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.

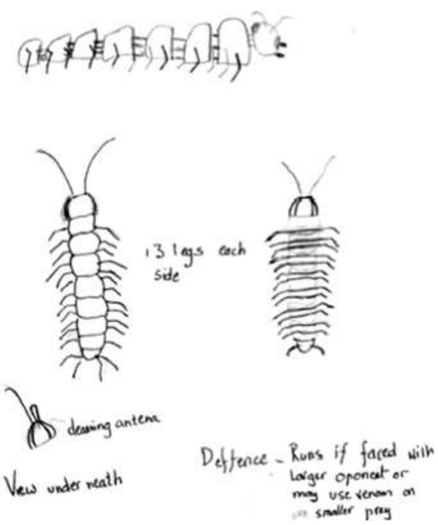

Figure 6.1. Centipede notebook entry.

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.

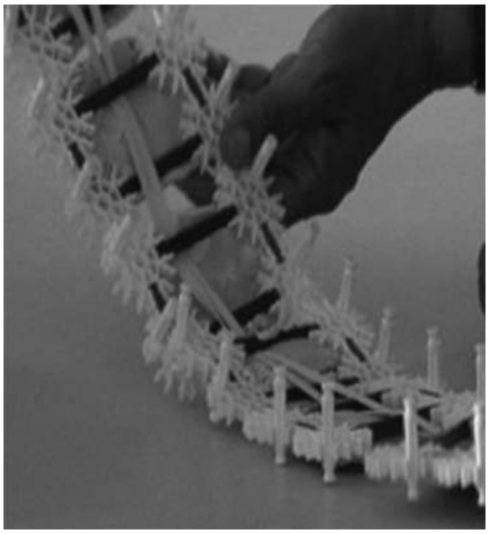

Figure 6.2. Centipede model showing elastic attachment of segments.

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.

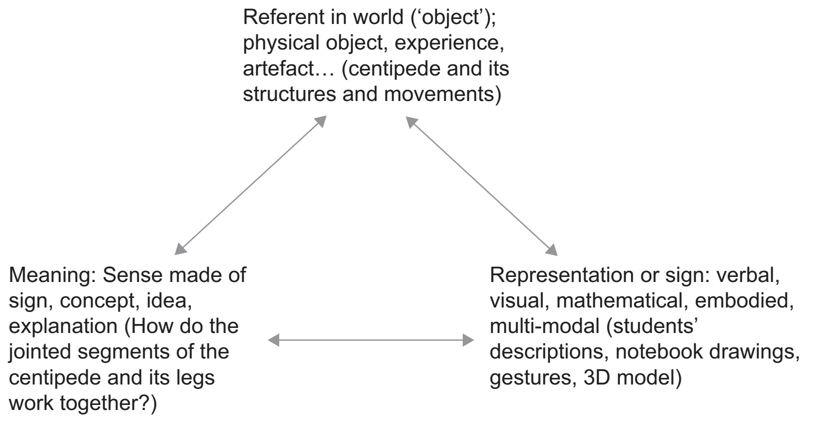

Figure 6.3. Peirce's triadic model of meaning making.

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.

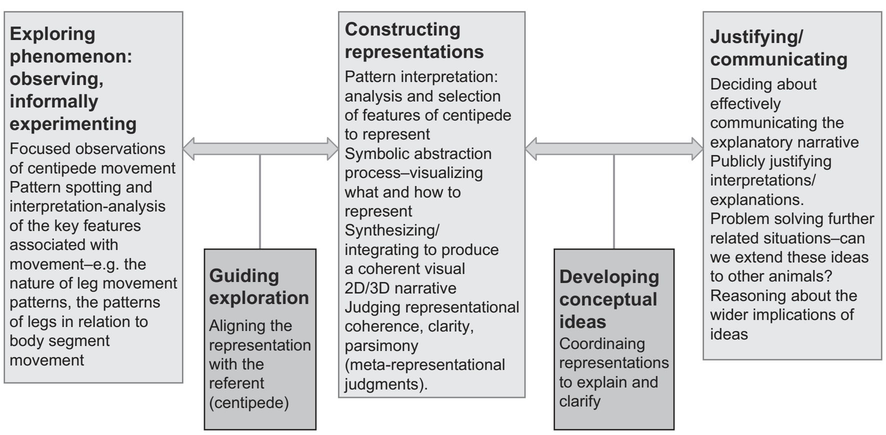

Figure 6.4. Reasoning processes within a representational challenge activity.

