Chapter 5
Representation Construction: A Guided Inquiry Approach for Science Education

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Abstract This chapter outlines a guided inquiry approach, called representation construction, which was successfully developed within an Australian Research Council (ARC) project that links student learning and engagement with the knowledge production practices of science. This approach involves challenging students to generate and negotiate the representations (text, graphs, models, diagrams) that constitute the discursive practices of science, rather than focusing on the text-based, definitional versions of concepts. The representation construction approach is based on sequences of representational challenges which involve students constructing representations to actively explore and make claims about phenomena. It thus represents a more active view of knowledge than traditional structural approaches and encourages visual as well as the traditional text-based literacies. The approach has been successful in demonstrating enhanced outcomes for students, in terms of sustained engagement with ideas, and quality learning, and for teachers enhanced pedagogical knowledge and understanding of how knowledge in science is developed and communicated. This chapter draws on specific examples of how the approach was implemented in a variety of topics, such as energy, forces, astronomy and ideas about matter within junior secondary science classrooms. It will also draw on the issues associated with the adoption of the approach in laptop/tablet classrooms where part of the curriculum is delivered in the cloud.

5.1 Introduction

This chapter describes an approach to inquiry teaching and learning in science that has been developed and trialled over a 10-year programme of research, which is based on students actively constructing representations in response to structured challenges (Tytler, Prain, Hubber, & Waldrip, 2013). The approach has its basis in a number of practical concerns and theoretical insights. There is mounting concern that traditional teacher-centred approaches to science are failing to engage students

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and, in particular, are not developing the inquiry and problem-solving skills, and creativity, needed by citizens engaged in the twenty-first-century workforce (Chubb, 2014). Despite a history of curriculum advocacy, inquiry approaches have failed to take hold:

> *Four decades after* Schwab's (1962) *argument that science should be taught as an 'enquiry into enquiry', and almost a century since John Dewey (1916) advocated that classroom learning be a student-centred process of enquiry, we still find ourselves struggling to achieve such practices in the science classroom.* (Osborne 2006, p. 2)

A decade after Osborne made this point, the situation in Australia has not changed much (Goodrum, Druhan & Abbs, 2012), despite growing evidence that inquiry and open problem-solving approaches lead to more robust learning in science (Chi, 2009; Furtak, Seidel, Iverson, & Briggs, 2012), as they also do in mathematics (Kapur, 2008).

Allied to the call for inquiry, there is increasing advocacy that school science should better represent the epistemic practices by which knowledge is built in science (Prain & Tytler, 2012). Recent research in science studies has yielded fresh insights into the way that representational work is central to discovery processes and the increasingly pervasive role of the diverse representational work in generating and communicating knowledge (Elkins, 2011). Increasingly we come to understand that scientific knowledge is built by more complex processes than rational, logical reasoning applied to hypothesis generation and testing for evidence. Scientific discovery involves imaginative and often communal processes of creation of models and representations as new tools that mediate our understandings of the world. Inscriptions such as graphs and diagrams, 3D models and, increasingly, digital images and simulations created by sophisticated software and hardware that itself mediates and transforms data, provide new conceptual tools for interpreting the world. Latour (1999) was an early commentator on laboratory work and the complex processes by which teams of scientists generated representations to guide and make sense of data generation. Studying the process by which two scientists studied the encroachment of agricultural land into the Amazon forest, Latour (1999) charted the process of representational redescription, through 'circulating representations', from ordered and labelled soil container arrays, to measurements of soil characteristics, to tables and finally graphs that were transported to Paris then transformed into the abstracted text that was the final published paper. Gooding (2004, 2006) analysed Michael Faraday's notebooks to show the key role played by visual representations in Faraday's developing thinking on the relationships between magnetism and electric current. Gooding identified a fundamental pattern of dimensional transformation, from 2D to 3D to 4D and back to 2D as processes were abstracted and communicated. He argued that complex informal, visual reasoning through a mix of inscriptions and artefacts was a fundamental but unacknowledged characteristic of scientific discovery processes.

These ideas are central to new understandings of how students learn in science classrooms. Lemke (1990, 2004) identified the key role of representational work in learning science, as students are introduced to the complex multimodal representations through which scientific explanatory work is pursued, often is quick succession from text to diagram to symbol to graph and often is without acknowledgement of the representational conventions and complexities of coordination that underpin deeper understanding. Often, in fact, knowledge is thought of in terms of appreciation of the abstracted textual forms in which curricula and textbook conclusions are framed, without due acknowledgement of the representational practices that underpin this knowledge and its use (Tytler, Haslam, Prain, & Hubber, 2009). With growing realization of the importance of representational work, there has been a strong strand of research in cognitive science focused on the role of different representational modes and how these might best be coordinated to support learning (Ainsworth, 2006, 2008). Sociocultural theorists (Lemke, 2004; Moje, 2007) have characterized representational work as central to the development of scientific disciplinary literacy through which students come to know and achieve competence in the discursive practices that characterize science.

