroscopic Behaviour of Matter

When challenged to construct particle models showing different samples of substances, like paper and plastic, the students created quite different models

(Figure 7.10). The three models in Figure 7.10 are quite distinct and yet were all judged by the class in terms of fulfilling their purpose, that is that paper and plastic are made up of small particles. The top model in Figure 7.10 represents the particle quite differently. It shows a movement away from the textbook convention of representing particles as circles. The other two models in Figure 7.10 show variation in particle arrangement and variation in bonding. Whilst none of these models would ever be found in a textbook they are nonetheless valid models in terms of their power to explain the given properties of the samples of substances that were given. What would be useful as an extension activity to a class critique of these models would be a discussion as to what other properties of paper and plastic are shown in these models.

For instance, whilst the intentions of the students drawing these models are not known one might argue, say for the middle model, that the close arrangement of the particles represents another property that the plastic is stronger than paper. For the bottom model the allowance for the bonds between the plastic particles could account for the property of the plastic to stretch whereas this is not represented in the bonds between the paper particles representing the paper's inability to stretch. The teacher could also add to this discussion by suggesting that scientists believe that different properties of samples of substances can be accounted for in a number of ways that include the types of particles, their arrangements and types of bonding.

Models of States of Matter

The application of the particle model to explain the states of matter occurred well into the teaching sequence although there were some challenges where students needed to represent samples of substances in different states. Figure 7.11 shows two examples of models of chocolate constructed by the students. The top model has represented the change of state with increased bracket symbols to represent an increase in temperature and curved lines between the particles to represent decreased bond strength. The bottom model shows an alternative conception where the student believes that the particles undergo the same macroscopic behaviour as the sample of substance.

To formally introduce the particle model to explain changes in state Therese showed the students a series of animations of particles in a solid, liquid and gas state. The animations also represented samples of substances changing state. She asked the students to first of all describe the motion of individual particles in each of the states. The students had already established that the particles representing a sample in a solid state were vibrating. They came to a consensus view that the particles representing the sample in a liquid state were moving around each other and that the particles representing the sample of a substance in a gaseous state were moving in straight lines. She then gave the students the challenge to represent the three states of a sample of a substance in pictorial form.

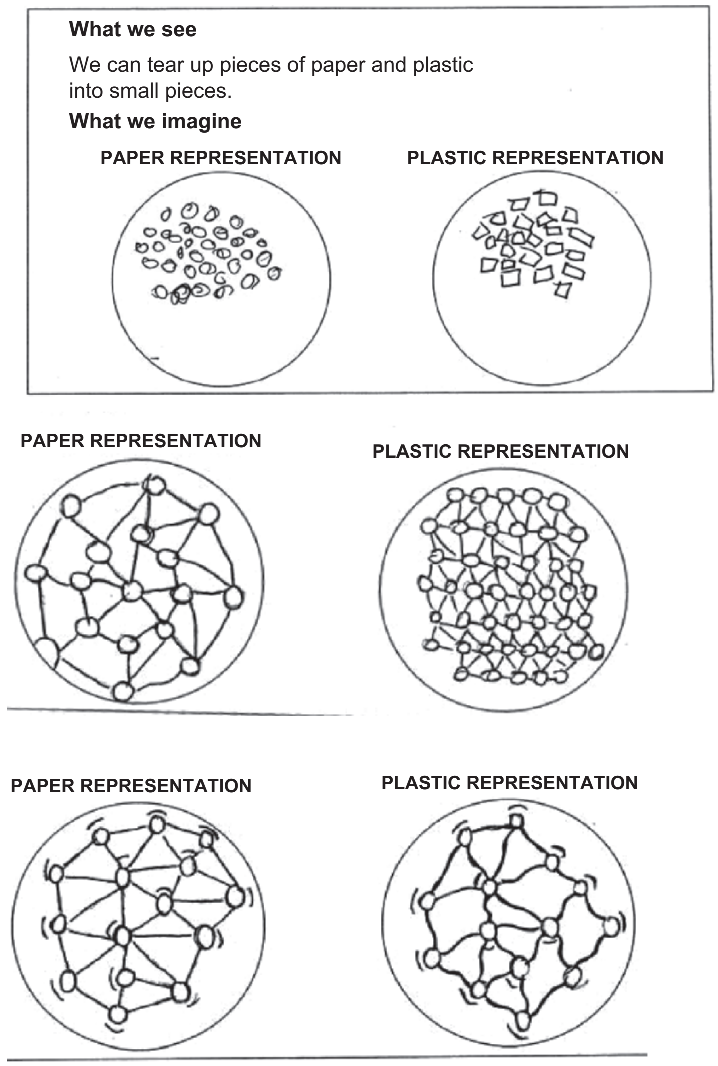


Figure 7.10. Three students' particle models of paper and plastic.

To offset the need to annotate their models where different symbols were used Therese initiated a class discussion whereby the class came to a class-based convention to illustrate particle movement representing different states. This is shown in the top model of Figure 7.12 where brackets were used to represent particle vibration, curved arrows to represent particles moving around each other and straight arrows to represent particles travelling in straight lines. Class consensus

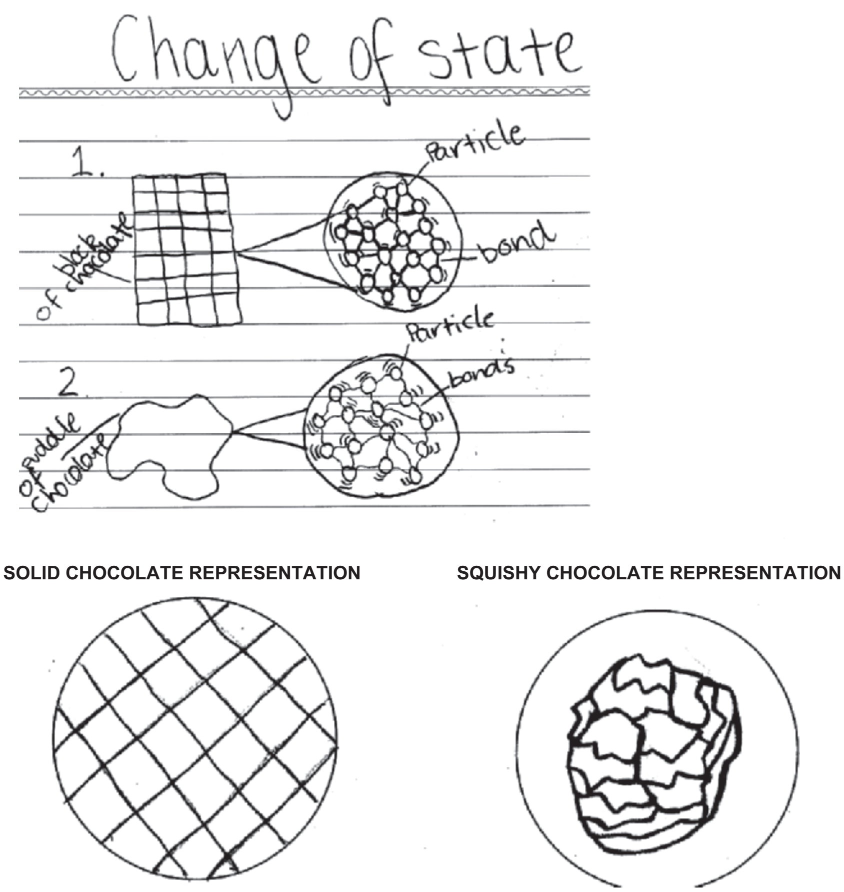


Figure 7.11. Student particle models of chocolate melting.

of the symbolic representations used by the students only occurred for the meanings of symbols representing particle movement. Students were at liberty to use their own symbols if annotations also accompanied the symbols. This is shown in the bottom model in Figure 7.12 where the student has represented particle vibration differently to the class convention and has represented strong bonding with thick lines.

As for the astronomy case, the modeling practice in this sequence illustrates the nature of representational challenges, involving students extending their representatonal resources, the public negotiation of the adequacy of the models, the existence of a range of acceptable models without a sense of homing in on one solution, and the promotion of meta-representational knowledge of the construction and role of models in knowledge building in science. This modeling practice, we would claim, mirrors the modeling practices in science itself.

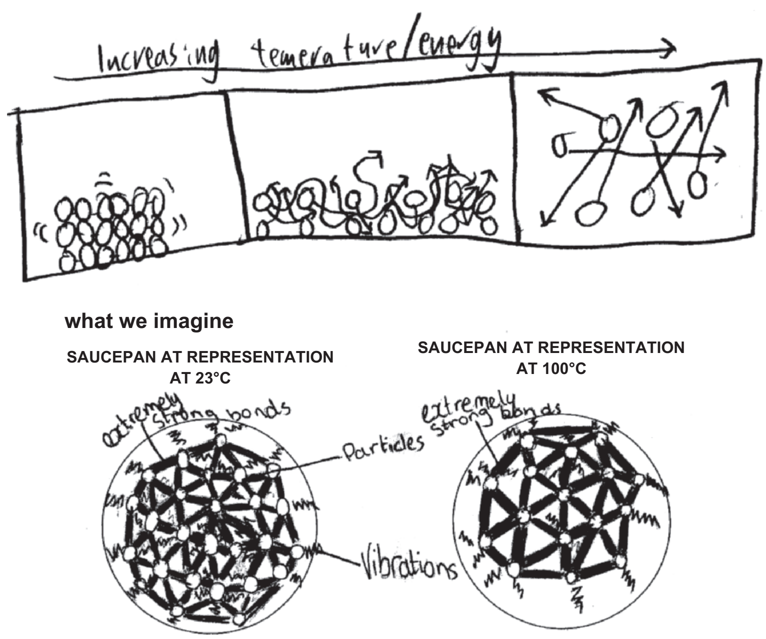


Figure 7.12. Student's particle models of matter.

TEACHER SUPPORT OF MODELING

The cases above demonstrate considerable pedagogical skill achieved by teachers in developing representational challenges and supporting modeling practice through challenge, and public negotiation of representational adequacy. They became adept at framing the challenge and the support to allow students freedom to produce a variety of models but constrained to the extent of arriving at productive outcomes. The sequences constitute clear evidence that these three teachers had a sophisticated understanding of the relationship between models and knowledge and learning in science.

With the primary school teachers we had the opportunity to observe the growth in sophistication of support for modeling practice, and the effect of this on the quality of student models. The animals in the school-ground unit was repeated two years after the initial 2007 experience, again involving the construction of a model of animal movement. The centipede example in Chapter 3 was from 2007 while the techno-worm in Chapter 1 was from 2009. In the second iteration the teachers gave less time to the construction phase, less support to students to amass standard modeling materials such as clay or lego, and there was a much more explicit focus on the purpose of the model to represent movement, distinct from physical reproduction of the animal. In 2009 Lauren, for instance, in moving round groups as they worked, focused their attention explicitly on the need to clearly model movement:

> The people that are going to be representing [movement of] worms somehow, you are going to really **think** how you are going to show [movement], and what kind of [pause] equipment [pause] material you are going to use to represent that?
>
> [19:18] "They are good, great diagrams. You don't have to draw the exact creature, but you have to show how it actually moves. Order, when that one goes when, [points out] when that one goes when." [Clarifies], so the front legs moves,
>
> [21:08] "Now do they move together? At the same time? So how are you going to show me that?"
>
> [21: 51] Show me in a diagram, show how it moves, that is interesting [reads annotations] the back one moves, then the middle one moves, then the back one moves again. Is that every time it …

The result was that the models in this second iteration were less focused on reproducing the animal's overall structure and more focused on the movement structures and mechanisms. The models from these occasions were classified into three groups: those that described the form of the animal generally (Level 1), those that modelled the physical structures of movement but required separate explanation to show how the movement occurred (Level 2), and those where the model attempted to model both movement structures and processes (Level 3). Both the centipede and techno-worm were level 3 models. The breakdown of numbers of models across these categories, shown in Figure 7.13, demonstrates the move towards explanatory abstraction supported by Lauren's explicit scaffolding.

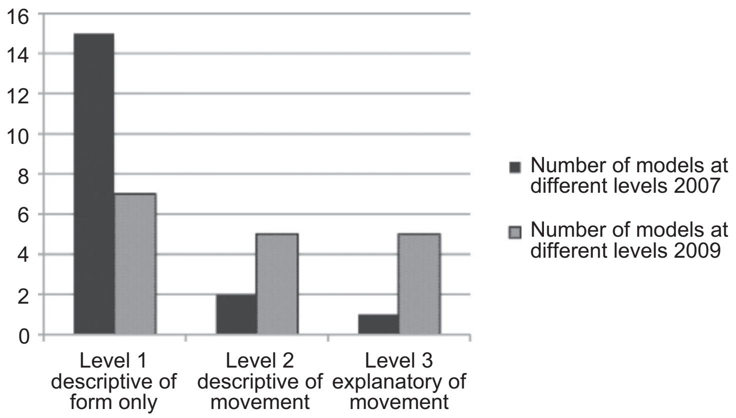


Figure 7.13. Comparison of explanatory abstraction in models in 2007 and 2009.

CONCLUSIONS

The accounts of the teaching sequences that have been presented in this chapter do not include all activities that were undertaken by the students and their teacher but do provide insights into the representation construction approach that require the students to gain some understanding of the canonical models that underpin each topic. In the case of the topic of astronomy the key scientific model is the visual/ spatial Copernican/ heliocentric model, which involves a rotating spherical earth revolving around a spherical sun and a rotating spherical moon rotating around the earth. In the case of the topic of Ideas about Matter the key scientific model is the abstract particle model, which has several key elements, such as particle movement and attraction between particles. The particle model in reality is not a unitary entity, but encompasses a multitude of possible models / representations – of bond arrangements, of modes of interaction, of shapes – that are played out for instance in the multitude of animations we might find on YouTube. These models can be of a variety of modes and types, from physical reproduction to quite abstract. The term 'particle model' or 'particle theory' is thus code for a complex and situated range of modeling practices and resources that allow us to explain an enormous range of phenomena. It was this feature of models that informed the teaching and learning of the topics of Astronomy and Ideas about Matter. The models that the students produce, of particle arrangements and bonding to explain macroscopic properties of materials, or particular representations of the sun-moon system, are imaginative extensions of representational resources to solve a particular problem. They are situated and individual, unresolved and approximate.

We claim that these student generated models differ from 'scientific' models not in any principled way, because of this unresolved and approximate character, but rather in the degree of 'finish' that comes in science by extended processes of development, challenge, appeal to evidence, and peer acknowledgement. Scientific models are constructed and modified to account for as many attributes of the target as possible. They are 'stretched' as part of the scientific modeling game (Gilbert & Boulter, 1995). We would argue that modeling practice in science moves from first, speculative constructions, possibly individual but often the result of group processes, to more refined and evidence-based, peer-reviewed models. This being the case, they are always selective, focused on solving particular problems, and incompletely resolved, as is the case with student models. These student models cannot be thought, then, as somehow illegitimate.

Even with a physical system such as the sun-earth-moon, the heliocentric model is code for a complex of associated models. While it might be initially tempting to consider a scale model of the system as a 'complete' sun-earth-moon model, models always involve a degree of abstraction – a system cannot be a model of itself. The situated models through which we might focus on particular aspects of the behavior of the system, from different perspectives, include abstractions like tables and graphs and targeted perspectival distortions.

Each of these models /representations focused on explaining a specific aspect of a phenomenon. These representations might be thought of as particular windows into the system that help explain aspects of phenomena. They are tools through which we see the system in particular and fresh ways. They are models by virtue of the fact that they are explicitly constructed and to some extent resolved abstractions intended to offer explanation/interpretation. The RILS teachers over time refined their strategies to encourage their students to model in a more selective, focused way, as illustrated by the animal movement modeling case.

This distinction between the refined, 'stretched' models of science, and students' less resolved, speculative models, can be informed by our distinction between representations and models. These models are all representations in that they purport to signify an aspect of the real world, the referent. However, in constructing and refining and communicating these models/representations we have offered many instances of students using informal, contingent and ephemeral representations such as gestures, turns of phrase or preliminary sketches that are not intended to offer a resolved version of a phenomenon but are part of the resources constituting an integral part of the modeling practice. Such representations we do not consider as models – they are transitory and lack considered intention to represent, as is the case with a model.

Through the representational construction approach the students were often challenged to construct models not only to demonstrate their understanding but also to use them as tools to solve problems. This sustained modeling practice provided students not only with access to substantive astronomical or particle ideas but also into this fundamental process through which scientists generate models to generate explanatory accounts (Schwarz & White, 2005). Models in science are generated to solve contextual problems and are part of the situated activity around which ideas are generated to make sense of phenomena. Similarly, student model generation should be situated in a genuine need to explain or solve a problem and are legitimate as representations and not subservient to canonical versions. This was the case in both teaching sequences. The students often generated models in response a challenge to explain or solve a problem, which were not the canonical versions and would never be seen in any textbook, but were nonetheless legitimate from the perspective of satisfying the purpose for which they were constructed.

Apart from learning to understand scientific phenomena though the use of models and actively participating in the modeling processes another important student learning outcome is to understand the role of models; meta-representational understanding. By constructing and peer-critiquing these models the students enhanced their understanding concerning the principled need for adequacy and fit-for-purpose of these models. Examples of such student outcomes were offered in Chapter 3.

In this chapter we have described sustained modeling practices in science classrooms, as a particular perspective on the representation construction approach. These have led to substantial student engagement with key science ideas in astronomy and substances. The approach differs in two important respects from traditional characterisation of modeling in school science: a) there is a strong focus on the construction and public negotiation of models that are informal and not necessarily consistent with canonical textbook accounts, and b) the key focus is on the use of models as tools to generate explanatory accounts, rather than on the achievement of coherent models envisaged as conceptual structures. We argue that traditional characterisations of mental models as key elements of conceptual change treat them as overly structural and resolved, and do not capture the way students, or scientists, develop these practices leading to the construction of complexes of refined, evidence-based models. We have argued that significant scientific models such as the particle model, or the heliocentric model of the solar system and associated earth-moon system models, in fact consist of a range of specific, situated models and modeling practices that constitute the representational resources that students need to build in order to engage in developing explanatory accounts of phenomena. What we are offering here is a successful pedagogy, but also an account of the ontogenesis of models as they are practised in science. Models do not appear from nowhere – the scientific community builds them from representations that are situated, multi modal, and often personal. This is the process we are describing, translated into the classroom, in these sequences.

