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

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

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

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

The representational challenges that are central to the approach are varied, and this variation will be explored in this chapter. However there are two key features of representational challenges that distinguish the approach from other student-focused approaches to school science. We see representational challenges as different to the types of tasks often undertaken that involve replication of ideas or processes in new situations. A representational challenge needs to involve some new coordination or
synthesis of existing representations – a fresh orchestration of elements. In this sense it will involve a claim concerning how a phenomenon should be represented and explained. The other feature is that it has the potential to individuate – the different representations will not converge upon one ‘correct’ account but will allow for individual variation in describing or explaining. Thus, these challenges align with problem solving/ investigative approaches that offer a variety of solutions. Unlike many open investigations, however, they serve a clearly defined conceptual agenda within the sequences.

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

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

THE SEQUENCES

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

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

The class discussions serve a number of purposes; introducing the challenge for instance, or evaluating student work. The representation in Figure 4.1 does not
include the actions of the teacher in moving round the room while students were working, challenging and scaffolding their work individually or in groups. This often led to brief interruptions to the lesson in which the teacher clarified or pointed out common errors. This monitoring helped in framing the whole class discussions that are represented here. The discussions were not purely verbal, but often included
demonstrations (e.g. using the bead model in lesson 5) or the presentation of student work on the board, or teacher exemplifications of the representation. The discussions were thus important in advancing the representational work.

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

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

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

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

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

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

In the astronomy unit there is similar variation, but more sustained use of physical models, role-plays and animations. Figure 4.3 shows three of the 8 lessons in the astronomy sequence. In the introductory discussion the partial nature of the globe as
a representation of the earth is discussed (see Chapter 7 for details of this sequence). Then a role-play is enacted to explain the relationship in space of the earth to the sun, and the important distinction between orbiting, and rotating. The representational challenge involves a role-play where students imaginatively extend this idea to speculate what two objects orbiting each other might look like. Students then re-represent their solutions in annotated drawings and some solutions are invited onto the board for class discussion. The second lesson starts with a discussion of prior ideas, then students are challenged, without significant scaffolding, to represent
how it can be day and night on earth at the same time. Their representations are discussed, before the teacher models day and night with a globe and a strong beam of light. Students are invited and challenged to use this representation to answer questions about the path of the sun in the sky at various points on earth. Finally they are given images of sun movement against a horizon and asked to explain these in terms of the representations they had been introduced to. This was not a straightforward task.

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

Figure 4.4 shows the structure of three lessons in the ‘animals in the school-ground’ sequence. Lesson 1 of the 2009 sequence involves observations of a stick insect and raises questions about the characteristics of living things. Lessons 2/3 of the 2007 sequence involved setting up and executing an exploration of a particular habitat. Lessons 6/7 in 2009 involved the setting of a modeling task for animal movement. The first lesson has a dual aim, in pursuing a discussion of the characteristics of living things, and in engaging with the challenge of representing animal movement, using multiple modes. The pattern here is similar to those we have seen in the other sequences. Lessons 2/3 involve a slower pace of discussion and representational challenge, in that the challenge involves a range of representations, including physical artefacts (quadrat) and digital microscopes, and the discussion is substantial. Teachers lead students to think about the relations between animals and a range of features of a habitat, what and how and why they might observe and measure, and the logic of sampling. The final poster presentation involves a multi modal display. The teachers’ comments in the discussions cover a range of issues, and are not as explicitly focused as other discussions have been. In this sequence, the focus is more on data generation than on exemplifying an idea. Finally, the animal modeling task is rich and multi faceted, and the teachers have time to engage at some length and depth with individual groups as they perform preliminary sketches, gather materials, and coordinate their different representations of movement. The stories of two of these models are told in Chapter 1 (techno-worm) and Chapter 6 (centipede).
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Figure 4.4. The structure of lessons 1, 2/3, and 6/7 of animals in the school-ground sequences (Grades 5/6).

DISCUSSION

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

The Nature of the Sequences

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

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

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

Representational Challenge

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

- An open representation of processes of manipulating plasticine, leading to the use of the arrow representation (see Chapter 3);
- The imaginative representation of what happens at the surface of a table which exerts an upward force (see Chapter 3);
• A role-play exploring what it might mean for two astronomical bodies to orbit each other (see Chapter 7);
• Teacher questioning and student consideration of the partial, selective nature of different representations of moon phases and how they relate to each other;
• The building of an account of a habitat through a variety of representations of animal diversity, biotic and abiotic factors, and animal behavior (Chapter 6); and
• Interpretive molecular model drawings providing an explanatory account of various evaporative phenomena (Chapters 3 and 7).

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

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

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

The Class Discussions

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

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

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

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

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

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

**The Principles Underpinning the Approach**

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

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

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

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

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

**Explanation, Argumentation, and Knowledge Generation**

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

**Perceptual Mapping**

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

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

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

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