Our work sits within an inquiry tradition of research with students actively generating representations rather than being taught to interpret teacher-generated representation. Researchers in this tradition argue that students benefit from opportunities to explore, elaborate, redescribe representations and coordinate them across multiple modes and to negotiate their meaning with support from teachers (Cox, 1999; Greeno & Hall, 1997; Hubber, Tytler & Haslam, 2010; Lehrer & Schauble, 2006a, 2006b; Tytler, Peterson, & Prain, 2006; Waldrip, Prain & Carolan, 2010). Different forms of representation support different insights, and students need to explore the advantages and limitations of particular representational forms and modes for reasoning about phenomena (Greeno & Hall, 1997; Cox, 1999). In theorizing the power of representation construction, we have developed a model (Prain & Tytler, 2012) through which we link classroom inquiry practices with those of science. We argue that each representation has a partial and approximate relation to scientific phenomena, with understanding involving accessing and coordinating multiple, multimodal representations. We argue that the value of each representation can be understood in terms of its affordances (Gibson, 1977) understood as productive constraints on thinking. Thus, a drawing achieves its affordance through its visual and spatial specificity, such as in speculative drawings of particle representations of macro phenomena or in selection and abstraction processes involved in representing complex ideas such as animal diversity or movement (Tytler et al., 2009).

From our perspective, representations actively mediate and shape reasoning such that the targets of classroom activities are on the representational resources needed to support scientific problem-solving and explanatory practices, rather than the establishment of abstracted concepts or mental models. In traditional accounts, representations are often cast as efficient and effective ways to introduce and illustrate abstracted concepts such as waves, chemical bonds or ecological interactions that are considered distinct from the representations through which they are generated and communicated. From our perspective, however, representations are the reasoning tools *through which* we imagine and visualize these concepts and model phenomena. This view is fundamentally Vygotskian, characterizing representations as the disciplinary language tools that mediate or frame our thinking and knowing (Moje, 2007).

5.2 The Development of the Representation Construction Approach to Teaching and Learning Science

This section outlines a guided inquiry approach, called representation construction, which was successfully developed and implemented within three Australian Research Council (ARC) projects that link student learning and engagement with the knowledge production practices of science.

Within the first of the projects, 'The Role of Representations in Learning Science (RiLS; 2007–2010)', the researchers collaborated with Middle Years teachers in several schools in exploring the role of representation in teaching whole topics of science. This exploratory work on representations led to the development of a set of pedagogical principles (detailed below) based on representations and came to be known as representation construction. Within the second project, 'The Role of Representations in Learning Science (RiLS; 2007–2010)', the principles were refined and trialled in several more Middle Years classrooms. The research was extended to involve the delivery of the representation construction approach in blended learning classroom environments in the third project, 'Developing digital pedagogies in inquiry science through a cloud-based teaching and learning environment' (iSTELR; 2014–2016).

This approach involves challenging students to generate and negotiate the representations (text, graphs, models, diagrams) that constitute the discursive practices of science, rather than focusing on the text-based, definitional versions of concepts. The representation construction approach is based on sequences of representational challenges which involve students constructing representations to actively explore and make claims about phenomena. It thus represents a more active view of knowledge than traditional structural approaches and encourages visual as well as the traditional text-based literacies.

Central to the representation construction approach is the view that understanding and practising science involve coordinating and reasoning with multimodal representations. These include verbal and written language (including topic- and process-specific vocabulary), drawing, three-dimensional modelling, mathematical (graphs, tables, equations) and gestural language. In learning these particular literacies of science, students are learning how to invest these representations with appropriate meaning as part of learning how to reason and communicate in this subject. The teacher's task in scaffolding conceptual understanding thus becomes, importantly, about representational processes and products. Whilst students have to learn how to interpret and critique authorized scientific representations, a focus on teacher-guided student construction and justification of their own representations can (a) develop conceptual understanding and reasoning capacities in this subject and (b) enable students to participate in knowledge production methods aligned with scientific practice. Given the teacher's role is to lead students to develop an understanding of the authorized scientific representations, the representation construction approach is considered a guided inquiry pedagogy.