PETER HUBBER

CHAPTER 8

TEACHER PERSPECTIVES OF A REPRESENTATION CONSTRUCTION APPROACH TO TEACHING SCIENCE

The representation construction approach detailed in Chapter 3 evolved from an ongoing collaboration between researchers and participating teachers. This chapter explores the teachers' perspectives of the approach as it developed over the life of the Role of Representations in Learning Science (RILS) project. The teachers became strong advocates of the representation construction approach, and what follows are their accounts of what it offered their practice and to explore what it was about the approach that they came to value.

To provide insight into the teachers' perspective, case studies are given of two secondary teachers whose participation in the RILS project extended over the life of the project. This chapter also raises the question of the potential of the representation construction approach to achieve wide scale acceptance, based on the experience of a teacher involved over a shorter period of time with the project.

THE RILS TEACHERS

Over the duration of the RILS project the researchers studied classroom sequences taught by 10 different teachers. The sequences were in a wide variety of topics that included Light, Astronomy, Forces, Motion, Cells and Genetics, Flight, Ionic and Molecular Structure, Living Things, Substance, Water, Energy and Ideas about Matter taught to students of various middle years levels (Years 5–10). Of this cohort of teachers the researchers worked particularly closely with five teachers in topic development, involving determination of the key concepts and skills that framed each topic and exploration of how the representation construction approach might be applied to teach such concepts and skills. Table 8.1 provides the dates, topics and Year level of students for these five teachers. It shows that there were two sets of teachers, Lyn/Sally and Lauren/Malcolm, who worked on the RILS project for four sequences each whilst Therese only became involved for one sequence. Although there was collaboration of the teachers with the researchers in topic development

R. Tytler, V. Prain, P. Hubber and B. Waldrip (Eds.), Constructing Representations to Learn in Science, 135–150.

these teachers were ultimately responsible for the operation of the ideas in the classroom and increasingly became autonomous advocates of the representation construction approach.

Among the secondary school teachers Lyn and Sally were both experienced classroom practitioners whilst Therese was just in her third year of teaching. It is quite common for teachers in Australian secondary schools to teach general science to students at Year 7–10 level and specialize in teaching a specific science discipline in Years 11 and 12. Lyn and Sally were biology trained specialists whilst Therese was specialist trained in both Biology and Chemistry. Lyn and Sally taught at the one school and worked closely together in planning and implementing the topics that were taught, whilst Therese taught at another school.

Table 8.1. Topic sequences taught by the teachers in collaboration with the researchers

Date	*Topic*	*Teachers*	*Year level*
Sept. 2007	Forces	Lyn/Sally	7
	Animals	Lauren/Malcolm	5/6
May 2008	Substance	Lyn/Sally	8
	Water	Lauren/Malcolm	5/6
Aug. 2008	Astronomy	Lyn/Sally	8
	Energy	Lauren/Malcolm	5/6
May 2009	Forces	Sally	7
	Animals	Lauren/Malcolm	5/6
Feb. 2010	Ideas about matter	Therese	7

The primary school teachers, Lauren and Malcolm, were both experienced classroom practitioners and taught at the same school. They each had responsibility for a single Year level class but often brought their classes together and team taught the combined class. They did this when teaching the science topics as part of the RILS project. Like Lyn and Sally these teachers worked closely together in planning and implementing the science topics.

SUPPORT FOR TEACHERS IN IMPLEMENTING A NEW PEDAGOGICAL APPROACH

The support provided to the RILS teachers provided professional learning experiences that impacted on their teaching practices and perspectives of teaching and learning science. The professional growth of a teacher that leads to a change of practice should be considered as a result of a complex process (Clarke & Hollingsworth, 2002). The literature points to several factors that may support a teacher's professional growth in addition to indicating factors that might inhibit growth. One possible inhibiting factor to a teacher's professional growth is the extent of the teacher's professional knowledge.

A teacher's professional knowledge determines the role they play in providing learning environments that result in successful learning outcomes for students in understanding science. The teacher's professional knowledge needs to include content knowledge of the discipline of science and pedagogical content knowledge (PCK, Shulman, 1986). Shulman (1986) defined PCK as "the way of representing and formulating the subject that make it comprehensible to others... an understanding of what makes the learning of specific topics easy or difficult (p.9)". Gess-Newsome (2001) makes the point that superficial content knowledge may restrict the ability of the teacher to teach in a creative and innovative manner, which encourages and makes use of students' questions. Instead, teachers with a superficial content knowledge tend to limit the use of students' questions in classroom discourse and the development of conceptual connections. To support teachers who lack content knowledge Cohen and Hill (2000) suggest that professional development should focus not only on content but also pedagogy. This view is supported by Brunsell and Marcks (2005) who state that professional development in science education should "focus on providing teachers with a coherent structure and methods of communicating that structure to students…. [and] continuing support to participants as they deepen their content understanding and change their teaching practices (p. 46)". The representation construction teaching approach provided the teachers with a coherent structure and methods of communicating that structure to their students. This was particularly pertinent in those topics that were taught by the teachers who in the past had less confidence in teaching because of their perceived lack of content knowledge. The researchers provided continuing support to the teachers as they implemented this approach in all the topic sequences.

To enhance a teacher's PCK Danaia and McKinnon (2008) suggest that they need to have some understanding of common alternative conceptions, including ways of dealing with those alternative conceptions their students bring to the classroom. Bakkas and Mikropoulos (2003) point out that the sometimes limited success of conventional teaching methods in overcoming students' alternative conceptions may be due to a lack of appropriate teaching aids in the form of representations that can intervene dynamically in influencing the learning process.

Prior to the beginning of each topic the researchers collaborated with the teachers in identifying the key ideas and their representational forms that would guide the representational work to be implemented in the topic sequence (Principle 1 of the approach – see Chapter 3). Part of this topic development also included an exploration of the student conceptions literature, which was provided by the researchers. Common alternative conceptions were discussed and ways to deal with them came to be viewed as a representational issue. Out of these discussions activities to address common alternative conceptions, based on a representation construction approach, were generated and work-shopped by the researchers and the teachers. Discussion of key ideas and common alternative conceptions also led to the construction of diagnostic tests that were informed by the research literature and were administered to the students as one of the first tasks in the topic sequences.

The collaboration between the researchers and teachers took several forms. In team workshops, the researchers would sometimes model representation construction activities to implement in the topic sequence, with the teachers taking on the role as student learners. These workshops engaged teachers in concrete tasks rather than abstract discussions of teaching. During the lesson sequences brief conversations between the researchers and teachers often occurred following the video-taping of lessons. Extended meetings also occurred during the topic sequences at times when the teachers were not teaching. During these times the development of students' ideas, as evidenced by their responses to the representational challenges embedded in the representation construction approach, were often discussed. Such discussions informed future planning of the topic, sometimes involving ideas for activities, or offers of practical resource support such as digital microscopes. Following the topic sequences further meetings were held to reflect on the teaching and learning that had occurred and, in particular, the efficacy of the representation construction approach for improving student learning outcomes. Throughout the RILS project there was constant two-way communication between researchers and teachers in terms of sharing of ideas and discussing the progress of the lesson sequence.

The nature and duration of the support offered to the teachers over the period of the RILS project had a number of characteristics consistent with the literature on effective professional learning practices. This literature supports the view that effective professional learning should be directly aligned with student learning needs, is intensive, ongoing and connected to practice, and focuses on the specific teaching and learning of academic content (Gell-Newsome, 2001; Stiles et al., 2010; Wei et al., 2009). The RILS teachers adopted the representation-construction approach within topics they would normally be teaching. A focus on student learning needs was very much part of the teaching approach and professional learning support was ongoing for the duration of the RILS project. The teachers' participation in the workshops that preceded the topic sequences provided them with a greater sense of efficacy for teaching the topics. This is consistent with the findings of Wei et al. (2009) who found higher levels of teacher efficacy where the professional learning experiences gave teachers the opportunity to undertake hands-on activities which enhanced their knowledge of the content to be taught and how it is to be taught.

To provide insight into the RILS teachers' perspectives of the representation construction approach the next section provides cases of Lyn and Sally. The data sources drawn on for these cases included video of each lesson, student artefacts, students and teacher interviews, discussions with teachers at wider research team meetings, and field notes by the researcher who sat in on each lesson. The video data from each lesson came from two cameras, one which was directed at the teacher, and another on a group of students. Studiocode software was used to analyse the video data.

THE CASES OF LYN AND SALLY

As previously mentioned, Lyn and Sally were experienced teachers who taught at the same secondary school. These teachers decided on the selection of the topics for the RILS project and its timing in delivery. These decisions usually matched the teaching program followed by the teachers in previous years. As part of the RILS project Lyn and Sally taught three topics (see Table 1) to the same group of students. In the first topic the students were in Year 7 and around 12 years of age; the second and third topics were taught to the students a year later when they were in Year 8. The duration of each topic was 12–14 lessons; most lessons were 45 minutes in duration and every third lesson was 90 minutes duration.

Planning Stage of Topic Sequence

Being biology-trained specialists each of the RILS topics had content that was outside the teachers' discipline expertise so the challenge for them was a combination of content knowledge and PCK. The initial approach to planning the topic sequence was similar for each of the three topics and represents Principle 1a of the representation construction approach whereby *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.* The teaching sequences were therefore informed by a clear conceptual focus. The initial lessons in each sequence focused on exploration of students' prior views, generation of students' representations, and introduction of the scientific conventions that underpinned each topic. Each teacher followed a similar sequence of activities, but in fact the video record showed that each was different in the way they introduced ideas, led discussions, and achieved some form of closure.

In taking a conceptual focus to topic planning the teachers moved away from their previous practices. This was clearly evident in the forces topic which was the first of the three topics taught (Table 1). In previous years the focus was in covering the curriculum content contained in the students' textbook (Lofts & Evergreen, 2006), and the title of the topic, *Forces in Action*, matched the chapter title in the textbook. The textbook chapter, and subsequent teaching, moved quickly through a range of forces, for example buoyancy and surface tension, electrostatic forces, magnetic forces, electromagnetic forces, gravity and air resistance.

During the planning stage the teachers gained confidence in moving in a direction away from the textbook that framed their pedagogical approach to more of a conceptual focus. In reflecting on this change following the completion of the topic Lyn commented:

> Before we crammed it all in and didn't know what to cut out…we were so pleased to actually pause, particularly in that forces unit, which was so superficial and done so badly according to the textbook that we were using.

> We were so pleased to go into depth. And it was so lovely to be able to develop ideas with the kids.

The conceptual focus resulted in less curriculum coverage than in previous years with its textbook focus, thus illustrating a current science education reform push for the distillation of science content coverage to develop deep conceptual knowledge in students.

Prior to the Astronomy topic both teachers expressed a reluctance to teach it based on their perceived lack of content knowledge. For Lyn, Astronomy "*has been difficult* to *understand and teach*" and this meant that she taught this topic in the past with "*more delivery of facts rather than exploration of understanding*". For Sally, the topic of Astronomy was one "*I had never done it in school myself and I have never learnt the topic myself, only read it through books and watching movies and so on but it was the fact that it was the topic that was endless*". Her main concern was that "*the kids could ask you lots and lots of questions and I was aware that half the time I may not have the answers straight away and would need to come back to them later. I mean that was the fear factor*".

In taking a conceptual focus at the planning stage the teachers developed the view that rather than dealing with what Sally initially referred to as an *endless* topic, the topic of astronomy should focus clearly on a set of interconnected key ideas about astronomical phenomena that arise from simple dynamic systems such as the Earth, Moon and Sun connected by gravity. The team work-shopped activities that had a representational focus and discussed the implications of these for student learning bearing in mind possible alternative conceptions the students might have. The workshop activities resulted in a greater level of confidence by the teachers in tackling the teaching of astronomy. This was evident in the following exchange with Sally.

> Researcher: I remember you saying something after our first workshop that you felt a little bit more comfortable about teaching *[Astronomy]* so what was in the workshop that gave you that confidence?
>
> Sally: I think the role-plays, how to actually go about teaching the topic and using ourselves, using the models, and understanding of relative distances… I think that really was a wow factor and I put myself in the shoes of the kids and I thought, yes that would be something I could feel comfortable in teaching.

The representational focus to discussion and activities in the workshop placed demands not only on the teachers' pedagogical content knowledge but also their content knowledge. The teachers found that both types of knowledge were enhanced by this process.

Impact of Students' Prior Knowledge on the Teachers' Practice

The students' conceptions research formed part of the discussions that informed the planning of the topic sequences as well as the development of diagnostic tests. These were administered to the students in each of the topics. For the topics of substances and astronomy the tests were administered at the beginning of the sequences and covered most of the ideas to be taught whereas the test for forces was focused only on the students' ideas relating to gravity and was administered during the topic sequence.

For the substances topic the teachers had planned a topic sequence that extended on a previous year's topic on changes of state and particle model with the introduction of the concepts of atom, molecule, element, compound, mixture and pure substance. The diagnostic test that was developed explored the students' understanding of the previous year's topic which involved the particle model. When the test was administered the teachers were somewhat surprised at the prevalence of alternative conceptions elicited by the students. This prompted them to rethink the way they were teaching particle ideas about matter.

The substances diagnostic test responses indicated that whilst the majority of students understood the term atom and molecules they exhibited several alternative conceptions that indicated a lack of understanding of the use of the particle model to explain macroscopic properties of matter. The teachers realized that they had been teaching the particle theory as a body of knowledge itself and only loosely using it to explain macroscopic behaviour of matter. They now thought that the teaching approach needed to have constant movement between macroscopic behaviour of substance and particle ideas through various forms of representation that explain the behaviour. There was also a view that there needed to be an emphasis on evaluating the adequacy of a particular representation to explain a particular behavior. These views are reflected in the following comment by Lyn:

> So what we would have done before is teach the particle theory and then incidentally relate it to real life. But through teaching the Year 8s we realized that the model has to sit within everyday experiences. But you know we're not teaching the particle model as in, this is the model and see how it relates to real life. It's more, this is real life and we have a model and does it actually explain real life, and does it explain this and that? And particularly, one of the areas I focus on, is how good is the representation?

Lyn's comment not only expresses a change in pedagogical practice it also points to an epistemological change whereby, according to Lyn, "*The model has to sit within everyday experiences*" and is not separate to how one thinks about explanations of the properties of substances. In thinking about the implications from the substances pre-test results the teachers shifted to a greater attention to students' prior views.

The greater conceptual focus in each topic resulted in a greater perceived awareness of the students' developing understandings of the key ideas. This is illustrated in the following comment by Sally:

> I found it a real valuable experience and its interesting how we pick up all these misconceptions and it has been a challenging experience as well.

Sally saw direct benefit in gaining knowledge of the research literature in terms of students' alternative conceptions at the planning stage in suggesting:

> I find it deeply rewarding that here is a list of things that kids often get wrong, and I have a look at them and actually have a chance to stop the kids from developing really deep misconceptions, and I love that.

The teachers saw benefit in the knowledge gained from the diagnostic tests in terms of targeting the teaching in resolving misconceptions that arose and for the students to be made aware of their own thinking as an important part of the teaching sequence. This view is reflected in the following comment by Lyn:

> Because we have more understanding of the misconceptions we can teach accordingly and we can single out misconceptions…we can tackle them straight away… if you are aware of what the misconceptions could be, you are explicitly telling the students that you know some people think this is so, it has a huge impact because the kids will not then go along those lines…The pre-test was used as a basis to begin discussions, it gave kids a good reference point.

Impact of Representation Construction Approach on the Teachers' Classroom Practice

Both teachers were strongly of the opinion that the representation construction approach had significantly impacted on their classroom practice. The two teachers reported there was a significant pedagogical change in the manner in which ideas were introduced compared to their previous practice. At each stage of the topic sequences key ideas were approached through the canonical representational forms and student generated representations in response to the representational challenges. According to the teachers, the explicit negotiation of and discussion of representations of force, substance and astronomical phenomena led to a richer range of classroom discussion and opened up lines of inquiry that were closed in earlier versions of the topics. The requirement on students to generate and coordinate representations led to refinement of ideas in a shared classroom discussion.

In the forces topic there was explicit discussion of representations such as those associated with explaining the action of forces in everyday events. The development of the scientific convention of straight arrows representing forces was embedded in an authentic need to know and involved discussions on the partial nature of this convention in explaining forces. Sally stated that "*when we taught forces previously you just barrel in, you start using arrows straight away, they just become incidental, so we never took the time to introduce the arrow or the significance of it… as representing force at all previously*". The students found that other visual representational modes such as drawings with annotations and curved arrows to indicate motion can enhance the explanation of an everyday action like screwing the top off a bottle of drink.

In the substances topic there was constant movement between macroscopic behaviour of substance and particle ideas through various forms of representation that explain the behaviour. Different particle representations, either generated by the teacher or the students, were discussed in terms of their adequacy in explaining properties of matter. Apart from the iconic pictorial representations of particles as spheres other forms, such as a picture of students on a bus, popcorn being made or a section of a jigsaw puzzle were discussed in terms of their particular features to explain macroscopic behaviour of matter in addition to those features that did not explain the behaviour. In other activities the students were challenged to generate their own representations, whether by role-play or in diagrammatic form to explain a variety of specific macroscopic behaviours of matter. For example, that candle wax goes ‘gooey’ when the candle is lit or that an elastic band can stretch without breaking.

In the astronomy topic there was an emphasis on coordinating different representational forms of the same astronomical phenomenon. For example, there was movement between the representational forms associated with perspectives of an observer from Earth, such as the photographic image of a solar eclipse, and representational forms associated with perspectives of an observer in space, such as role-playing the relative positions of Earth, Moon and Sun for a solar eclipse. The affordances and constraints of the representations formed part of the classroom discussions. For example, there was explicit discussion of the globe as a representation of Earth in space in terms of the affordances it has for representing certain features of Earth in addition to discussions as to the limitations of the globe in terms of not representing certain features of Earth. The students came to recognize representations as being intrinsically partial, such that a full account of an astronomical phenomenon required coordination of multiple representations.

A key feature of the representation construction approach is the generation and negotiation of student constructed representations in response to challenges and the canonical representational forms introduced by the teachers. This feature raised an issue for the teachers in terms of increased time allocation within a classroom lesson for negotiation and discussion of representations. Sally commented that she spent more time “*when this approach is used because there is much more student debate and involvement as they challenge their own ideas and those of their peers*”. This resulted in less curriculum content coverage when compared to the teaching of the same topics in previous years. However, the teachers were content to sacrifice coverage for the greater depth offered by this approach which paid dividends in terms of student learning. This view was expressed by Sally thus:

> We cover less content but we are tackling the big ideas much more effectively. I think that we make up for this slower pace when we extend concepts later in the syllabus. I expect this is due the deeper level of student understanding that is so much higher - because representations are used and introduced in this way.

