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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.*

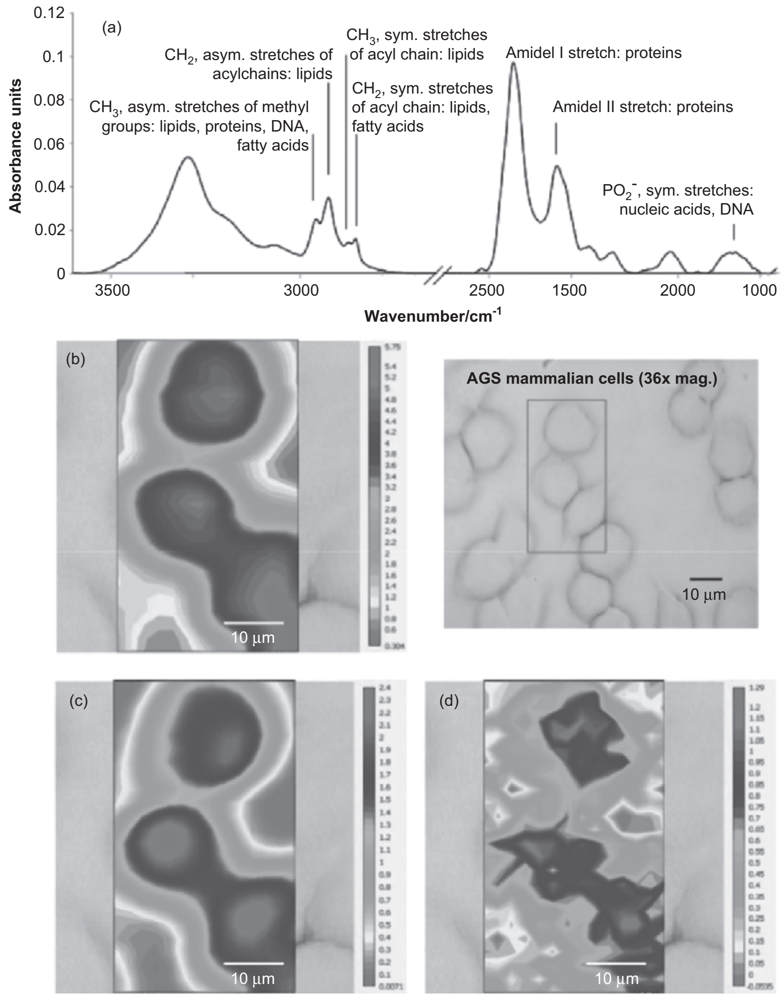



*Figure 1.1. Synchrotron images of chemical maps for AGS cells.*

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.

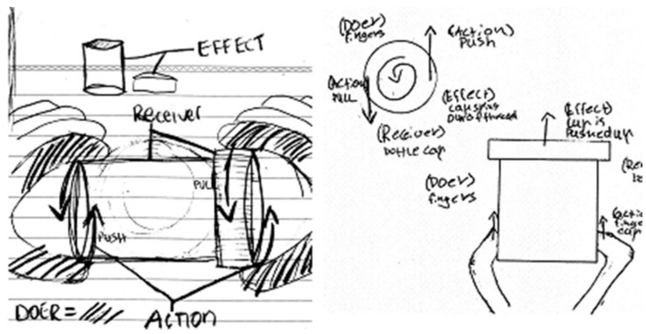



*Figure 1.2. Student responses to a challenge to represent the forces involved in opening a screw top container.*

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

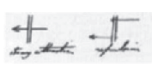
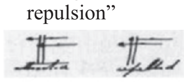
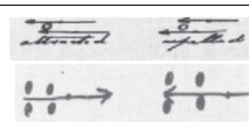
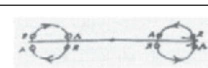
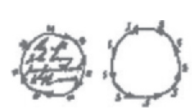
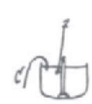
Several research agendas have contributed to the current strong interest in a representational focus in science education, including sociocultural research in science education, conceptual change research, and socio-semiotic research.

### *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.

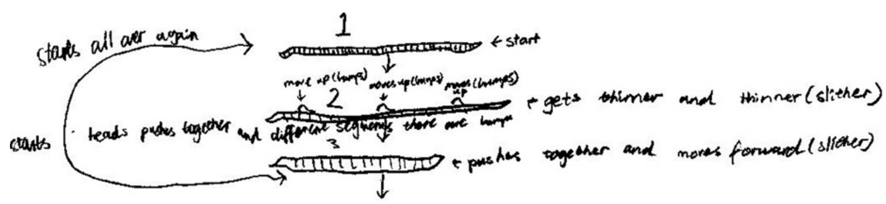



*Figure 1.3. Ivan's workbook entry representing the movement of an earthworm.*

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.

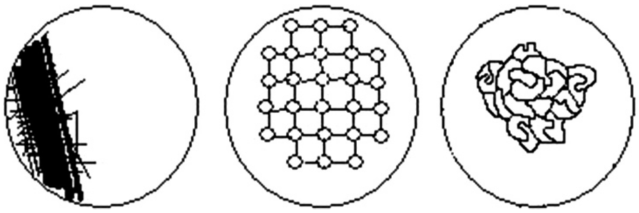


*Figure 1.5. Student representations of particle arrangements to explain how paper keeps its shape.*

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.