The set of principles that underpin the representation construction approach (Tytler et al., 2013, p. 34) are described as:

1. *Sequencing of representational challenges involving students generating representations to actively explore and make claims about phenomena:*

   (a) *Clarifying the representational resources underpinning key concepts*: Teachers need to clearly identify big ideas, key concepts and their representations, at the planning stage of a topic in order to guide refinement of representational work.

   (b) *Establishing a representational need:* The sequence needs to involve explorations in which students identify the problematic nature of phenomena and the need for explanatory representation, before the introduction of the scientifically accepted forms.

   (c) *Coordinating/aligning student-generated and canonical representations:* There needs to be interplay between teacher-introduced and student-constructed representations where students are challenged and supported to refine and extend and coordinate their understandings.

2. *Explicitly discussing representations*: The teacher plays multiple roles, scaffolding the discussion to aim at student self-assessment as a shared classroom process:

   (a) *The selective purpose of any representation:* Students need to understand that a number of representations are needed for working with multiple aspects of a concept.

   (b) *Group agreement on generative representations*: There needs to be a guided process whereby students critique representations to aim at a resolution.

   (c) *Form and function:* There needs to be an explicit focus on representational function and form, with timely clarification of parts and their purposes.

   (d) *The adequacy of representations:* There needs to be ongoing assessment (by teachers and students) of student representations.

3. *Meaningful learning*: Providing strong perceptual/experiential contexts and attending to student engagement and interests through choice of task and encouraging student agency;

   (a) *Perceptual context:* Activity sequences need to have a strong perceptual context (i.e. hands on, experiential) and allow constant two-way mapping between objects and representations.

   (b) *Engagement/agency:* Activity sequences need to focus on engaging students in learning that is personally meaningful and challenging, through affording agency and attending to students' interests, values and aesthetic preferences and personal histories.

4. *Assessment through representations*: Formative and summative assessment needs to allow opportunities for students to generate and interpret representations. Students need to be supported to extend and demonstrate learning through developing explanations that involve coordinating and re-representing multiple modes.

The following sections provide illustrations of practice taken from case studies from the ARC projects that adopted the representation construction approach. Examples are also provided from a successful statewide professional learning programme, Switched on Secondary Science Professional Learning (SOSSPL 2010–12), funded by the Victorian Department of Education that introduced representation construction to over 300 teachers across the state which they then trialled in their schools (Hubber, Tytler, Chittleborough, Campbell, & Jobling, 2012).

5.3 Introducing Ideas About the Representation Construction Approach

In enacting a representation construction approach, importance needs to be given at the planning stage of the key concepts that underpin the topic to be taught (refer to ***Principle 1a*** above). These concepts need to be expressed as statements of understanding that are couched at a level of language that is readily understood by the students. For example, 'Object like the Earth and Moon spin, or rotate, on an axis, and revolve, or obit, other object' [Year 7 Astronomy] or, 'The temperature of an object is related to the average kinetic, or motion, energy of the particles that make up the object' [Year 9 Energy].

Teachers who are initially introduced to the representation construction approach readily understand that whilst a planning document for a topic might include a series of concepts as statements of understanding, the regurgitation of such statements, say in a topic test, does not necessarily imply understanding. Understanding a concept implies an ability to make links between multiple modes of representations. Figure 5.1 gives examples of a representational challenge given to groups of 3–4 secondary science teachers in which the group was given the challenge to represent their understanding of the concept of 'temperature' on a mini whiteboard.

The group-generated representations of Fig. 5.1 illustrate multiple modes of representation from those associated with everyday experiences to the more formalized canonical forms of representation that might be found in a science textbook. Discussions with teachers who have undertaken this task, from a pedagogical perspective, usually generate a view that their role is one of guiding students in linking the everyday representations they have about a concept, and which they bring to the classroom, with the canonical representations. This representational challenge has also been seen by the teachers as a useful activity they might employ in the classroom, particularly as a formative assessment task designed to elicit students' understanding of a concept at the beginning of a topic (***Principle 4***). The use of a mini whiteboard was seen as beneficial to use instead of butcher's paper as it allows for editing by those who generate the presentation.