This comment also points to the importance of establishing in students a deep understanding of key ideas that can form a strong base for future learning given the interconnectedness of ideas linked by representations.

Lyn found the time factor associated with negotiation and discussion of representations needs to be considered in lesson planning to allow "*sufficient time to for students to formulate and consolidate their ideas …. one needs to be prepared for the series of questions that students will generate and expand on the topic*". Thus, a certain amount of flexibility is required by the teacher, associated with the greater agency given to the students in determining the direction and flow of the lesson. For the teachers this meant a change in their lesson planning practices where they were now preparing for possible changes in direction resulting from classroom interactions rather than following a fixed planning schedule which was their previous practice. Sally described it thus:

> …you plan your lesson with a lot of possibilities. You think about okay what if the students ask me this question, what kind of activities can I have and I'm a little bit more prepared …now way back, if I did this last year, I would've prepared a whole 5-week lesson and I'd be teaching it lesson, by lesson, by lesson. So that's the progression.

The teachers considered that the amount of discussion was more than experienced in previously taught science topics. Sally described how "*there were more discussions, we did a lot more application how does it work in the real world kids were given time to actually think*". Lyn commented that is was "*most rewarding thing taking stuff in their everyday experiences into the science room…that type of conversation would not have occurred before, and that's the richness where you get the kids having science debates and conversations, rather than delivery of fact; it's a higher order level of thinking and that was really fantastic*".

The teachers reported that they now paid more attention to discussing with the students the form and function of representations at those times when they were introduced by the teacher or naturally arose from the classroom interactions. For example, in the forces topic taught by Sally, a representational challenge to categorise action words to manipulate plasticene in tabular form in terms of 'Push' or 'Pull'. Given there were some terms declared both a push and pull some students suggested a better representational form to a table might be a Venn diagram. This led to a discussion by Sally as to the function and form of Venn diagrams and instances where such a representational form might be suitably used. In reflecting on the need to discuss with the students the function and form of representations Lyn stated that

> … we found that we had to teach the students the skills, and understanding how the representations work and what they meant. And once they had an understanding about what they were about, … they were thinking about what they were drawing, rather than drawing a diagram for the sake of drawing a diagram, to show what was on their mind… the kids were going further into it

> and thinking of different ways [of representing]. So I think going further into it and teaching them why we choose certain representations, gets them in deeper.

From an epistemological perspective the teachers came to terms with the culturally produced nature of representations in the topics of force, substance and astronomy and their flexibility and power as tools for analysis and communication, as opposed to their previous assumption that this was given knowledge to be learnt as an end point. These realisations became empowering as they learnt to use representational challenges to drive classroom discussions and to achieve greater understandings themselves to interpret force and motion situations, apply particle ideas to explain properties of substances and interpret astronomical behaviour in terms of the interplay between simple dynamic systems of celestial objects. The power of the representational challenges was seen by Lyn as "*...what you're seeing with representation is that you're seeing what's in their brain, not what they're regurgitating*". For Sally:

> It's good to give them a representation, but it's more powerful when they re-represent it…it helps in their reasoning… it's a very powerful way of showing understanding and getting the kids to think. And the other thing too, is it allows kids to be creative in showing their understanding with different representations. And we can all see different ways of doing it.

Over the three topics the teachers enhanced their content knowledge and pedagogical content knowledge, which was driven by undertaking the representation construction approach. The following quotes gives insight into the manner in which the teachers now perceived the role of representations in understanding science:

> Lyn: Sometimes the representation will help us to get to that knowledge. So it is a continuous feed-back; as Sally said, if we try to understand the concepts we have to go to various types of representations…Representations help us get the knowledge, we use the knowledge to help to build our representations.
>
> Researcher: So is it two-way?
>
> Lyn: A circle. The representations helped our knowledge and our knowledge helped our representations and the more representations helped our knowledge and the more knowledge helped our representations. So it was more a continuous feedback working.

ISSUES RELATED TO A WIDER ACCEPTANCE OF A REPRESENTATION CONSTRUCTION TEACHING APPROACH

The case of Lyn and Sally highlights the efficacy of a representation construction teaching approach in terms of increased student engagement and improved learning outcomes. However, the approach does places epistemological and pedagogical demands on the teacher. The challenges for Lyn and Sally were in terms of moving away from delivery of content that is conceived of as resolved knowledge structures, to pedagogical practices based on a discursive, more active view of knowledge and learning. In terms of the dissemination of the representation construction approach more widely the issue of the magnitude of the teacher learning task needs to be explored. If the representation construction approach is to gain wide acceptance we need to identify the type and duration of support needing to be given to teachers being inducted into the approach, for them to make the types of shifts experienced by Lyn and Sally.

The collaborative and ongoing support given to Lyn and Sally over the period of the RILS project is not viable as the basis for widespread implementation of the representation construction approach. Such professional development is simply too time intensive to be practicable at system level. The question then arises as to 'what core skills and knowledge do teachers need to be supported to develop in being inducted into the approach, under conditions of restricted time and support implied by large scale professional development?' The RILS project involved the participation of one or two teachers in single topics only, rather than support over multiple topics over two years. Therese is a teacher who was supported over one unit only, to develop the representation construction approach. Her case is offered as an example to explore whether restricted support compared to that offered Lyn and Sally might still be effective in supporting teachers to implement the approach.

The Case of Therese

Therese's involvement in the RILS project was only in respect of teaching one topic, Ideas about Matter, to a class of Year 7 students. In contrast to Lyn and Sally, Therese was not an experienced teacher being in only her third year of teaching. However, Therese did have expertise from the perspective of content knowledge of the ideas about matter topic as she was a Biology and Chemistry specialist teacher. Therese's involvement in the RILS project came at the end of the project (see Table 1) and by this time the research team had greater insight and confidence with the representation construction approach which helped brief Therese and offer examples. The research team collaborated with Therese from the development stage of the topic ensuring a conceptual focus was undertaken.

The epistemological and pedagogical demands on the teacher in adopting a representation construction approach to teaching ideas about matter were not seen as significant for Therese. For example, in respect of the function played by the particle model Therese was asked, "*what do you see as the main purposes of introducing the particle model to Year 7?*"*,* and she responded:

> I see that the main purpose of introducing the particle model at Year 7 is that it gives the students the foundation of the true essence of Science. We aren't able to see everything in the world around us so we do experiments

> after experiments to try and make sense of it. The particle model enables the students to come up with their own idea of what substances are made up of and how they explain the behaviour of different states.

From a pedagogical perspective Therese was not surprised by the alternative conceptions evident in her students' diagnostic test responses. She felt that "*pre-test results for any Year 7 class should be quite similar. Therefore, there was nothing surprising for me for my classes*". According to Therese this perspective from the students' conceptions literature was gained from "*my [science teaching] degree where most of my assignments dealt with alternative conceptions with any topic.*"

The topic sequence adopted by Therese was described in detail in Chapter 7. It draws on the principles described in Chapter 3. The initial lessons involved the students exploring properties of different substances, for example, comparing the properties of a rubber band with those of a stick of chalk. Particle ideas were then introduced on the basis of a need to explain a specific property of a substance. For example, after the students had been informed that scientists, whilst being unable to see inside matter, imagine it to be composed of particles, the students were set the representational challenge to draw the state of the particles to explain the property of a piece of paper's ability to hold its shape. After students undertook this task three students were chosen to share their representation with the rest of the class (Figure 7.7 shows the students' representations). Each representation was evaluated by the class as to whether it served its purpose.

The sequence continued with students challenged to construct particle representations that would account for a range of macroscopic properties such as chewing gum being able to be stretched without breaking. The student generated representations then formed the basis of class discussions focused on evaluating their success in making sense of the phenomenon. Representational conventions were negotiated and agreed upon by class consensus. For example, the class agreed on a multiple bracket convention to represent particles of a sample of a substance in a solid state; curved arrows to represent particles of a sample of a substance in a liquid state; and straight arrows to represent particles of a sample of a substance in a gas state (see Figure 8.1).

In reflecting on changes to her practice with the representation construction approach Therese felt "*there was more class discussion in this teaching sequence as there were a lot of open ended questions set out to the students…. They all felt a part of the group if they got to share what they thought*". Therese cited more use of representations when she commented that "*we normally just gave them the textbook representations. Now there is more getting them thinking them up themselves*". Therese felt that the students "*get engaged more, it's like a puzzle because they have to come up with a specific explanation like how can you explain why a piece of paper holds its shape*".

Just like Lyn and Sally, Therese found that taking a conceptual focus to planning the topic meant less curriculum content coverage. However, the interconnectedness

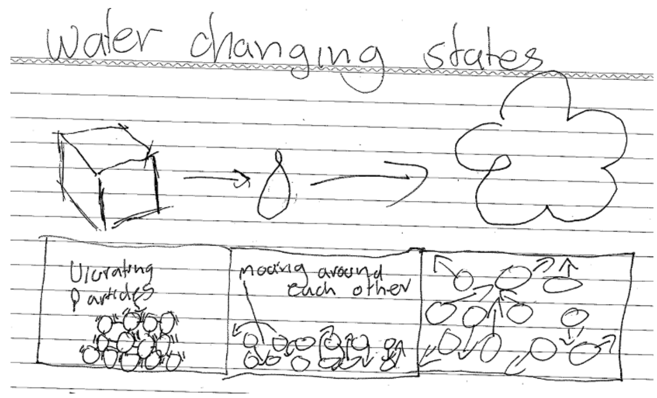


Figure 8.1. Year 7 class conventions in showing particle movement in pictorial representations of samples of substances in different states.

of ideas meant Therese introduced particle ideas about temperature earlier on in the sequence and had students thinking about bonding of particles when this wasn't the case in previous iterations of this topic.

As for Sally and Lyn, less content coverage resulted from the representational focus. This is not surprising given that they spent class-time in getting students to generate and negotiate their own and canonical representations, which is something Therese, Sally or Lyn had not undertaken in the past. Therese stated that "*I noticed this year that we were able to choose a couple of concepts that blended together well and used the time available to really connect with the students*". In justifying the introduction of particle ideas associated with temperature and bonding Therese stated that:

> Temperature related to states of matter and is critical to the particle model as energy of particles is related to temperature. In the past we never really did bonding but we had the students thinking about bonding in this topic…because the students needed bonding to explain the properties of matter that were given as challenges, it explains how a rubber band can stretch.

Finally, Therese saw great benefit in getting students to generate representations as it provided an environment "*to open up different ideas*" and, from a formative assessment perspective, "*this gave insight into their thinking and how they interpreted my teaching so this gave constant feedback on their understandings*". It was clearly evident that Therese embraced the representation construction approach in her teaching of a single RILS topic and her perceptions of the approach were similar, pedagogically and epistemologically, to those of Lyn and Sally.

Therese's case provides some evidence that, with the more focused support enabled by the researchers' growing experience of the approach and with a teacher sympathetic to the ideas, the representation construction approach can be successfully supported over one unit of work. In Chapter 11 we will describe the outcomes of a professional learning initiative that explored the possibility of supporting teachers implement the approach through carefully planned workshops.

CONCLUSION

A key implication of the RILS study is the need to shift practice in teaching science from its current focus on the delivery of content that is conceived of as resolved knowledge structures, to the pedagogical practices of this representation approach based on a discursive, more active view of knowledge and learning. We argue that these classroom practices bear many resemblances to the epistemic practices of science itself. The shift will require changes in conceptions of the role of the teacher in the science classroom, and changes in how knowledge and learning are thought of in science. To make this change, teachers need to:

- understand the role of representation in learning science, implying both a pedagogical and an epistemological shift;
- develop understandings of the key representational resources underpinning a science topic;
- develop the skills to provide a representation rich environment and opportunities for students to negotiate, integrate, refine and translate across representations;
- make explicit to students the role of representation in learning science; and
- conceptualize learning in science in terms of students' induction into the representational conventions and practices of science and their capacity to coordinate these.

The RILS teachers with whom the researchers worked closely exhibited in their teaching practice the dot point items listed above. These are the perspectives and capabilities needed by teachers learning to implement the approach. An issue for more widespread adoption of the approach concerns how teachers might be effectively but realistically supported to develop these capabilities. Given current concerns about the engagement of students in meaningful science learning, and the relatively limited success of pedagogical approaches based on cognitive views of learning, we would argue that this is an agenda that needs to be vigorously pursued both in research and policy.

BRUCE WALDRIP, PETER HUBBER & VAUGHAN PRAIN

CHAPTER 9

ASSESSMENT

In this chapter we first review accounts of effective formative and summative assessment in science to frame our report on the particular practices and effects of formative assessment and the learning outcomes of summative assessment when teachers use a representation construction approach. In analyzing these practices, we also draw on our research on the teaching and learning principles (refer to chapter 3) relevant to implementing effective formative assessment within a representational context. We conclude by considering the implications for future practice in relation to the goals and methods of formative and summative assessment in learning in school science.

LITERATURE ON ASSESSMENT IN SCIENCE

While there is an extensive literature on assessment of learning generally, and in science in particular, Black and Wiliam (1998) noted that the theoretical basis for assessment, particularly formative assessment, is at best under-developed, with many assumptions about teacher and learner capacities to participate effectively in assessment practices remaining tacit or ill-defined. These researchers also pointed out that the justification for any widespread assessment practice inevitably entails larger questions around the broader purposes and effects of education, including the desirability and capacity for education systems to promote economic, cultural and social justice goals.

Attempts to define and broaden accounts of formative assessment over the last 10 years are indicative of some of the challenges around these issues. Early accounts claimed that formative assessment simply entails a straightforward focus on processes that provide timely support for learning in class. For Tunstall and Gipps (1996, pp. 185–6) "formative assessment is the process of appraising, judging or evaluating students' work or performance and using this to shape and improve students' competence", thus concurring with Cowie and Bell (1996, p. 102) that "formative assessment is the process used by teachers and students to recognize and respond to student learning in order to enhance that learning, during the learning". These accounts assume that the specific aspects of science or science literacy that

R. Tytler, V. Prain, P. Hubber and B. Waldrip (Eds.), Constructing Representations to Learn in Science, 151–170.

should be learnt in class, what feedback enables learning or direct benefits, and how students should respond to these opportunities, are well understood. This raises the further issue of what underpinning explanatory pedagogical theory explains the inevitability (or failure) of this learning from timely guided feedback, assuming that all learners benefit equally from exposure to standardized processes. For Black and Wiliam (1998), these accounts of formative assessment imply considerable agency on the part of students to manage their own learning and a willingness to align their efforts with teachers' goals.

For Black (1998) and Black and Wiliam, (1998, p. 53), assessment serves a formative function when "comparison of actual and reference levels yields information which is then used to alter the gap" between current and desired performance. This conception of formative assessment, like its predecessors, is dependent on dominant accounts of (a) what should count as learning in science (presumably student performance against standardized measures of conceptual knowledge), and (b) how this learning is best enabled and assessed. More recently Black and Wiliam (2009, p. 9) claimed that a practice in a classroom is formative when evidence of student achievement is "elicited, interpreted and used by teachers, learners or their peers, to make decisions about the next steps in instruction that are likely to be better, or better founded, than the decisions they would have taken" without this evidence. This account clearly recognizes a potentially larger group of factors or influences in the process of effective formative assessment, and is more cautious about what should count as progress towards learning goals, and for whom. Black and Wiliam (2009) then claimed various types of activities enable successful formative assessment, such as teachers' sharing success criteria with students, classroom questioning, teachers' written feedback on student work, peer- and self-assessment by students, and formative use of summative tests to guide subsequent student test performance. From this perspective, the researchers claimed that the teacher needed to establish what learners knew, what goals needed to be addressed, and what strategies would support achieving these goals. Again, this account of appropriate practices assumes as unproblematic (a) what learners should learn in science, (b) the individualistic nature of student learning processes, and (c) how student agency and motivation "naturally" lead to learning gains.

Further, this account of formative assessment assumes that (1) subject-specific learning goals, progressions and outcomes in science are sufficiently clear and understood by teachers and students to provide a shared basis for guiding learning planning and outcomes, (2) teachers have high metacognitive evaluative skills to enable them to interpret/coach student performance/understanding, and that students are motivated to develop self-regulatory learning capacities to respond effectively to this feedback, (3) a range of explicit feedback strategies, activities/scaffolding will enable students to understand and regulate their learning goals, opportunities, and processes through self-assessment and informed action to improve academic performance, and (4) that a cognitive, information-processing model of how learning can be enabled/configured through an explicit teacher focus on procedures, structures, templates, rubrics, and meta-knowledge, can support incremental learning gains. All these assumptions are supported by research literatures on desirable practice in science teaching (see Duschl, 2008; Osborne & Dillon, 2008), but are not necessarily enacted in mainstream science teaching in the middle years in many countries. This account of formative assessment has also tended to ignore addressing representational challenges students face in learning science concepts. While Jewitt (2007) and Jewitt *et al* (2001) have focused explicitly on learning science literacy as entailing the coordination of multi-modal representations, these researchers did not consider in detail the implications of this orientation for effective formative assessment practices that address directly the adequacy of students' representational choices and products.

Our theoretical justification for focusing intensively on student-generated representational work as a basis for learning in science and our development of aligned pedagogical principles (and by implication relevant formative and summative assessment practices) has drawn on four inter-related literatures about how learning goals in science might be theorized and enacted. These are: (1) theories of the variety of processes that enable learning in science, (2) epistemic theories of science as a set of knowledge-production practices, (3) semiotic theories of the nature of learning tasks in science, and (4) theories about the nature, needs and capacities of learners. Each of these literatures entails complex accounts of diverse perspectives and research histories, and the following summary is intended to provide only a brief overview of key substantive points guiding our general rationale.