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?*’

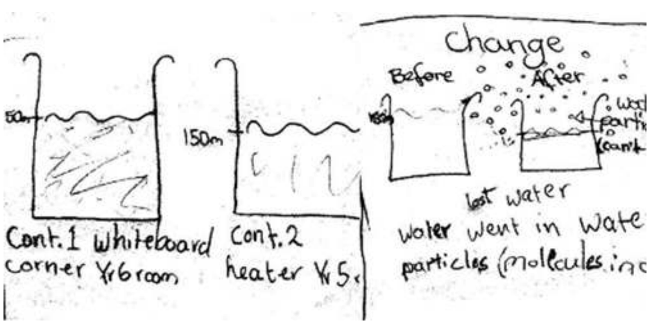

Figure 6.5. Student 5S’s representation of change in water level, before and after Malcolm’s challenge.

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.

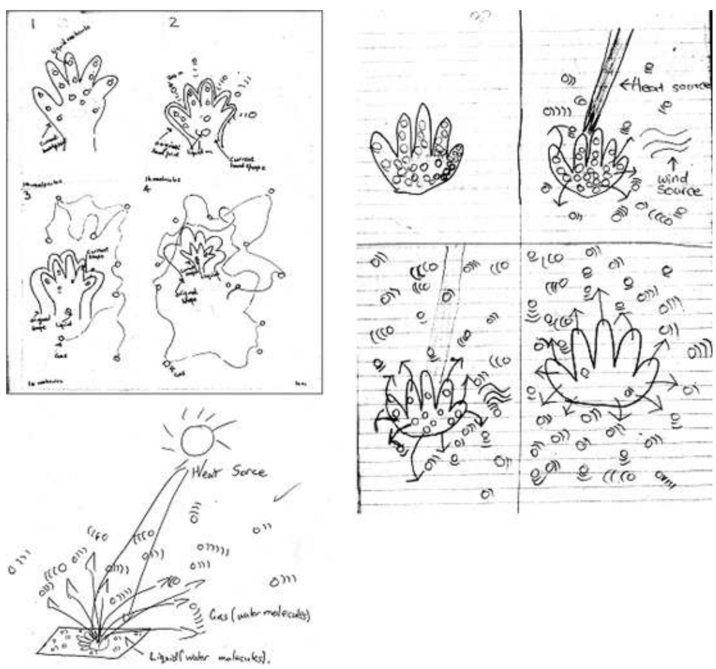

Figure 6.6. Variation in student representations of an evaporating handprint.

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.

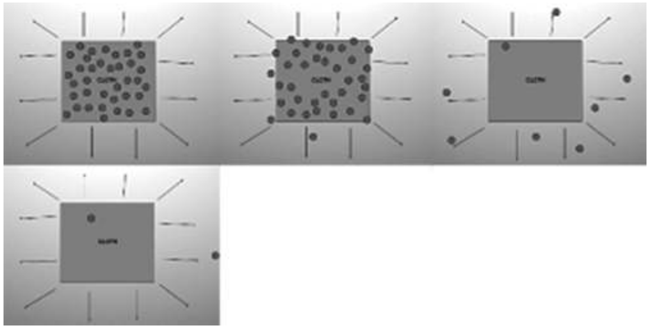

Figure 6.7. Part of student 5G's animation of a drying cloth.

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).