Given the definition of a representation as something that explains some aspect of nature and the means by which we understand and communicate our science understandings, teachers readily provide graphic and physical representations such

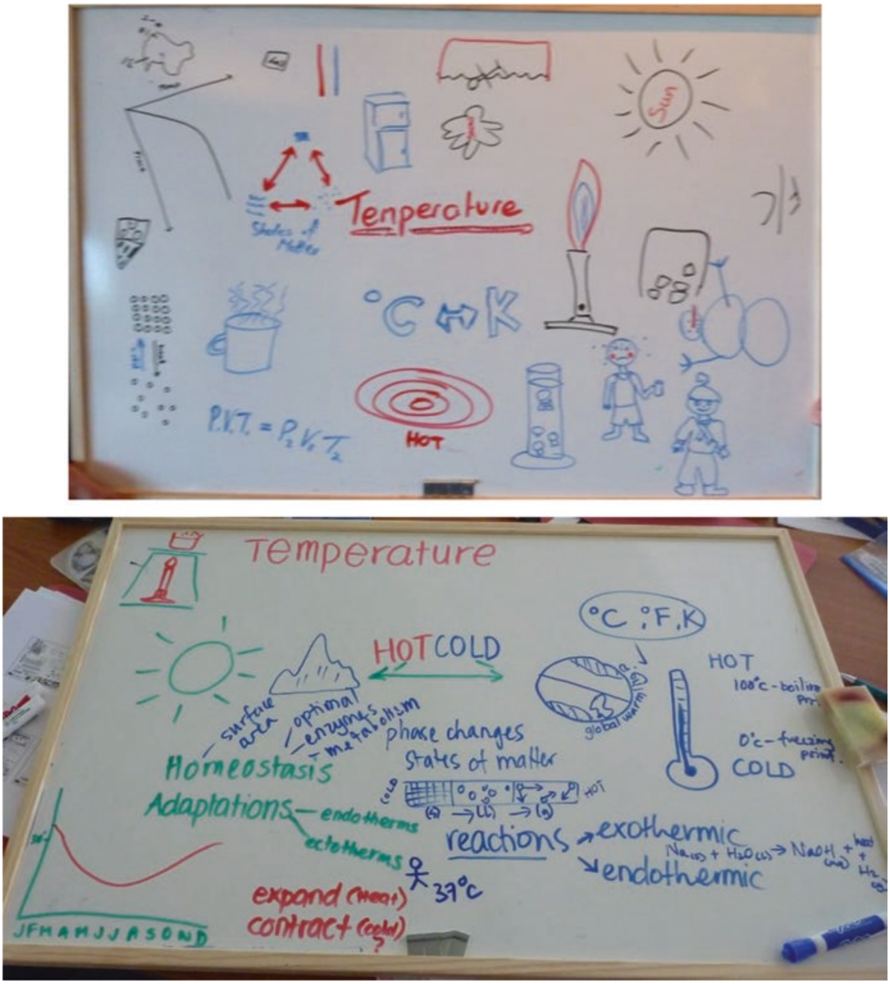


Fig. 5.1 Group challenge to represent the concept of temperature

as diagrams and 3D models. It takes some teasing out for them to recognize that language both in verbal and written forms is a key representational mode they use in the classroom. Apart from thinking about the affordances of individual representational forms, there needs to be some thought to the ways in which different representations can be linked. For example, embodied representations in the form of gesture can provide a link between representational forms. In introducing an idea to a class represented in a diagram, a teacher might provide a verbal explanation whilst at the same time pointing to various parts of a diagram or gesturing to represent movement or spatial relations. Individuals given the representational challenge of explaining how a snake moves through the grass find the task quite difficult as they are not allowed to use gesture to accompany their verbal explanation.

A key element of the representation construction pedagogy for teachers to know and for students to learn is that any one representation is only partial in its explanatory power of the target phenomena, idea or process (***Principle 2***). To illustrate this point, consider that the target concept is *the human heart*. Figure 5.2 provides three representations of the heart. It is important that when presenting a representation to students that discussions with them not only involve those features of the target concept that are shown by the representation but there are also discussions about what features of the target concept are not shown by the representation. For example, Table 5.1 lists some features of the human heart that are shown in the Fig. 5.2 representations and some features that are not shown. Table 5.1 illustrates that collectively the three representations provide more insights into providing an understanding of the target concept than any single representation can possibly provide. In addition, representations, such as those shown in Fig. 5.2, are not things that are readily understood by all those who view them, for example, the significance of the coloured arrows in Fig. 5.2b or mechanical pump as a metaphor for the function of the heart. Such representations need to be interpreted with accompanying text that might be given in a textbook or verbal explanations given by the teacher in the classroom.