Theories of the range of processes that enable learning in science include Biggs' and Tang's (2007, p. 50) focus on "constructive alignment" of the curriculum, where teachers need to ensure that their teaching and learning goals, their organization of classroom learning experiences, and their assessment tasks align with one another. They note that this alignment poses significant challenges for many teachers. For example, in summative assessment that aligns with learning goals, students should demonstrate how they can apply concepts to new contexts, rather than simply repeat learnt propositional knowledge. Other key processes that support learning include meaningful and usable feedback (Black, 1998; Hattie & Timperley, 2007), with Hattie and Timperley (2007, p. 90) noting that feedback can focus variously on how students process tasks, on student self-regulation of their learning, and on encouraging the learner's "self as a person". However, these researchers claimed that feedback was mainly effective when academic goals were clearly salient for students, and where they could identify how to self-regulate their own performance. More broadly, student learning is generally enabled by timely teacher feedback that guides students' attention to critical dimensions of learning tasks or hard-to-learn aspects of a topic (Bruner, 2004). More recently, as noted by Klein (2006), Wilson (2008), and many others, current research by cognitive scientists on cognition has identified the important role of previously downplayed influences and resources in learning processes, such as perceptual clues, affect, embodiment, metaphor, analogy, and informal reasoning (see Tytler & Prain, 2010). This implies that students can learn in science from a complex interplay of multiple resources and strategies, using both (a) discipline-specific frameworks such as precepts, guidelines, scaffolding, templates and concepts, and (b) more informal contextual, associative processes entailed in role-play, thought experiments, improvisations, visualization, projection, and use of imagination in problem-solving. There is also a strong research literature on the effective role of group work in conceptual learning, incorporating both cognitive and sociocultural perspectives (Akkerman, *et al*, 2007).

Epistemic theories of science as a set of practices focus on how knowledge is generated in science, and imply the need for these processes to align with student learning experiences in this subject, enabling these experiences to function as an induction into this domain and its discursive purposes and resources. From this perspective, knowledge production in science is understood as diverse forms of inquiry using appropriate instruments and reasoning tools, leading to participants making and rebutting evidence-based claims (Ford & Forman, 2006; Yorke, 2003). Semiotic theories of the nature of the learning task in science that have guided our research (as well as our proposed learning practices) have emphasized the need for students to learn disciplinary representational competence as both a record of learning and as an epistemological tool for further reasoning and knowledge-building in this subject (diSessa, 2004; Lemke, 2004; Sampson & Clark, 2008). In conceptualizing learner diversity and its challenges for teaching science, we consider that teachers need to take into account the range of students' developmental and differentiated needs, their capacities, histories, interests, and motivation, as well as cultural, social, psychological, affective, and discursive influences and preferences affecting students' engagement with science (Yorke, 2003; Gee, 2004; Hand et al., 2003).

We consider that integrating these four literatures provides a basis for identifying key learning goals in science. We concur with Duschl's (2008, pp. 275–8) account of how science learning should address "the conceptual structures and cognitive processes used when reasoning scientifically, the epistemic frameworks used when developing and evaluating scientific knowledge, and the social processes and contexts that shape how knowledge is communicated, represented, argued, and debated". He further claimed that science learning and assessment is improved through the use of "learning environments that promote active productive student learning … and activities and tasks that make students' thinking visible". Our pedagogical approach aligns with Duschl's (2008, p. 275) view that learning in science should be conceptualized as a rich interplay of understanding and enacting epistemic and social practices, where students are expected to learn how and why to build theories and models, construct arguments, and to "use the specialized ways of talking, writing and representing phenomena". By implication, information-processing models struggle to encapsulate and address this complexity around formative assessment.

From previous studies we have identified various pedagogical practices that promote an effective focus on student-generated representations for learning in science (Carolan, Prain & Waldrip, 2008; Prain, Tytler, Waldrip & Hubber, 2009; Hubber, Tytler & Haslam, 2010; see also chapters 3 and 4 of this book):

1. *Sequencing of representational challenges involving students generating representations to actively explore and make claims about phenomena*
2. *Explicitly discussing representations:* The teacher plays multiple roles, scaffolding the discussion to aim at student self assessment as a shared classroom process.
3. *Meaningful learning through representational/perceptual mapping:* There needs to be provision of strong perceptual/experiential contexts, encouraging constant two-way mapping/reasoning between objects and representations.

These practices speak to the need for teachers and students to understand the conventions and purposes of representations and to assess their clarity and adequacy as evidence of students' emerging thinking, reasoning processes, and conceptual understanding. By implication, formative feedback from students and teachers needs to focus on timely judgements and guidance about processes or strategies that assist students to understand representational tasks, redress misunderstandings, confusions, ambiguities and omissions. Formative feedback should also lead to strategies that enable students to self-regulate their next attempt at representation, or at integration of multiple representations to show conceptual understanding.

Below, we report on case studies in the teaching of two topics, motion and astronomy, with particular emphases on teacher practices around formative and summative assessment. We sought to identify changes, if any, in students' performance in summative topic testing after experiencing a representation-rich learning environment. The mixed methods approach to the research entailed collection and analysis of quantitative and qualitative data using a case study approach (Merriam, 1998) The topic of motion was taught by Liz to her Year 10 students and the topic of astronomy was taught by Lyn and Sally to their Year 8 classes.

CASE STUDY OF LIZ: THE TOPIC OF MOTION

The Year 10 teacher, Liz, was a respected and experienced secondary science teacher whose main academic interest was in biology. She wanted to try an approach that would engage a disaffected student group in the topic of motion. In Australian schools, teachers are expected to teach astronomy, biology, chemistry, environmental studies, geology and physics in the lower secondary school, irrespective of their subject specialization. This topic entailed about thirteen hours of teaching. The classroom was traditional in its setting in that students were seated in rows in a science laboratory. Instruction consisted of one 50-minute theory class and one 100-minute practical class per week for six weeks. Liz perceived these students as low achievers and explained that they had diverse science backgrounds because of past learning experiences. She also stated that some of the students had not done well in previous years, a fact that was verified by the researchers in discussions with students during class. One student stated that she had failed science dismally in previous years and hated science, while another said that success in science depended on which teacher you had.

Data sampling and analysis in all classes included observation and videotaping of the teachers' classes, analysis of classroom interactions, teacher and student interviews, examples of students' work, and analyses of students' examination scripts. Scripts from Liz's class were analyzed in terms of students' use of appropriate scientific vocabulary, complexity of sentences in scripts, text readability, number of representational modes used by students in relation to quality of text, and the extent to which modes were integrated through explicit textual ties or embedding.

The findings of our study are presented in terms of (a) diagnostic and formative assessment practices in Liz's class, and (b) student performance on the topic tests.

Diagnostic and Formative Assessment

In Liz's class, the topic began with the representational challenge of asking the students to write down what they thought was the meaning of the following terms: instantaneous speed, average speed, acceleration, de-acceleration, stopping distance, and stopping time. Students were asked to discuss with their partner to share and negotiate the meanings of these terms. This set the scene for testing the adequacy of student verbal meanings in a diagnostic and formative environment. Diagnostically, students were asked to demonstrate their understandings using simple everyday equipment, such as toys, balls, and balloons.

In each subsequent lesson, Liz would prompt students to test and justify the adequacy of their understanding by a new question or an activity that was designed to challenge the clarity and comprehensiveness of the representation of their emerging explanations. The activities and questions required students to take a 2D (or 3D) representation and then re-represent these explanations (3D or 2D). In each case, after the students had negotiated an account within their group, the class discussed each perspective in a student-student, student-teacher, and teacher and/ or student-led discussion. This public justification stimulated a robust debate about the persuasiveness and clarity of different representations. Students were asked to reflect on the adequacy of their representations and, where appropriate, to modify them. In a number of cases, students raised examples that challenged other students' accounts of key concepts. Many questions were asked to prompt students to think why their proposed explanations were reasonable.

In each lesson, Liz facilitated student discussion where students showed their understanding of a concept and justified their views. In these discussions the students were asked to represent a claim, provide evidence for it, and then after further representational manipulation, refinement, discussion and critical thought, to reflect on and confirm or modify their original case. About seven weeks after the topic had been taught and the students had completed topic tests, some students were interviewed about their understandings, so the researchers had an understanding of the robustness of conceptual understandings and could identify what was not reasonably resolved. In reporting our findings on student diagnostic and formative understanding during each phase of the topic, we present an account of the context to clarify our findings.

In reasoning about *average speed,* one student group used a blown balloon attached to a straw on a fishing line to demonstrate and explain average speed. These students used hand gestures to illustrate direction and speed of movement to reinforce their view. The students measured the time and distance travelled by the balloon when it was released and then calculated average speed through computation (5 metres divided by 1.9 seconds). They were asked to justify or speculate whether a person could walk at this speed, but the students were unsure. These students then applied a formula from a text that they saw in a book with little understanding as to how it was derived. They had little conception of whether their time measurement was accurate. The group defined *instantaneous speed* as the speed the balloon was travelling at a point in time.

The class tried to represent and explain *acceleration and de-acceleration* in various ways. One group rolled a model car down a ramp, claimed that as it went down, it was accelerating but when it hit the bottom and started to slow, it was de-accelerating. This group was challenged by the teacher and some students as to where the de-acceleration actually started. Another group felt that they had a more complete explanation. They used a balloon filled with air that was attached to a fishing line, claiming once they released it, it was accelerating first because of the air pushing out of the balloon made it go forward, but that it quickly de-accelerated to a stop when it hit a person's hand. They said that if they had a longer string, it would have had room to slow down and would have shown a stronger case of de-acceleration. This group had the view that de-acceleration occurred after some pre-defined event. In addition, these students role-played acting out the motion of the balloon showing where they felt it accelerated and de-accelerated, breaking down the motion into stages and explaining what they felt was happening.

During these representations of students' understandings, Liz, as well as other students, would probe the adequacy of each claim. This resulted in vigorous class discussion as to what each term meant and what was an effective way to demonstrate their understanding. It caused students to re-represent their ideas to the class. To conclude the class, Liz asked the students to record their refined understanding of each term.

Here, Liz diagnostically established students' initial understanding of the concepts of motion and in subsequent lessons, she used formative techniques to explore what is the current state of student understanding and to prompt students to explore alternative perspectives, largely through the use of appropriate questions and judicious use of activities to promote new thinking. This process was influenced by (a) prior understanding of the need to build a coherent account that links properties/behaviour of objects with plausible claims, (b) prior experience with science class methods and the need for accurate measurement of change as the basis for hypothesizing, (c) informal qualitative reasoning around patterns of observed phenomena, and (d) everyday language use of technical terms of topic and everyday ontological accounts of causality. This re-representation work also drew on perceptual contextual clues, as students attempted to identify key observed aspects of phenomena for investigation, as well as problems/gaps/inconsistencies, and also evaluated the adequacy of their own views compared to what they observed with other groups. Liz noted that the focus on representational adequacy had the following effects on her formative assessment practices: (1) her feedback and student discussion were more specific and focused on particular features of the representations. (2) teacher and student feedback focused on the precise meaning (or meanings) as well as limitations of meaning entailed in different representational choices, and (3) she focused far more on students' intentions and questions than in past approaches.

Cases of Formative Assessment

In Liz's class, students were asked to re-work their explanations and include examples. They could draw a picture to clarify or elaborate their explanations. The students were expected to defend their understanding through a teacher-facilitated class discussion. All students seemed to participate in class discussion and were willing to draw on the whiteboard for all to see, to demonstrate their current understanding, and to argue their case. This was a major change from the start of term where students were unwilling to be involved in either class activities or discussions. Finally, they were asked to record their current understanding of these concepts. Liz was finding this approach to be an effective method of exploring and monitoring students' understanding of the concept. She started to utilize this approach with other science classes.

In one of Liz's classes, and as part of the reflection process to explore students' ability to re-represent and to re-interpret their understanding to new but related settings, she presented a representational challenge for them to explain in any form they chose what was happening if a table-tennis ball was dropped into a bowl of water. Some students considered what was happening at various stages while others students focused on the ball when it just reached the surface or it was just under the surface. Figure 9.1, a notebook entry, shows one student's initial perspective of the forces involved when the ball was under water.

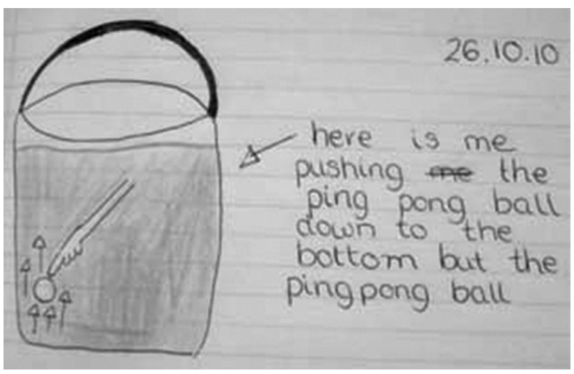


Figure 9.1. Student's visual representation of forces involved in submerging the ball.

Figure 9.2, a public representation on the whiteboard, shows a student's perspective on why a ball floats. The student appeared to accept that opposing forces are involved.

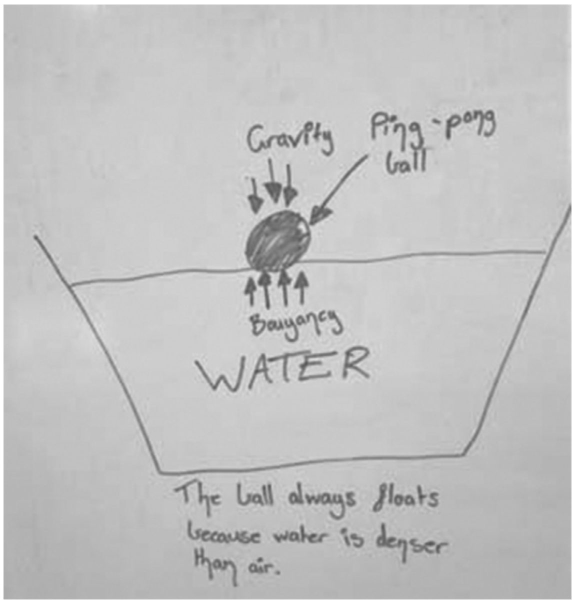


Figure 9.2. Student view on buoyancy, from the whiteboard.

Liz had the students discuss their initial thoughts and then asked them to think about what was happening at each stage when the ball fell into the water and what forces were involved when the ball movement stabilized. Once the students had discussed and recorded their views, some students explained their views to the rest of the class. Figure 9.3 shows a student's view of the forces involved as the ball rises to the surface. In providing formative feedback, Liz suggested the need to develop a representation that synthesized accounts of different stages of the process.

During the student-led discussion, they reasoned about which representation and accompanying verbal account provided a more coherent explanation of the interplay of the forces involved. They related their reasons to what they had learnt and their prior experiences. This included whether the sizes of the forces were appropriate and whether the number of force arrows was important. Liz's formative assessment focused on identifying gaps and inconsistencies in the new representations.

Student A, in addressing this representational challenge on the public space of the whiteboard (Figure 9.4), stated that gravity pulled the ball down. Once it hit the surface, the ball went into the water. This student also addresses different phases

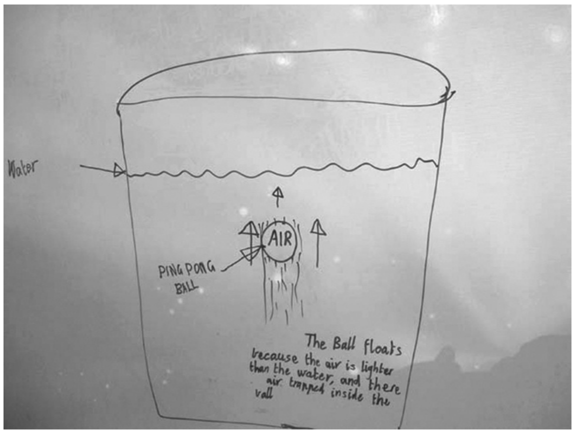


Figure 9.3. Ball rising to the surface.

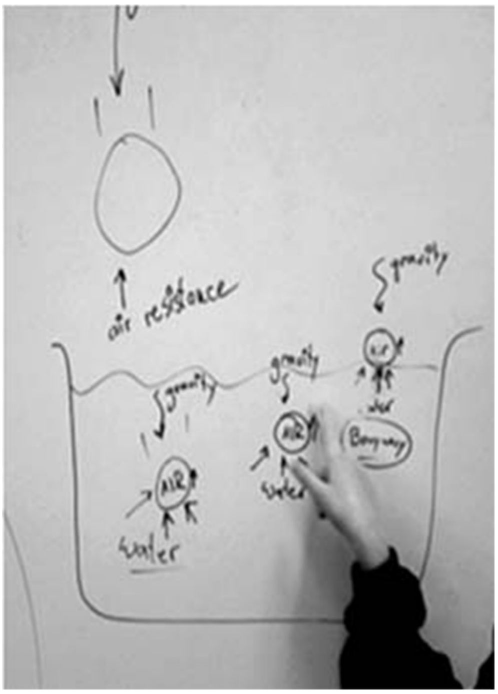


Figure 9.4. Student A's explanation of buoyancy.

of the ball movement in her verbal explanation which was coordinated with the diagram:

> As the ball went deeper into the water, gravity got weaker and the water and the air is pushing upwards. The gravity gets so weak that gravity has no effect and so it goes upwards. It stays there [on the water] as the gravity can't put it down and the water and air combined can't push it higher.

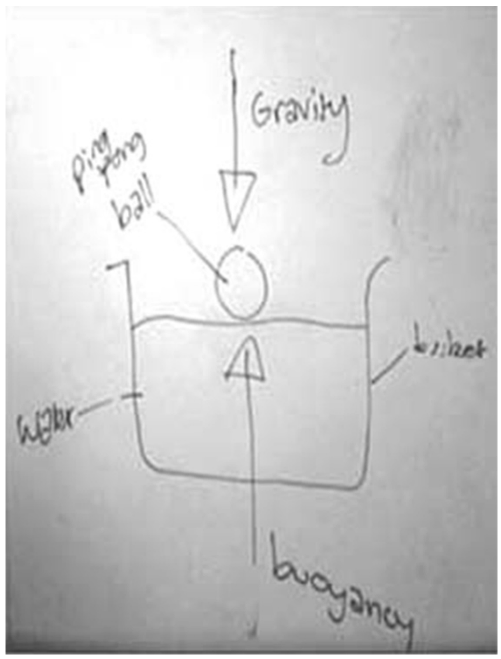


Figure 9.5. Student B's explanation of buoyancy.

Student B, also representing the force situation on the whiteboard (Figure 9.5), disagreed with Student A's explanation and said that it floated because the force of gravity is balanced by the buoyancy. Liz probed and challenged this student to elaborate the meaning:

> T: What happens to gravity when the ball hits the water?
>
> S: It gets less.
>
> T: Does the gravity get less under water?