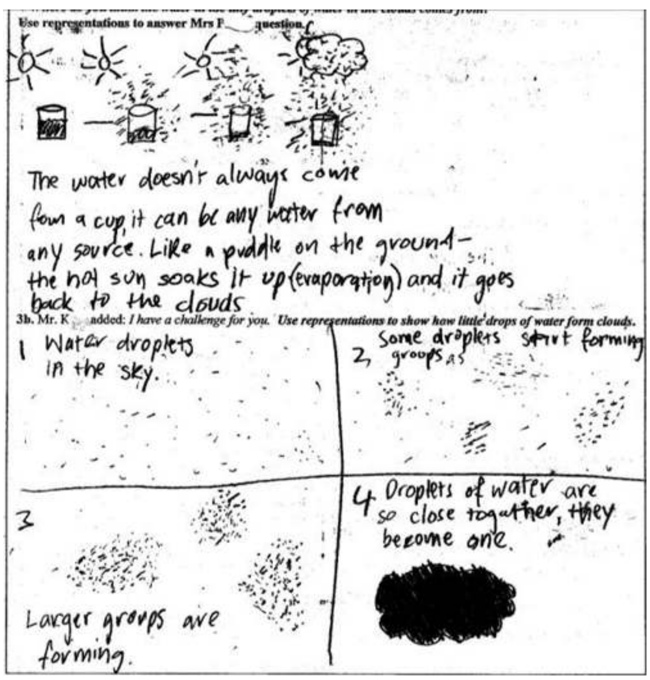

Figure 6.8. Student 6H's response to the post test question "How do little drops of water form clouds".

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

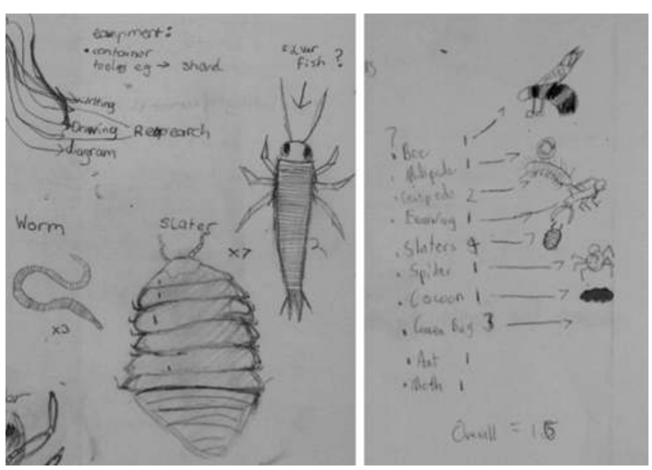

Figure 6.9. Student notebook sketches.

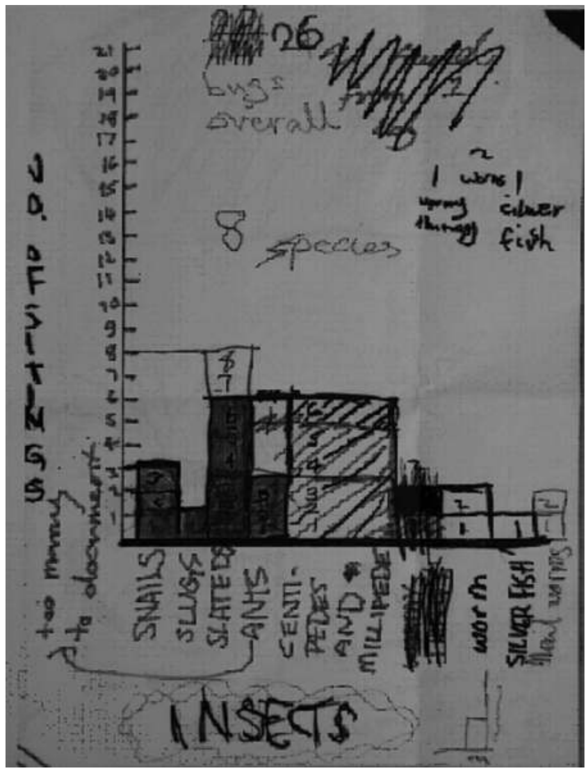

Figure 6.10. Student graphical representation of diversity in a habitat.

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.