All students used visual, verbal and gestural representations to put their case. Some students were confusing gravity with the balance of forces. Because an opposing force was counteracting gravity, they reasoned that it must be getting weaker. This confusion was not the case for all students. Other students were able to reason that the force of gravity was being opposed by the up-thrust (buoyancy) and as the depth of the ball increased, so the up-thrust increased. They related their argument to friction opposing surface movement. The discussion about the adequacy of their representation led these students to refine their viewpoints towards what can be considered as scientific explanations. Liz provided a further challenge at this point by asking students to consider effects on the motion of the ball if the forces were not equal. Discussion enabled students to clarify their sense of the resultant forces on the ball. Students revised their visual representations, discussed their adequacy, leading to a more explicit explanation of their understanding. The students said that publicly stating their views using drawings, analogies, illustrations and demonstrations allowed both the presenter and the listener to clarify their understandings. In addition, the process of judging which presentation, including diagrams, presented the most defensible explanation caused their own views to be modified and embedded in a meaningful context.

In summary, during the course of the unit the students used a range of processes and strategies to generate and critique their own and others representations. These included informal, contextual practical reasoning based on observations and data collection, perceptual pattern-spotting, approximations, enactment and re-representation of experiments, dialogic classroom conversations and elaboration of contested perspectives to clarify claims, inductive reasoning from examples, deductive reasoning from principles to new cases, logical analyses of the adequacy and coherence of their own and others' representational and re-representational claims, and negotiation of enacted and verbal/linguistic shared understandings. The complexity of these processes cannot be captured by an information-processing model of formative assessment.

Summative Assessment: Students' Topic Test Performance

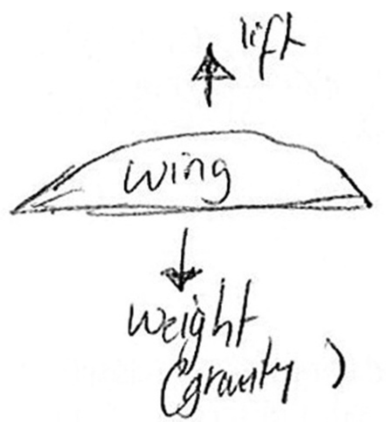
Analyses of the students' topic test performance across a range of motion concepts using a class that involved a representational focus compared to a class covering the same material and same tests without a representational focus, identified the following patterns:

- Students' scripts provided more detailed responses than in the second class. These responses contained more use of appropriate scientific vocabulary, more words, and the concepts were written about at a higher level of readability.
- The students were more likely to use diverse representational modes in their responses, and to incorporate effective textual ties, such as arrows, captions and labelling to link modes. Students who had practised generating their own representation were more likely to realise, in subsequent interviews, the limitation of their representation as a complete answer.

- During interviews with students, students explained that their representations allowed them to show properties and understandings that were difficult to verbalise, and that this use allowed them to communicate key ideas more easily.
- Students were still partly bound by examination expectations in that they perceived that teachers gave more weight to written responses than to other representational modes.

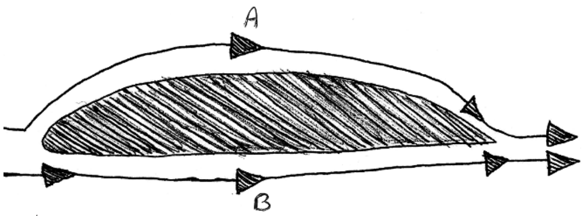
Given the extended emphasis on students' representational challenges, it is perhaps not surprising that Liz's students were more likely to reproduce these learning experiences in topic test explanations. However, the quality of their test answers indicated that this broad approach supports successful conceptual learning in science, even when the test is a traditional one, and where students were not guided to use or integrate multiple representations in their answers. While these findings suggest some positive effects of a representation-rich classroom on student learning, judging from their interviews, students felt constrained by normal assessment practices and expectations in how conceptual understandings should be shown.

The following sample of lower and higher quality student answers to a test question on air pressure provides further insights into the representational challenges entailed in demonstrating scientific reasoning and relevant conceptual understanding in science topics. Lower quality student answers tended to present a linguistic or a diagrammatic representation on its own, or where they did present multiple representations, they were not mutually supporting and did not develop a coherent causal claim. Figure 9.6 gives an example of this, where the diagram and the accompanying text seems to involve separate ideas. In stronger students' answers (see Figure 9.7) the text and diagrams were mutually supporting, each serving to explicate the other in a combination of visual/spatial, and narrative reasoning.



Student Comment:
The lift is generated by the air/wind underneath.

Figure 9.6. Lower Quality Student Answer.



Student Comment:
Wings are shaped to make air move faster over the top of the wing (at A). When the air moves faster, the pressure of the air decreases. Since the air on top of the wing moves faster, the density becomes lower than at the bottom (B) and there is less pressure. This difference in pressure (A compared to B) makes the wing lift upwards.

Figure 9.7. Higher Quality Student Answer.

CASE STUDY OF LYN AND SALLY: THE TOPIC OF ASTRONOMY

Lyn and Sally's participation in the RILS project involved the teaching of three topics, which were forces, substances and astronomy. Over the period of the project these secondary science teachers became strong advocates of the representation construction approach the features of which were evident in the video record of their classroom teaching. This was particularly evident in the topic of astronomy, which was the third topic taught by the teachers with this approach[1].

The representation construction approach raised a number of issues for Lyn and Sally in relation to both formative and summative assessment. From a formative assessment perspective the teachers saw great benefit in the knowledge gained from the pre-tests in terms of targeting the teaching in resolving misconceptions that arose and for the students to be made aware of their own thinking as an important part of the teaching sequence. This view is reflected in the following comment made by Lyn on the information gained from pre-tests.

> Because we have more understanding of the misconceptions we can teach accordingly and we can single out misconceptions…we can tackle them straight away... if you are aware of what the misconceptions could be, you are explicitly telling the students that you know some people think this is so, it has a huge impact because the kids will not then go along those lines…The pre-test was used as a basis to begin discussions, it gave kids a good reference point (Lyn, interview).

There were many instances during the teaching sequence where the students were given the opportunity to interpret and generate representations which gave the teachers insights into the students' development of ideas. Lyn commented that "*...what you're seeing with representation is that you're seeing what's in their brain, not what they're regurgitating*". The class discussions held in terms of evaluation and negotiation of the student-generated representations and the canonical representations provided a means by which the teacher might move the students towards a greater level of understanding of the key ideas.

As an example of the formative assessment practices undertaken by Lyn and Sally, early on in the astronomy teaching sequence they elicited the students' understandings of two of the key motions undertaken by celestial objects, these being revolution and rotation. The students were challenged to show their understanding of these motions through role-play. Having shown their understanding of these motions Lyn and Sally set them representational challenges whereby the students were required to use role-play as a reasoning tool to address each challenge. Sally challenged her students to show if it was possible for two celestial objects to revolve around each other[2]. Lyn challenged her students to show evidence, via role-play, of any rotation of the Moon as it revolves around Earth each lunar month. Following the lesson that involved these challenges Sally was asked why she had not given any notes about revolution and rotation for students to record in their note books. She responded that it was "*because that activity said it all*" indicating that her assessment of the students' response to the challenges gave sufficient insight that further teaching of these motions was not warranted. Formative assessment arises automatically, and inevitably, as part of students' responses to the representational challenges as well as the public negotiation process involving class critiques of the student generated representations.

For the astronomy topic there was a change in the type of notebook used by the students. In changing from an A4 lined page book to a larger than A4 project type book Sally commented that such a change was, "*much better than what we used to do because the kids liked the fact that there were these blank pages where they knew, ah okay, I can draw this here and write what is on the other side.*" It was in their project books where students often re-represented a particular situation. For example, in the diagram below (Figure 9.8) the students were to re-represent the diagram on the left for a midday observer on Earth. This student's re-representation, shown on the right hand side of Figure 9.8, made explicit links between the original representation and her re-representation through numerical labels. The direction of sunlight is indicated through lines and use of shadows.

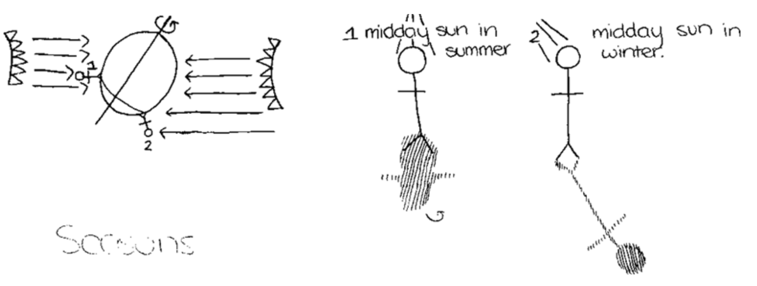


Figure 9.8. Student's representations of midday Sun in winter and summer.

For the Astronomy topic the teachers continued with their normal summative assessment practice of administering a paper-based topic test. In determining the conceptual understanding of the key ideas the test had a balanced mix of multiple choice and short answer questions. The short answer questions had a representational focus whereby students where challenged to create their own representations or interpret a given representation, often from a different perspective. The teachers made an explicit decision to provide a space rather than lines for the students to respond to short answer questions. Lyn felt that doing so provided the opportunity for students to use multiple representational forms which may generate "*a greater depth of knowledge than by just relying on the written word*".

Multiple representational responses and a variety of forms were evident in the responses the students gave to the short answer questions. This is illustrated by the sample of responses (see Figure 9.9) made by students to a test question which asked: "An astronomer investigating the motion of *Europa*, which is a moon, or natural satellite, of the planet *Jupiter*, found that it *revolved* as well as *rotated*. Use the space below to clearly explain what each of these motions mean."

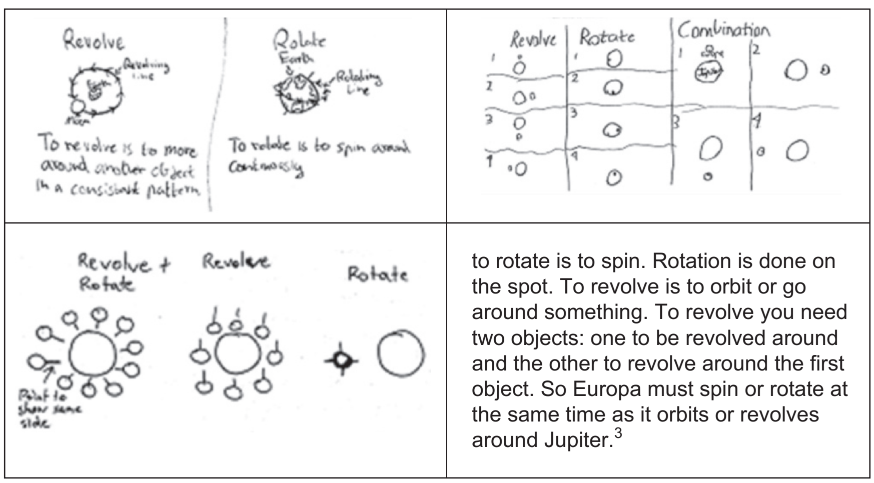


Figure 9.9. Four students' responses to a post-test question about rotation and revolution.

The representations in Figure 9.9 are scientifically correct and yet show a significant variation within and across different modes. This should not be seen as surprising given that during the sequence there were many instances where students were expected to interpret a particular representation and generate others in explanation. Also, the evaluation of representations did not imply a uniquely correct representation. The spaces in the test booklet gave the students the opportunity, permission and authority to adopt a range of representational modes in responding to the challenges that were given.

An example of a test question whereby the students were required to interpret a representation and re-represent it from another perspective is given in Figure 9.10 below.

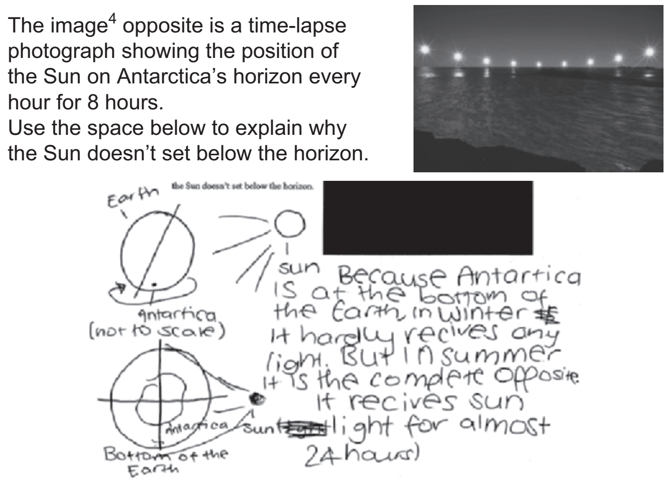


Figure 9.10. Post-test question and one student's response.

The pre-test that incorporated multiple choice and short-answer type questions elicited several alternative conceptions similar to those found by other researchers cited in the introduction. In evaluating student learning over the period of the teaching sequence the pre- and post-tests contained the same set of multiple choice questions which had previously been used in other studies (Trumper, 2001; Kalkan and Kiroglu, 2007). Table 9.1 indicates the students' results for these questions and provides a comparison to results obtained by another Year 8 class taught at Lyn and Sally's school and a study undertaken by Kalkan and Kioglu (2007) who pre- and post-tested 100 pre-service primary and secondary education teachers who participated in a semester length course in astronomy. The other Year 8 class was taught during the same period that Lyn and Sally taught their students, by a teacher called Tom. He was a physics trained specialist who participated in the same pre-topic workshop as Lyn and Sally and taught the same astronomy concepts as Lyn and Sally to his Year 8 class, but withdrew from his involvement in the representation construction research.

A measure of comparison of pre- and post-test results is the normalized gain index, $\langle g \rangle$, the ratio of the actual average student gain to the maximum possible average gain: $\langle g \rangle$ = (post% – pre%) / (100 – pre%), reported by Zeilik, Schau, and Mattern (1998). Gain index values can range from 0 (no gain achieved) to 1 (all possible gain achieved). The mean gain reported by Kalkan and Kiroglu (2007, p. 17) was considered a "respectable 0.3". This is comparable to that obtained by Tom's class (0.24) but contrasts significantly with that found by Lyn and Sally's class with a mean gain index of 0.65.

Apart from the conceptual growth shown in the multiple choice questions there was also evidence of growth shown in the students' responses to the short answer questions. For example, when asked, 'If objects like apples fall to the ground then why do you think the moon doesn't also fall to the ground? Explain why.' One student responded:

> Pre-test response: The moon is out of reach for the earth's gravity to pull it to earth.
>
> Post-test response: The moon is constantly falling but it is falling at a sertain (sic) speed so it is orbiting the earth due to our gravity.

Table 9.1. Correct answer ratio and gain index (<g>) according to pre- and post-test results for three cohorts of students

	Item	*Year 8 Students Tom's class N=17*			*Year 8 Students Lyn & Sally's classes N=33*			*Kalkan & Kiroglu (2007) study N=100*		
		Pre-test	*Post-test*	*Gain*	*Pre-test*	*Post-test*	*Gain*	*Pre-test*	*Post-test*	*Gain*
		% correct		*<g>*	*% correct*		*<g>*	*% correct*		*<g>*
1	Day-night cycle	64	94	0.83	61	92	0.78	91	93	0.22
2	Moon phases	24	53	0.38	43	81	0.66	23	30	0.09
3	Sun Earth distance scale	12	24	0.13	9	49	0.44	18	22	0.05
4	Altitude of midday Sun	24	0	-0.31	10	66	0.62	29	39	0.14
5	Earth dimensions	24	41	0.23	30	63	0.48	5	14	0.09
6	Seasons	12	24	0.13	13	63	0.57	54	82	0.61
7	Relative distances	53	71	0.38	70	85	0.51	46	71	0.46
8	Moon's revolution	59	88	0.71	38	83	0.72	49	60	0.22
9	Sun's revolution	94	88	-1.00	86	97	0.79	61	77	0.41
10	Solar eclipse	29	59	0.42	31	86	0.79	26	42	0.22
11	Moon's rotation	24	41	0.23	21	61	0.5	13	28	0.17
12	Centre of universe location	65	76	0.33	78	95	0.75	65	88	0.66
13	Seasons	76	88	0.50	73	97	0.89	67	88	0.64
		mean <g>		0.24	mean <g>		0.65	mean <g>		0.31

We have shown in this case the sophistication and flexibility of understandings demonstrated by at least some students as they generate representations. Table 1 data also provides some evidence to support a view that engagement with constructing representations improves student learning as measured on a traditional conceptual test. However, more research is required to substantiate this view.

CONCLUSIONS AND IMPLICATIONS

The literature on formative assessment, as outlined in this chapter, suggests that teachers should have an advanced repertoire of diagnostic and enabling skills, including diverse workable strategies, if they are to provide timely support for individual students to progress in science learning. However, this literature, largely drawing on cognitive approaches to learning as individualistic information processing, has tended to ignore semiotic theories of disciplinary meaning-making, epistemic theories of how science knowledge is produced and validated, and sociocultural theories of the role of group participation in learning. Our case studies suggest that a focus on student representational challenges, informed by these perspectives, can provide a practical and valuable focus for formative assessment in this subject.

As noted by many researchers, and summarized by Osborne & Dillon (2008), current constrained assessment practices in school science often entail rote memorization and recall, and therefore fail to (a) measure the depth of student learning, (b) provide useful feedback to learners, and (c) match the richness of experiences and representational challenges faced both by learners in the classroom, and by scientists in research teams. While we recognize that much current assessment of science learning suffers from these limitations, these case studies indicate improvements in student performance in tests and learning outcomes arising from their experience of a strong focus on representational challenges in learning science topics, even when traditional short-answer topic testing methods were used. We consider that assessment processes that expect students to use a wide range of representational resources would partly address these concerns about traditional testing practices.

We further suggest that:

1. Teachers need considerable professional learning support to change to the orientation and strategies proposed in these case studies.
2. Teachers need to develop students' ability to make and critique claims in representations as a crucial aspect of developing science literacy.
3. There is a need to investigate the adequacy of current mainstream summative assessment methods for promoting or measuring this literacy.

We suggest that this guided student representational work and accompanying claims and conjectures provide critical learning opportunities for students' conceptual learning as well as their understanding of the key role of representational adequacy in claim-making in science. These lesson sequences provided multiple opportunities for the teacher to utilise formative assessment and to address student misconceptions. By using these representations as contestable artefacts needing justification and elaboration, students are practicing habits of mind and reasoning skills central to scientific literacy. In this context, students were invited to be assessors of their own learning, and also function as an audience and sounding board for other students, thereby co-operatively fostering scientific reasoning and literacy development aligned to scientific practice on a micro learning-community scale. Importantly, the teacher facilitates this guided inquiry through critical feedback on the adequacy of student-generated claims evident in their representations. As noted by Ford and Forman (2006), unless school students learn to construct and interpret accounts of their observations and reasoning, and become active in the learning process, then their learning can become constrained and superficial. However, students' own language and representational approximations are crucial resources and starting points for guided productive reasoning about these topics.

NOTES

1 An account of the astronomy teaching sequence can be found in Chapter 7.
2 Sally later made a connection of this possibility with the mutual revolving motion of stars in binary star systems.
3 The students' written response was re-written to provide clarity.
4 Taken from Photo taken over period of five hours, on the longest day of the year, Framnes Mountains, Mawson. Photographer Wayne Papps, Australian Antarctic Division © Commonwealth of Australia, http://www.classroom.antarctica.gov.au/the-big-white/sun-and-earth/

RUSSELL TYTLER & VAUGHAN PRAIN

CHAPTER 10

THE NATURE OF STUDENT LEARNING AND KNOWING IN SCIENCE

As outlined in previous chapters, the representation construction approach is underpinned by sociocultural, pragmatist, semiotic perspectives on learning and knowing. In this chapter we will:

- review how each of these perspectives relate to this pedagogy, illustrating with the animals in the school-ground classroom sequence,
- explore how this classroom practice relates to practice in science itself
- discuss how the pedagogy promotes understandings of the nature of science, and
- clarify the nature of quality learning, and knowledge, from this perspective.

LEARNING AS PARTICIPATING IN AND ENGAGING WITH PRACTICE

The fundamental point of departure for sociocultural perspectives is that learning in science is envisaged in terms of increasingly expert participation in the discursive practices of science. These include the way representations are generated, negotiated and justified within the scientific community and subjected to rigorous scrutiny through agreed evidential processes. At one level the approach could be seen as an effective way of addressing the recognized problem of supporting students' acquisition of key science concepts, through promoting a more active and student centered approach to learning, and that is the initial perspective of teachers we have worked with in developing and disseminating the pedagogy. However, the participatory metaphor is much more congenial to our work than the acquisition metaphor (Sfard 1998) in that it better captures the way representations are generated and used to solve problems, as tools capable of negotiation and refinement, rather than as ideas that have a settled and agreed provenance. We will return to this notion of conceptual change, and concepts, later in the chapter.

Allied with this perspective is that of the classroom as a 'community of practice' which acts as a site for knowledge generation and negotiation, in a process of co-construction whereby teachers and students together hold up ideas for scrutiny and refinement, in pursuit of a shared need or problem. The emphasis is different

R. Tytler, V. Prain, P. Hubber and B. Waldrip (Eds.), Constructing Representations to Learn in Science, 171–184.

from traditional cognitive 'acquisition' perspectives on two counts – first, in terms of the control of knowledge, which is recognized as jointly generated, with students having some agency in the process of establishing a need, and generating, critiquing and refining representations in a public process. Second, the end product is viewed differently, being seen in terms of competent action within this community, rather than declarative knowledge in a person's head.

The pragmatist perspective emphasizes that meaning-making and problem-solving in science occur when the cut and thrust of language (broadly conceived of as dialogue, debate and logical proof) and the manipulation of other representational tools are used to engage with situated challenges (Wittgenstein 1972), rather than view science learning as the acquisition of stable conceptual structures with appropriate interconnections, as in conceptual change accounts. This view is exemplified by the Peircian triad of meaning making, with representation and referent tightly interconnected in a hermeneutic process of meaning making. The recognition of the multi-modality of the representations used in science to generate knowledge, and in classrooms to support student learning, constitutes the semiotic turn in this perspective.

Key concepts in this account of learning are those of mediation, and artefact. From a Vygotskian perspective, learning is inevitably a meditational process where language, and representations and artefacts more generally, are the means by which learners are supported to develop new practices implying new ways of looking at the world. Thus, language forms, such as technical terms, analogies and metaphors, multi modal forms such as diagrams and animations, role-plays, and models, or physical tools and equipment, are the means through which students are inducted into more expert practice in a field. These language forms – words, or diagrams and other visual forms – are constitutive rather than illustrative of ideas. In these discussions we are taking the terms 'representation' and 'artefact' as being broadly synonymous, but they tend to be used in different theoretical traditions, with different emphases. Artefacts, in the distributed cognition literature for instance, are man-made objects constructed to improve cognition (Hutchins 1995). They can be tools and symbols, including verbal language, and even abstracted ideas and processes (Tytler et al. 2012) as well as tools that are not necessarily conceived of as being in relation to objects or conceptual ideas. A representation, on the other hand, is thought of as standing in for something else, and in Peircian terms has an intimate relationship with a referent and the meaning attached to this. In practice, however, it could be argued that the terms occupy the same territory, within a given theory.

These ideas have been used to justify the construction of representations that is central to the pedagogy, a departure from the more common concern with supporting students to interpret the canonical representations of science, to achieve conceptual clarity and accuracy. We will further explore this notion of representation construction in a discussion of quality learning, later in the chapter.

There are many instances illustrated in the preceding chapters in which the role of representations in mediating learning has been explored. The coordination of representations / artefacts such as drawings, role-plays and 3D models as part of the discursive tradition around particle ideas, was described in chapter 5 and linked to notions of affordances of the different modalities, and to the epistemic practices of science more generally. Support for this perspective on learning science is given in the case study of the Year 5/6 Animals in the school-ground unit of work, parts of which have appeared in earlier chapters.

Mediation and Representation / Artefact

The mediating role of artefacts / representations is often thought about in terms of activity theory, in particular with Engestrom's (1992) formulation in terms of activity theory triangles. Figure 10.1 shows a major activity triangle dealing with the mediating role of artefacts in the animals in the school-ground unit.

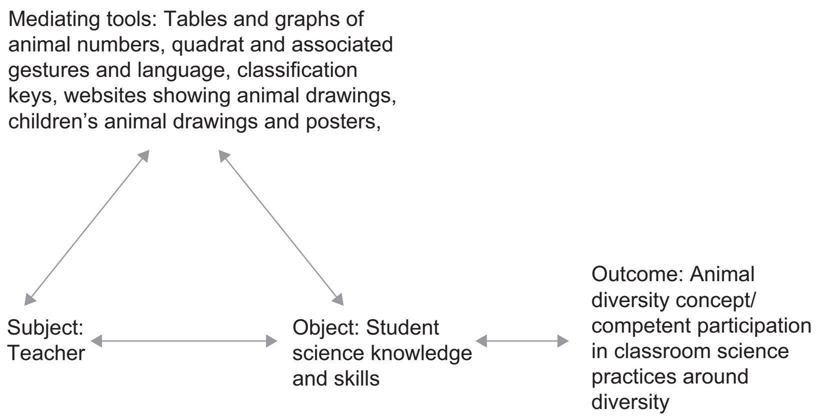


Figure 10.1. Engestrom's activity theory triangle showing the meditational role of representations and artefacts in establishing children's understandings/practice in relation to animal diversity.

A simplistic rendering of the notion of mediation represented by this diagram would have the mediating tools as being simply effective means to the end of establishing students' concept of animal diversity, thought of as declarative knowledge that somehow jumps clear of the means by which it was achieved, as though a difference could exist between the nature of a concept and how it is generated. A sociocultural perspective however would recognize that the outcome is intimately bound up with movement around the triangle, and that understanding is best thought of as an emergent practice involving communal negotiation and use of a variety of representations/ artefacts. The understanding involves competent participation in these discursive practices, and is itself emergent, unresolved, and situated in the activity. This also accounts for the necessary persistence of conceptual pluralism in all scientific research.

Engestrom's triangles are representations of a pedagogy built around the notion of mediation, with the teacher envisaged as driving an intentional process. The Peircian triad (Figure 10.2) is a more fundamental way of looking at the mediation process, linking representation with the referent phenomena in a circulating process of meaning making. The triangle does not speak directly to a pedagogy, but implies that the conditions for quality meaning generation involve the opportunity for constant circulation round the triangle, coordinating multiple, multi-modal representations linked to experience and evidence to build practice.

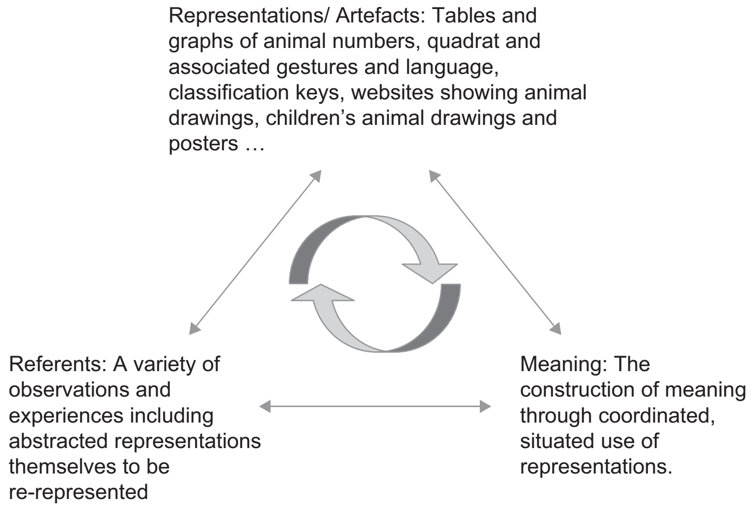


Figure 10.2. The Peircian triad showing the mediation role of representations in generating meaning in the area of animal diversity.

The triangle represents an idealisation of meaning-making in theory, but also implies the particular meaning-making practices of individuals entailed in the resolution of the links between representation, referent and meaning. In practice there will multiple and incomplete alignments for individual learners, and between individuals in groups of learners, as the situated meanings of individuals encounter slippage and inconsistency over time. However, we argue that this focus on representational coherence and adequacy entails a practical way to address this fundamental challenge of learning science.

It was argued in Chapter 5 that the key to the mediation function of representations is the way they channel and focus attention through their particular affordances. Each representation (and physical artefacts such as quadrats, other measuring tools, or digital microscopes) offers a selective view of an aspect of a phenomenon or process. The generation of meaning can be understood as the coordination of these multiple perspectives to solve a problem such as analysing a situation and communicating an explanation. Thus, deepening understanding can be viewed as increasingly agile and insightful performance of disciplinary discursive practice. These ideas will be explored, through student learning in the Year 5/6 unit: *Animals in the school ground*.

ANIMALS IN THE SCHOOL GROUND

This unit had two distinct parts; the first was an exploration of animal (invertebrate) diversity in school-ground habitats, the second was a study of animal movement (form and function) through model construction. The unit was described in broad terms in Chapter 6, to analyse the role of representation in reasoning. The sequence of events in the first part of the unit is described below.

1. Introduction to the school environment – identification of habitats to study. The overall questions for the unit are a) what animals are found in the school ground habitats? b) what characteristics do the animals have that enable them to survive? and c) how do the living things interact and depend on each other?
2. Students undertake a preliminary investigation of their habitat. They predict what they will find there. They spend time drawing and observing as much as they can. They report back.
3. The idea of scientifically studying a habitat is introduced, and the need to develop quantitative data through sampling, measurement and representation. Students were introduced through discussion to the idea of sampling distributions.
4. Students explore their habitat, counting animals and recording a range of environmental conditions. They take notes as a group with a view to developing a poster.
5. Direct teaching occurs concerning diversity and classification (broad animal groupings)
6. Students develop and display posters representing an account of their habitat, and present preliminary ideas about how the animals and plants interact.

In introducing students to the idea of animal diversity, and to habitat sampling, the teachers worked through a series of representational challenges, supported by introduction of a variety of mediating tools (representations/artefacts) through which the students came to explore and conceive of the diversity of animals in the environment.

Mediation Role of Representations

The sociocultural perspective, including the mediation role of representations, the operation of the Peircian triad, and the coordination of multi modal representations, can be seen in the sequence through:

- The discussion during the introductory class forum of a need to sample leading to the introduction of the quadrat, with gestures and words being used to establish the idea of a sample space. The idea of counts of animals was expressed through suggestions of tallies, and graphs.

- The role of drawings and tables and graphs in focusing attention and supporting reasoning. This was discussed at some length in Chapter 6 where it was argued that these representations play an active role in shaping understanding of the distribution and variety of animals in the environment. Branching diagrams were used to represent animal classification, and formal naming systems were introduced, which were used by students in their internet searching to identify animals they found.
- The task of generating a poster focused attention on the need to coordinate representations of a variety of aspects of animals in the habitat.

Digital microscopes were used to study and photograph close up features of animal structure. These photographs were used to illustrate animal structures in the poster presentations. Short video sequences were used to study movement details.

The mediating role of multiple representations including sketches, physical models, role-plays, and talk in generating understandings of animal movement, was discussed at some length in Chapter 6. Each operates to confer further insight by virtue of the affordance (productive constraint) offered by the particular mode. Again, we argue that Jesse and Paul's understandings of centipede movement generated by this process, for instance, do not jump clear of these multiple representations to form some essentialised version of how the centipede moves. These representations, together with the practice of which they are a part, are continuous with / constitutive of the understanding that the boys generated of the animal's movement.

Epistemic Agenda and Community of Practice

A central perspective of the representation construction approach is conceptualizing classroom activity around the notion of practice that reflects the knowledge building practices of science. There has rightly been criticism of some characterization of investigative classroom activities as being 'authentic science', on the grounds that the purposes of school science are not the same as for science itself, the motivations of students are not that of scientists, the knowledge is not in the same sense 'new', and there is no equivalent person to the teacher, in science laboratories. Nevertheless, we would claim that pedagogies in science classrooms can to a very different extent represent legitimate practice and that an important aim of any science classroom purporting to focus on introducing students to the way science is practiced in real settings, needs to pay attention to understandings of its epistemic processes.

To this end we draw on the work of scholars such as Latour (1999) or Nersessian (2008) who have studied the generation of knowledge in science laboratories, emphasizing the communal generation of representations / models as central to the knowledge building process and the development of languages and artefacts that are deeply contingent and situated in their work to solve contextual problems. In their and others' work (e.g. Clement & Rea-Ramirez 2008; Gooding, 2004, 2006) a central process of scientific knowledge generation is model building. A further characteristic of scientific knowledge building is the process of alignment of ideas with evidence, and the small and large scale patterns of reasoning and argumentation by which knowledge is legitimated through rigorous scrutiny. We argued in Chapter 6 that the process of argumentation in science classrooms, if it is to adequately represent epistemic practices in science, needs to be situated in explorations based on genuine and agreed questions, that are subject to situated contingencies similar to those that occur in science, and that involve public processes of challenge and negotiation.

The aspects of the representation construction pedagogy conforming to these views of science epistemic practices, that are evident in the *animals in the school-ground* unit, are:

- The framing of a genuine need to know – how do we understand the diversity and distribution of animals in the environment, and how they interact? In the sequence the students were challenged to think about how they might investigate their allocated habitats in terms of the processes of data generation and how to represent what they found.
- At each point in the unit the classroom discussion was open and interspersed with representational challenges. The discussion was built around the generation of ideas of animal diversity, structure and function, and adaptation, and teachers mostly introduced canonical ideas as tools offered as solutions to agreed problems.
- The class operated as a community of practice at a number of levels; that of whole class agreement on processes (strongly framed by the teachers but in an important sense open to variation), group generation of data and interpretations, and individual commitment to exploration.

Wenger (2006) talks of a community of practice as involving sharing a concern or a passion for something they do and learning how to do it better through interacting regularly. He identifies three elements of such a community that need to develop simultaneously: 1) the domain, which is the shared interest around which members collectively learn from each other, 2) the community, collaboratively engaged in activities and discussion, and 3) the practice, what members 'do' when they interact. These three elements were all in evidence throughout the animals unit.

During the unit the students, together with the two teachers, operated as a community to establish and communicate practices in exploration, reasoning and explanation. The groups exploring their habitats developed their own representational systems including language, and these were further shared in the class in what became a common purpose of locating, identifying, describing and modeling animals through writing and drawing, internet searching, digital microscope images, gesture and talk. This was achieved through frequent classroom discussion of ideas, common tasks and opportunities to collaborate, and a communication focus. The unit, through emphasizing the generation by students of their own representations, and reasoning practices, exemplifies the discursive nature of learning as knowledge generation rather than simply knowledge reproduction. These classroom practices, while not 'authentically scientific' in a number of senses of professional practice in science are nevertheless closer to the knowledge producing practices of science than is the case with more transmissive approaches to teaching and learning science. For these students, the knowledge they generated and shared was new to themselves.

In coming to know and use the discursive practices appropriate to investigation of animals, students moved along a trajectory from being legitimate peripheral participants (Lave & Wenger, 1991) to a core role within the learning practices of the community. Their learning, which could be cognitively viewed as acquisition of concepts (diversity, classification, distribution, structure and function, interdependence), was situated within the social context of the classroom community, involving engagement with a set of discursive practices built around a need to know.

The Nature of Science

Traditional versions of the nature of science (NOS) tend to characterize it in terms of universalizing statements (such as that there is a fundamental distinction between theories and laws, that science involves human imagination, that scientific knowledge is subjective, and tentative and subject to change, or that scientists' work is culturally influenced – Lederman & Lederman, 2012). Osborne et al. (2003) identified a set of themes on the basis of a Delphi study involving different communities knowledgeable about science, including the role of scientific methods and critical testing, creativity, and the human nature of science.

However, others have argued that the nature of science is better seen in terms of situated practice whereby knowledge is built through a process of community representation and model generation, in a highly contingent and contextual process (e.g. Nersessian, 2008). Latour (1999) argues that the theory – evidence relationship that is so central to any characterization of NOS is best seen through a process whereby data is generated and transformed through in a series of 'representational passes'. A key feature of a pragmatist understanding of the NOS must be the evidential trail through which data is represented and re- represented in theory development and interpretation.

In the animals unit, students completed a pre test which included a 'working as a scientist' probe: A diagram shows two scientists looking at a forest floor, with the explanation that they are researching a particular small beetle that lives in the leaf litter. The questions were: What questions might the scientist ask? What are some methods they would they use to answer these questions? What would their journal look like? Students found this difficult to answer, with responses being often non-scientific, or trivial. In the post – test with the same probe, the responses were considerably more sophisticated. Figure 10.3 shows one of the more sophisticated responses showing the range of investigative understandings demonstrated.

We argue that the representation construction approach provides a significant way forward for science classroom practice through 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.

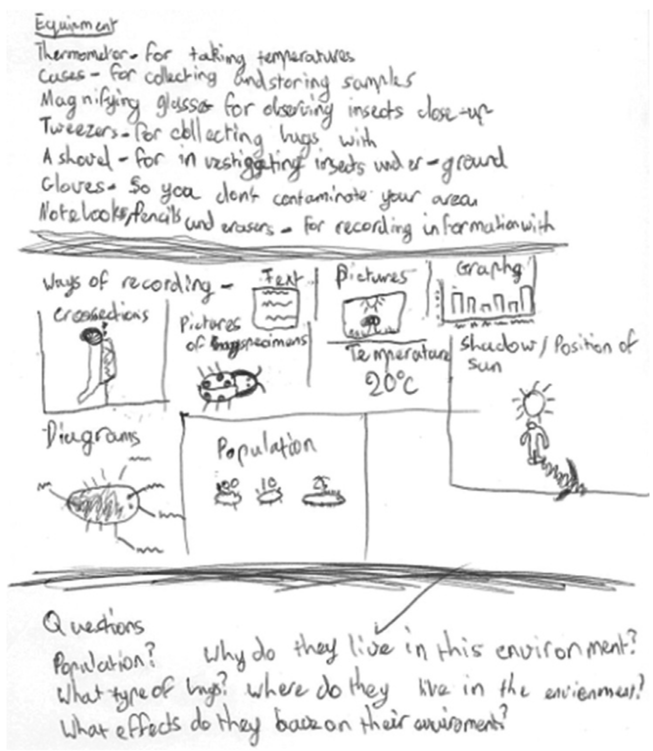


Figure 10.3. Post-test response describing equipment, recording and questions for an environmental study.

The Nature of Knowledge and Learning

The concept of animal diversity was instantiated in this unit through a variety of representational practices such as animal tallies, graphs, classification keys, drawings, and Venn diagrams. To develop a comprehensive understanding of diversity would involve being able to coordinate these representations into a coherent explanatory narrative in response to a question or a problem.

A concept such as *animal diversity* can only be thought about and communicated through constituent representations, and conceptual understanding cannot be separated from the capacity to work with these representations. Figure 10.4 is an attempt to illustrate the way these representational practices might be imagined to cluster around the diversity concept. To fully explore each aspect of the animal diversity concept would require using a number of representations, each partial yet specific, in elucidating an aspect of diversity. The concept of diversity is (incompletely) composed of this set of representations. For the students in this study, the representations of figure 10.4 were the reasoning tools by which they came to understand how the concept is used in science, to make sense of phenomena and construct and communicate explanations.

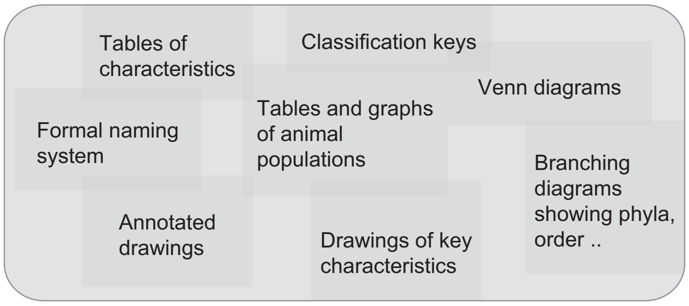


Figure 10.4. The representational practices constituting the concept of 'animal diversity'.

Curriculum designers in science typically focus on identifying clusters of concepts that comprise a topic, often not specifying what might count as evidence of students' learning of these concepts. While accepting the convenience of this approach, with its implied distinction between an idea and its expression in practice, we would argue that it does a disservice to the richly representational practices of science. The representation construction approach focuses on developing students' representational resources in a context of representational challenge and problem solving. Nevertheless a key moment in the planning is the identification of representations that relate to key ideas clustering around target concepts. The question thus becomes – what do we mean by 'concept'?

In the conceptual change literature, this question of the nature of a 'concept' 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 (Wittgenstein 1972). We argue that it is fruitful to think of concepts as privileged linguistic markers through which conversations in the domain can productively proceed. Concepts are core entities within the language practices of experts discussing learning and knowing in science. Thus, while understanding *animal diversity* 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. Thus in this unit, terms like 'animal diversity', and 'adaptation' were used in conversation to demarcate an area, but the real work of situated interpreting, reasoning and communicating was done through the associated representational practices.

Privileging of 'concepts' performs a very valuable function in enabling flexible communication around a conceptual area, and acting as a marker in higher level discussions. Concepts are used as organizing entities to shape learning sequences. The danger is that if we ascribe to a concept a 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 involves a degree of mastery of a range of constituent 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.

Quality Learning

The characteristics of quality learning from this sociocultural, pragmatist semiotic perspective, as described in the sections above, fundamentally involve active and increasingly competent participation in the representational / discursive practices of a classroom built around guided inquiry. In the set of principles described in Chapter 3, the process of learning, and effective support for learning, are characterized by representational challenges in which students generate representations in response to an established problem, and these are subject to public or group negotiation and refinement. In this process there is generally a strong link between the representations and perceptual experience, characteristic of idea generation in science more generally. The representational refinement process involves an interaction between individual representations and the canonical representations of science as introduced by the teacher.

Thus, students in representing animal diversity constructed their own drawings, but drawing conventions such as scale were discussed. Increasingly students had access to drawings and classification keys through the internet so that canonical representations were increasingly accessed. Teachers made formal presentations of some representations such as branching diagrams in introducing formal animal groupings. Thus, while the conditions for quality learning include active representation construction, in some cases this means representational challenges prior to the introduction of canonical forms, in other cases canonical forms are introduced prior to construction involving variation of these to solve contextual problems. This variety of forms of representational challenge was discussed in Chapter 4 in relation to the structures of learning sequences.

The argument for active construction of representations as a key condition of quality learning, rather than as a major focus on interpretation of canonical representations, is based on at least four positions:

- Learning, conceived of as involving increasingly competent participation in the discursive practices of the science classroom, inevitably must involve active engagement with these practices rather than simple exposure to and interpretation of them.
- The act of constructing representations focuses student attention on the particular affordances of the mode and form, which act to constrain thinking and channel attention on selective features of phenomena. Thus, with the centipede modeling described in Chapter 6, each mode offered a specific, different but complementary version of the animal's movement.
- Actively constructing representations attunes students to features of the problem space, and prepares them to appreciate canonical solutions introduced by the teacher (Schwartz & Bransford 1998). Thus, finding and describing and then identifying a variety of animals through a series of representations prepared students to actively engage with classification keys and drawings and naming systems in their internet searches.
- 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 (Cazden 1981, following Vygotsky 1978).
- Quality learning also involves epistemological understandings about the nature of models/ representations and their selective purposes. This meta representational knowledge arises from explicit discussion of representations, and feeds back into selection and refinement processes.

There has been considerable comment in many countries about students' lack of engagement with science and declining enrolments in science courses (Tytler, 2007). Interview studies have linked this with the transmissive pedagogies associated with traditional science classrooms, and the fast pace and shallow coverage of content forced by many science curricula (Osborne & Collins, 2001; Lyons, 2005). There is some suggestion also that this engagement issue has an identity dimension, in particular that for many students a subject that is very authoritarian in approach, that does not allow students to express imagination or personal perspectives and opinion, is incompatible with their expectations of a fulfilling identity (Haste, 2004; Lindahl, 2007; Schreiner & Sjoberg, 2007). Quality learning, from this perspective, must involve the capacity for students to align the science they are learning with an identity that is attractive to them, and this involves for many students a sense of agency in learning, and opportunity to express themselves. We argue that the representation construction approach encourages students to imaginatively respond to challenge and to allow room for individual expression of understanding. It does this while maintaining a strong conceptual agenda managed by the teacher, at a slower pace but deeper level than traditional approaches. In this way the approach is a serious attempt to balance the need for inquiry and individual expression, with the need to introduce students to canonical content and practice.

There is a considerable body of research on the impact of identity on young people's educational engagement (Tytler & Osborne, 2012; Archer, Hollingworth & Halsall, 2007). Glen Aikenhead (2005) argues that for many students, especially indigenous students, 'to learn science meaningfully is identity work' (p. 117). He argues that presenting science as value and context free, without multiple or contested views, tends to marginalize some students on the basis of their "cultural self-identities" (Aikenhead and Ogawa, 2007, p. 540). The identity work at stake has been explored for a range of cultural and other groups including Maori women scientists (McKinley 2005), minority females in the US (Johnson, 2007), and marginalized groups in many countries. Researchers working in a critical sociocultural tradition see the issue as representational in nature (Moje, 2007), in that the problem centres on negotiating the representational resources of cultural groups with the canonical representations of science. While the RiLS project did not tackle this issue directly, we argue that student construction of representations, and the challenge and explicit negotiation involved in assessing these and aligning them with canonical forms, offers the possibility of acknowledging and negotiating different representational traditions to engage all students in the discursive practices of mainstream science, flexibly conceived. The process, properly managed, is capable of opening up multiple identity possibilities through these representational deliberations. The representational challenges, seen in this way, become boundary objects (Akkerman & Bakker, 2011) through which students learn to take on science-engaged identities.

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CHAPTER 11

IMPLICATIONS FOR THE FUTURE

In this chapter we review the main themes that have driven previous chapters in the book, concerning the nature of the representation construction pedagogy, the theoretical underpinnings of the approach, and what RILS has achieved concerning student and teacher learning. We focus on three main questions that drive the three sections of the chapter:

1. What are the implications of the approach, and of the research findings, for science curriculum policy?
2. What further research is needed to explore the approach in wider contexts such as different cohorts of students and different aspects of science learning?
3. What are the key issues for teachers and for systems in scaling up the approach?

THE IMPLICATIONS OF THE RESEARCH FINDINGS FOR CURRICULUM POLICY

The pedagogy explored and promoted in this book has significant implications for both how school science knowledge is conceived and for the classroom processes by which quality learning is supported. The research program has produced evidence, involving video records, student artefacts, pre- and post- test findings, and teacher testimony, that the approach leads to quality learning and knowledge of key science concepts. From a curriculum perspective, the research throws up the challenges of how to effectively articulate for teachers the nature of quality learning and of the pedagogy that supports this, and how to reflect these approaches to science teaching and learning in curriculum documents and resource policy. In this section of the chapter we will explore four dimensions of this challenge: a) how to characterize and support quality learning in science, b) the implications of the approach for assessment policy, c) the implications for conceptualizing curriculum progression in science, and d) the effective use of technologies implied by the approach.

These challenges, of course, also have implications for the ongoing research program surrounding representation construction and learning.

R. Tytler, V. Prain, P. Hubber and B. Waldrip (Eds.), Constructing Representations to Learn in Science, 185–192.

Supporting Quality Learning

Quality learning is characterized in this research as involving the imaginative construction and coordination of representations to solve problems and develop explanatory accounts in science. This constitutes a more active view of the process of learning science than in traditional accounts of knowledge acquisition, or in customary practice. It constitutes a challenge also to traditional views of the products of learning. The pragmatist semiotic perspective we have adopted takes knowledge as being constituted within representational practices, rather than thought of as command of resolved conceptual structures. The sociocultural turn underpinning the approach treats quality learning as involving participation in a classroom community of practice, where disciplinary literacies become the focus in a public process of generating, challenging, refining, justifying and judging explanations, processes and methods in science.

The classroom processes implied by this perspective on quality learning include:

- The introduction, negotiation, and coordination of a range of representational modes
- The explicit discussion of representations and their role in learning and knowing
- Extended class discussion where ideas are negotiated, and the teacher acts as an intermediary between student-generated representations and the canonical representations of the scientific community

The approach places demands on the pedagogical skills of the teacher in running open discussions and in developing the insight needed to guide the classroom tasks and conceptual negotiation. It also involves an epistemological shift for teachers as they begin to appreciate the active role of representational work in shaping reasoning and learning.

The approach has implications for teacher learning and support, for curriculum framing, and for assessment, all of which will be discussed in subsequent sections. It has implications also for the design of curriculum resources, including the way learning and knowing is characterized in curriculum documents and in text books and other resources.

Chapter 3 described how teachers in the forces unit needed to alter their text-book based practice of a ‘run through’ of a multitude of force types where force conventions were used in an unproblematic, taken-as-given way. The implications of the approach for text book and other resources need further exploration, but we would suggest that there needs to be a more in-depth approach that focuses on core representational competencies, with embedded tasks that involve representation construction, and reflection/discussion of a meta-representational nature. For curriculum framing, the traditional run-through of syllabus topics needs to be trimmed to focus on major ideas, and these expressed in a way that acknowledges their representational, knowledge-in-use nature, rather than as verbal conceptual statements, as is currently the case. The discussion of curriculum accounts of conceptual progression will be discussed below.

Assessing Learning in Science

One of the key features of the representation construction approach is the way that formative assessment is embedded within the pedagogy, arising from the central element of public (or small group) disclosure of students' ideas and negotiation and refinement of these in the classroom 'community of practice'. Thus, both the teacher and other students have access to these emergent ideas and are part of the process of evaluation of adequacy and subsequent co-construction of refined representations. The other feature of the approach relates to the multi-modality of the representational generation and coordination. This has the dual effect of demanding clarity of students as they respond to the particular affordances of each representation, and opening to scrutiny by the teacher and class their use of representational resources in making claims.

From the teachers' perspective, the approach demands ongoing judgments and negotiation of these emergent ideas, and the response is necessarily complex and contingent. We have pointed out the inadequacy of current formulations of formative assessment as the identification of 'gaps' and the design of tasks to bridge these. Learning through a representation construction process, and we would argue any teaching and learning process, is more complex than this, because the ideas are emergent and multi-faceted and the target flexibly conceived. Teachers' responses are framed within an emergent practice, rather than being concerned with filling a uni-dimensional gap between student and target conceptions.

The challenge for the teachers is thus two-fold. First, making judgments about the quality of student constructed representations, which may be extremely varied, and about their potential for effective claim-making, is a demanding task requiring insight into the conceptual territory. Second, the management of discussion and ongoing tasks may require complex judgments by the teacher. The approach demands, therefore, good subject content knowledge and also pedagogical skills beyond those needed for transmissive approaches. The benefits, however, for student learning, are considerable. The issues associated with teacher learning are discussed in a later section of this chapter.

There is a number of implications for summative assessment. First, our work has demonstrated the richness of student responses when they are encouraged to use multi-modal representations. This implies the possibility of more insightful and valid assessment of student capabilities based on multi-modal responses. We have demonstrated an advantage in encouraging students to respond to questions using multiple representations across modes, through the devices of developing an expectation that this should occur, framing questions appropriately, and leaving sufficient unlined space for students to respond. The difficulty, however, is the extra load in making reliable, defensible judgments when faced with the inevitably varied responses. There is a need to develop processes for making such judgments. We have argued that quality of student responses is lifted, resulting from the teaching and learning approach and also the opportunity to respond multi-modally. High level responses effectively coordinate the different representations used.

There is evidence that representational capability is being increasingly acknowledged in framing curriculum and assessment. Working with and coordinating representations is part of the new Australian Science Curriculum. The PISA assessment of scientific literacy recognizes student representational knowledge and capabilities as part of its framework. There is thus a need to research the dimensions across which we might think of representational competence, and how to assess these.

Implications for the Framing of Curriculum Progression

Framing learning progressions in science curricula has always been problematic because of the organization of content into so many topics, each of which involves different concepts and contexts. The difficulty of application of ideas depends critically on context. Thus, a content sequence that moves from physical to chemical change can be read as a progression in ideas, but in fact there are everyday contexts of physical change that require the use of ideas succeeding those needed to understand everyday chemical change. Contexts bring their own conceptual demand. To frame curriculum in a defensible way, we need better constructs to make sense of conceptual progression that will cut across topics.

There is currently considerable interest in developing defensible progression maps in particular topics, as a way of conceptualizing curriculum sequencing, and also to underpin assessment. We need, however, progression dimensions that occur across topics, to underpin curriculum and assessment planning. Some schemes, based on Piagetian ideas, have been designed to provide a generalized account of quality of response to problems within assessment. The SOLO taxonomy (Biggs & Collis, 1982) is one such scheme. It does not, however, provide guidance on structuring content in a curriculum. There have been schemes developed to describe progression in procedural knowledge. There is interest in using representational demand as the basis for sensible curriculum structuring and some inroads are being made into this (Lehrer & Schauble, 2007). In RILS we found that students grew in their meta-representational knowledge that seemed to transfer across topic boundaries. In framing the primary and secondary school topics on substances and changes to matter there were differences in the sophistication of the representational types and challenges that seemed sensible, but there was no guidance beyond the intuitive, and tradition, that we could draw on. We argue that there is a need to explore systematically the way in which representational competencies progress across the school years.

Representational competence, associated with meta-representational knowledge, underpins conceptual work, transcends topics, and seems promising as a way of conceptualizing progression generally. Work is needed with teachers in classrooms to identify these progressions more systematically.

Technologizing the Curriculum

Digital imaging and analysis technologies are becoming increasingly important in science. In RILS, teachers sometimes worked with digital technologies (animations, internet searching, digital microscope capture) to good effect. These technologies can constrain and afford a range of representations, analogies, examples, explanations, and demonstrations to help make subject matter more accessible to the learner (Mishra & Koehler, 2006). They will become increasingly important as part of teachers' representational armory. Sutherland et al. (2004) argued the importance of young people being able to work with both digital and non-digital tools.

There are numerous examples in the literature of digitally based expert representations (animations, simulations, data bases, video) being used in learning sequences, involving students being educated to interpret these. There is a need, however, to build experience with student use of digital technologies to construct representations, such as animations / simulations (Linn, 2003), or stop frame video (Macdonald & Hoban, 2009). The theoretical underpinnings of RILS are well placed to support this happening in a productive way, with students engaging in discussions about the relative merits of the different tools. In becoming resourceful learners, they build awareness of the affordances of the ICT tools they use to construct, work with, critique and communicate representations. There is a need to further explore the incorporation of digital technologies into the representation construction pedagogy.

WIDENING THE SCOPE

Socio Scientific Issues and Wider Scientific Literacy Concerns

We have purposely focused on the role of representation in learning foundational concepts and methods in science in the middle years of schooling because of the centrality of this focus in mainstream science curricula in many countries. However, we also recognize the growing emphasis on teaching and learning about socioscientific issues (SSIs), where science is understood as one powerful resource, knowledge base, and repertoire of methods and strategies, among several, for contributing to possible solutions to real-world problems. SSIs tend to be loosely structured complex topics, where solutions are multiple and uncertain, and also influenced by ethical, economic and cultural factors. Researchers in this field, such as Bencze, Sperling and Carter (2012) and Tomas and Ritchie (2012), recognize the theoretical and practical value of students constructing re-representations of their SSI understandings and findings, where these representations can function as both science-based knowledge claims and evidence of ethical and other understandings of the SSI. Clearly this work entails major representational challenges in integrating primary and secondary scientific evidence, claims, and findings with cross-disciplinary evidential claims, leading to new enactments of science literacy. In characterizing and addressing SSIs, teachers and their students face significant major challenges around representational coherence, adequacy, and short-term/long-term fit for purpose. However, we would argue that our approach entailing sequences of representational clarifications/justifications provides instructive leads in (a) enacting pedagogical processes that will develop students' understanding of the necessarily constructed and partial nature of the knowledge claims that can be made about SSIs, and (b) developing the symbolic and cultural resources needed to generate and judge these claims.

Catering for Diverse Student Cohorts

While our research in RILS was conducted predominantly with middle-class or low socio-economic students, it will be important to investigate whether this approach is applicable to other student groups. We acknowledge that science education researchers from cross-cultural perspectives are seeking to identify and build effective pedagogical bridges between the values, interests, discursive practices and representational resources of different student cohorts and science disciplinary literacy learning (Alvermann, 2004; Ford & Forman, 2006; Gee, 2004; Lee, Luykx, Buxton & Shaver, 2007; Lee & Roth, 2003; Moje, Collazo, Carillo & Marx, 2001; Moje, Peek-Brown, Sutherland, Marx, Blumenfeld & Krajcik, 2004; Wallace, 2004; Waldrip, Timothy & Wilikai, 2007). These researchers assume that this learning is enabled when teachers work with students to (a) negotiate effectively between everyday discourse, culture, and values and those of the science community, (b) develop explicit understanding of the rationale for the norms of science knowledge production and communication, and (c) sustain connections between expression and values in both cultures.

However, as Moje (2007, p. 30) has noted, this "cultural navigation perspective" on science disciplinary learning has tended to take up global, interdisciplinary viewpoints rather than focus on the specifics of textual practices in science, and has often failed to suggest practical ways in which everyday text production can be linked precisely to the literacies of science. On these issues, we suggest that our approach to learning science, in encouraging student representational approximations and negotiation of intended and shared meanings, and multiple opportunities for re-representation, can provide rich and responsive pathways for cross-cultural teaching. Such an approach respects student ideas and range of perspectives grounded in their culture, where a focus on negotiation and clarification of canonical representations can align with the development of cross-cultural understandings.

Integration and Adaptation with Other Subjects

Encouraging results from our approach in both primary and secondary science classrooms has led some teachers to adapt this approach to other subject areas, with claimed positive outcomes. In RILS, we did not investigate this issue. However, following Lemke's (1990) view of learning in science as partly about communicative competence in this domain, it is reasonable to suppose that a sustained student focus on representational challenges could be used in other subjects, where students are expected to develop understanding of the domain's discourse through engaging with its goals and methods. Many successful students are unaware of the discourse (i.e. underlying ways of knowing, thinking and making meaning) of different school subjects because they have learnt this competence through immersion and teacher mimicry. Our representational approach has the potential to facilitate more explicit student knowledge of how the resources of any subject discourse are used to generate and judge its knowledge claims. In RILS we have focused on the affordances of generic and domain-specific representations for learning science, but argue that focusing on both generation and evaluation of representations in other domains can build a classroom community of shared understandings around disciplinary literacies.

Our work in science offers a proof of concept for this domain, but this literacy approach could be adapted to other subjects, such as mathematics or history. In a post-RILS study we have explored the adoption of this approach in Mathematics and English with some encouraging results, but there is a need to explore what subject areas could benefit from this approach. In our representational approach to mathematics, students first prepare a response to a mathematical challenge and share their response and reasons for this response with a group of peers who then develop a common response, with reasons. This approach has been beneficial for improving and clarifying student thinking.

SCALING UP THE APPROACH

In Chapter 8 the question was raised as to the issues involved in scaling up the representation construction pedagogy to system level. These issues are: a) the demands on teacher PCK involved in the approach, especially the need for the teacher to make judgments about the quality and possibilities of student representations, and respond accordingly in individual or classroom settings; b) changes in teacher epistemological beliefs implied by the approach, and c) the time-intensive professional development approach that was used in RILS and the impracticality of extending this to system level. Thus, there is a need for research that further explores approaches to teacher professional learning that could be effectively used to support teachers adopting the approach.

Thus far, we have two indicators of ways forward. The first is the case of Therese, described in Chapter 8, which showed how a receptive teacher can innovate within the approach after even a short period of support. The second is evaluation of a large-scale professional development initiative that was based on representation construction and guided inquiry.

The Switched On Secondary Science Professional Learning (SOSSPL) program entailed two full days of professional learning workshops, which highlighted the representation construction approach. Following the initial two days of the program the 191 participating teachers were required to implement a small scale classroom-based project that trialled an aspect of representation construction approach in their classroom practice and then return for a third day of professional learning to share their findings. On the basis of their experience in SOSSPL the vast majority of the teachers perceived the representation construction approach as beneficial to their classroom practices. This was reflected in the surveys and focus group interviews that evaluated the program as well as presentations from the teachers on their classroom-based projects.

Some of the key ideas about representation construction approach were appreciated by the teachers after just the first day where they agreed or strongly agreed to the following Likert statements on the Day 1 evaluation survey.

> I have developed an understanding of a science concept as a multi-representational entity (97.6% of teachers).

> I have understood that science involves coordinating and reasoning with multi-modal representations and so generating and negotiating representations is the focus of teaching and learning (93.9% of teachers).

The appreciation for the representation construction approach by the teachers is reflected in the following comments made by individual teachers during focus group interviews that were held following the completion of the SOSSPL program.

> But I think for us, it's reminded us that we shouldn't be creating them [representations] all the time, that the student needs to create them.

> …it does focus attention on students actually puzzling out their own response to key issues that you want to put before them, and it also creates then the conversation that allows you to interact with a student...the engagement between you and the student is more authentic.

> I found value in representations as a novel concept of a way of delivering content to students without being a teacher-centred zone. I thought it was a genuine new approach that has a lot of potential.

The evaluation of the SOSSPL program occurred over a short time and did not identify substantive changes to the teachers' classroom practice. However, the SOSSPL program did provide the seeds for change given the teachers' perceptions of the value of the representation construction approach and their willingness to embrace the notion of active student representation construction. The benefits of the approach will only be fully realized, however, if teachers move beyond this position.

Currently members of the team are engaged in further research on the representation construction approach, using an action learning team approach to teacher professional development in schools and school networks (Aubusson, Ewing & Hoban, 2009). There is a need for further research exploring the possibility of supporting significant change in classroom practice on a system wide scale.

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CHAPTER 12

REPRESENTATIONS AND MODELS

Aspects of Scientific Literacy

COMPONENTS OF SCIENTIFIC LITERACY

The provision of formal science education for those who may become scientists and engineers has long been recognised as necessary. It is only in the last two decades or so that the need for the entire population to attain 'scientific literacy' has gained widespread official acceptance. This has triggered a prolonged debate about what should be included in such an education (Laugksch, 2000; Roberts, 2007). The most contentious area has been that of 'nature of science', where

> 'NOS typically refers to the epistemology of science, science as a way of knowing, the values and beliefs inherent to scientific knowledge and its development (Lederman, 2007, p. 833)

Success in the teaching and learning of NOS in schools has been mixed, for a variety of reasons (Abd-El-Khalick, 2005). In the light of this, ambitions for the attainment of scientific literacy are apparently being trimmed back to that of 'public engagement' (Bauer, 2009). This latter implies the possession of key skills that can be applied to scientific content, when it is encountered, in order for the learner to appreciate the epistemological grounds for its acceptance as valid knowledge. In this chapter I revisit the relationship between the ideas of 'representation' and 'model' in Chapters 6 & 7, arguing that, if the idea of 'visualization' is added to their use, the outcomes are key skills that, when attained, contribute substantially to the capacity to participate in public engagement with science.

REPRESENTATIONS, MODELS AND TEACHING

Some Matters of Definition

Any efforts to support the attainment of skills are, because of their inherently abstract nature, bedevilled by the definition of what is intended. This is certainly so in respect

R. Tytler, V. Prain, P. Hubber and B. Waldrip (Eds.), Constructing Representations to Learn in Science, 193–198.

of to ‘represent’ and to ‘model’. Most definitions in the literature conflate the two, leading to a tautology. I personally have been guilty, as charged e.g.

> ‘A model is a representation of an idea, object, event, process, system, initially produced for a specific purpose’ (Gilbert, J. K., Boulter, C. J., 2000, p. vii).

The two *can* be separated, with that for ‘model’ emphasising the notions of ‘an evident link to a phenomenon of interest’ and that of ‘simplification for a purpose’ in that

> ‘—phenomena can be organised, through the processes of idealisation and abstraction, into a model, which in turn provides useful insight for the development of a new theory’ (Oh, P.S., Oh, S.J., 2011)

While the inclusion of ideas from semiotics, in this volume, gives a representation a separate status as *standing* for a model. This standing enables a model to be directly perceived by one of the senses. Thus:

> ‘We view representations—as signs that stand for something that will be meaningful to someone, and distinguish between a concept, its representation, and phenomena in the world’ (Hubber, P., Tytler, R., in press)

It therefore seems reasonable to suggest that, whilst models are attempts to identify, or construct, a simplified version of a phenomenon in order to explain it in some way, representations ‘stand for’ either the whole of, or parts of, a model. This book, in essence, asserts that teaching the ‘nature of a model’ and how a model can be represented, key aspects of understanding the nature of science, must involve the active engagement of the students. The next question then becomes: In what way is that active engagement of value to the teacher in addressing those tasks?

The Significance of Student Engagement

Chapter 7 states that

> ‘We would argue that modelling practice in science moves from first, speculative, constructions—to more refined and evidence-based peer-reviewed models. — they are always selective, focused on solving particular problems, and incompletely resolved, as is the case with student models. These student models cannot be thought, then, as somehow illegitimate’ (Hubber, P., Tytler, R., 2013)

I suggest that, far from being ‘illegitimate’, students’ models are indeed clearly related in two ways to the status of models in science *per se,* and are therefore proper components of education about the nature of science.

The first of these ways relates to the range of possible epistemological states that a model *in science* can attain over periods of time. It can be an *expressed model*, that which is placed in the public arena by its originators for the perception of others.

An expressed model that has been subjected to empirical testing by the scientific community, accepted as worthwhile to be used as the basis for research by being published in a refereed journal, is a *consensus model*. An *historical model* is a consensus model that has been superseded as the basis for 'cutting edge' research. Such models are not abandoned: they both remain in use as the basis for some routine, unproblematic, explanations and become enshrined in the school science curriculum. A *curricular model* is a simplified version of a consensus or historical model that is included in science syllabuses as knowledge to be acquired. A model that attains all these states over a period of time is one that has been produced by the community of scientists. However, students' models, a theme of this book, are *all* expressed models, with *some* achieving a temporary status as consensus models, the latter being constrained by the degree of testing to which they are subjected in the science class.

The second of these ways is related to the passage of time. Where a phenomenon is of sustained interest to scientists, enquiry into it makes use of a historical sequence of models, each of which has greater explanatory power than its predecessor. In fields of central importance to science, progress involves a relatively few models that form the basis of research for many years. A good example is models of force: Aristotle's (5^{th} Century BCE), Newton's (16^{th} Century CE), Einstein's (20^{th} Century CE). In other fields, progress is slower, with adaptation rather than revolution being the norm. A good example is that of 'chemical kinetics', where eight distinct consensus models, in historical sequence, were identified (Justi, R., Gilbert, J.K., 1999). It therefore seems reasonable to assert that students' expressed models, particularly where they acquire temporary consensus status in a class, are analogous to the early stages in the evolution of consensus models.

Teachers thus have every justification for teaching about 'representations and models' in their classes. What, then, is involved as students come to create personal meanings for these abstractions?

REPRESENTATIONS, MODELS AND LEARNING

The first answer to this question is that they must come to understand and use the 'conventions of representation' that relate a given mode of representation used for a model to the phenomenon that is being depicted. The second answer is that they must be able to form a mental model of the abstractions being discussed.

Employing Suitable Modes of Representation

Representations can be placed into a broad fivefold typology based on the physical 'mode' involved (Gilbert, J.K., 2008). To a first approximation, each mode enables particular aspects of a model to be represented. However, the situation is made more complicated by the existence of sub-modes within each mode. Models in the *concrete (or material)* mode can be perceived by touch as well as by sight. For example, the 'crystalline solid' model of a chemical substance can exist in the 'open' (ball-and-stick), 'space filling', or 'orbital' sub-modes. The *verbal* mode can adopt either a spoken or a written sub-mode. In addition to the normal conventions of a given language, rendered very complicated by the specialist nouns that science develops, the verbal mode relies heavily on the use of analogy (Hesse, 1966). The *symbolic* mode consists of algebraic abstractions, the sub-modes being mathematical equations and chemical equations. Whilst the respective intellectual communities that make extensive use of these have developed their universally-applicable 'codes of representation', the history of that development has left behind a detritus of earlier versions that are still in use in school textbooks (Gilbert, J.K., 2008, p. 16). The *visual* mode, using the most heavily relied- on faculty of sight, has thrown up a wide range of sub-modes (even sub-sub- modes), that are known as graphs, photographs, diagrams, animations (Gilbert, J.K., 2008, p. 11–16). The *gestural* mode uses the movement of the whole or part of the body. Although under-researched, the representations produced in the gestural mode have a very positive impact on learning (Gilbert, J.K., 2008, p. 9–10).

Students must, then, know the 'conventions of representation' for all the modes and sub-modes that they are likely to encounter in the learning of science. I know of no comprehensive analysis of what that might entail or of a curriculum that, at the moment, specifies such learning. However, what is entailed has been the subject of analysis (Stevenson, 2005).

The Forming of a Mental Model: The Act of 'Visualization'

Again, we encounter a confused terminology in the literature, for the words 'representation' and 'visualization' are used in a variety of ways. Both words are used as alternatives with which to label an ontological entity that is open to common experience e.g. a graph ('the graph represents the array of data' and 'the graph is a visualization of the data'). They are also used to describe the mental meaning that is made by a person of that object in common experience e.g. 'I formed my own representation of the data' and 'I visualized the array of data in the graph'. To avoid confusion, it is therefore helpful to distinguish between *external representations or external visualizations*, which are the public display of information (Tufte, 1983) and *internal representations or internal visualizations*, which are mental, personal, and inherently private. Although the perception of an external representation/visualization and the formation of an internal representation/visualization depend on the same mental faculties, we can never be sure that the two are identical. Terminological exactitude is thus called for.

A fluency in the production of external representations, with its implications for the production of internal representations, may be termed *meta-representational competence* (Gilbert, J.K., 2008). To demonstrate this, a person – here a science student – must be able to do three things. First, to demonstrate an understanding of the 'conventions of representation' for all the main modes and sub-modes used in the discourse of science as it is met by the student. Second, to demonstrate a capacity to 'translate' a given model between the modes and sub-modes in which it can be depicted. Third, be able to construct both an internal and an external representation for a given purpose using the conventions of any of the modes and sub-modes of representation in common use. How, then, can representational competence be linked to the capacity to generate models?

FORGING RELATIONSHIPS BETWEEN REPRESENTING AND MODELLING

There are five broad approaches that have been taken to acquiring the knowledge, skills, and epistemological commitments, involved in representing and modelling (Justi, R. & Gilbert, J.K., 2002).

The first of these is through the *learning of curricular models*. This is the most conservative approach, where the learning of the nature of particular historical or consensus models is mandated in the curriculum, taught by transmission methods, and assessed as factual knowledge. The scope for the learning of the general modes of representation in this, essentially case study, approach is very limited. The active engagement of students in the processes of modelling and representing can be increased in two ways. One is to use 'teaching models', analogies based on phenomena with which students are very familiar. (Treagust, D.F., Harrison, A.G., Venville, G.J., & Dagher, Z., 1996). The other is the adoption of a 'story – line' approach would enable the historical and philosophical aspects of model emergence and representation use to be addressed (Stinner, A., Williams, H., 1998).

The second of these is the learning to use models approach. Here, after the nature of a model has been grasped (see above), that understanding is deepened and extended by applying it to a range of situations and allied phenomena (Arnold, M., & Millar, R., 1996). In this way, the vexed issue of 'transfer of knowledge' is addressed, this requiring the active creation of representations (Marton, 2006).

The third of these is the *learning to revise models* approach. Here, after the nature of a particular model has been grasped and its use extended, the scope of the model is broadened by applying it to phenomena that are not obviously related to that in which it was initially learnt. Such an approach does require students to actively engage in the actual construction of representations (Stewart, J., Hafner, R., Johnson, S., & Finkel, E., 1992).

The fourth approach is that of *learning to reconstruct models.* Here a known model is recreated by the students on the basis of a simple visual representation of it and prompted by a progress series of questions that they have to address about its nature and properties (Barab, S., Hay, K., Barnett, M., & Keating, T., 2000). Whilst the essence of the model itself is already known, students have to use representations in a creative way in order to create a fully-functioning model.

The fifth approach is that of *learning to construct a model de novo*. Whether the phenomenon to be investigated is represented to the students or whether they decide upon it themselves, they have to pose questions, construct representations, test their products, and evaluate the overall outcome. This approach is exemplified by the case study given in Chapter 7. A systematic approach to the implementation of this approach is also given in Justi and Gilbert (2002).

It may have seemed strange to include all these five approaches to developing the skills of representation and modelling, since only the fifth of them actually involves the *de novo* construction of a model. However, the realities of common practice in science education classrooms suggest that only the first approach is usually employed by teachers. Moving through the approaches, from the first to the fifth, will be an educational sequence for both students and their teachers.

SOME CONDITIONS FOR SUCCESSFUL LEARNING

A number of conditions must ultimately be met for a student to be said to demonstrate meta-representational competence and the capacity to generate models. First, as has already been said, the codes of representation for the commonly-used modes and sub-modes must be known. Second, it must be possible for students to try to produce models of phenomena that are either unknown to them or unknown to science. Third, they must be able to collaborate with their peers in model construction, for this is the usual practice in science. Fourth, their teachers must practice the arts of education as opposed to those of instruction.

If these conditions are met, students will be equipped, partially at least, to take an active part in the public engagement with science, for key aspects of the nature of science will have been learned.

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