5.4 Enacting Representation Construction in the Classroom

The following classroom examples relate to the topic of energy taught at Year 9 in a blended learning environment and a Year 8 class. Most of the examples are digital in nature and reflect both the teachers' use of representations in teaching ideas about energy and students' use of representations in learning ideas about energy.

5.4.1 Representational Challenges with Student-Generated Word Clouds and Mindmaps

The following two examples relate to our iSTELR project where Year 9 students were given cloud-based challenges (***Principle 1***) related to the topic of energy given as initial tasks in the topic of energy. The first challenge asked students to create a word cloud (Fig. 5.3) that represented their understanding of energy and then upload their representation to their cloud-based learning platform (STILE https://www.stileeducation.com/). The function and form of word clouds were explicitly discussed with the students prior to the task (***Principle 2c***). The word clouds in Fig. 5.3 not only show the words the students associate with energy, but they also show which words the students considered as more important (greater font size). The second challenge for the students was to construct a mind map (Fig. 5.4) to represent how different forms of energy connect with their daily lives (***Principle 3b***).

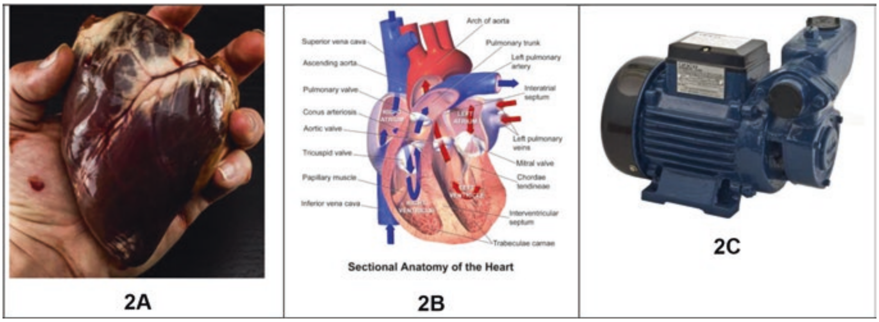


Fig. 5.2 Three representations of the heart

Table 5.1 Some features of the human heart that are shown and not shown in the Fig. 5.2 representations

Representation A		Representation B		Representation C	
What it shows	What it does not show	What it shows	What it does not show	What it shows	What it does not show
Shape	Placement in the body	Internal structure with names of parts	Placement in the body		Shape
Surface feature on one side	Internal structure	Direction of blood flow	Colour	Key function of the heart as a pump	Internal structure
Colour					

It is important to note that a key element of all representational challenges is to have some evaluation of the student-generated representations. Challenges in the classroom usually lead to evaluative discussions amongst the students or in class discussions by the teachers. In the cases illustrated in Figs. 5.3 and 5.4, students shared their word clouds/mind maps in small groups. The teacher had access to all students' representations through the STILE platform which she used to inform her subsequent teaching and to initiate class discussion by projecting selected students' word clouds or mindmaps for the whole class to view.

The technical features word clouds and mindmaps are different and afford and constrain the representations that are constructed. Knowledge of these features by the students allows them to make certain decisions in what they wish to express in their representation. It is the role of the teacher to ensure that students gain such knowledge not only for the specific task as described above but to add to the students' kitbag of representational forms they might draw on in the future (***Principle 2***). In this way teachers have a role to play in developing students' meta-representational competence (diSessa, 2004). According to diSessa (2004) meta-representational competence includes:

- The ability to invent novel representations
- The ability to critique existing representations
- Knowledge of the functions that representations perform
- Knowledge that facilitates the rapid learning of new representation

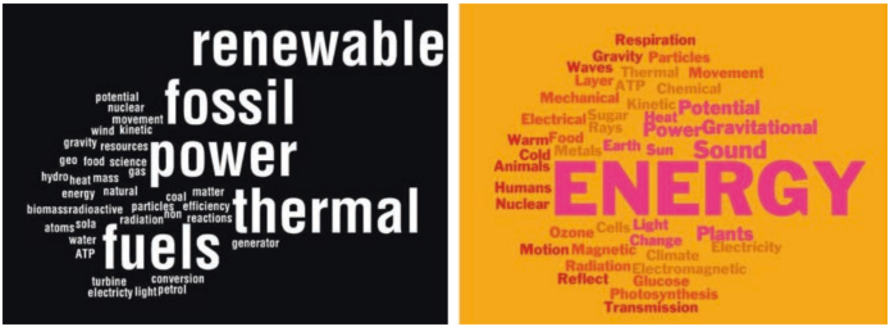


Fig. 5.3 Year 9 students' word clouds of the concept of energy

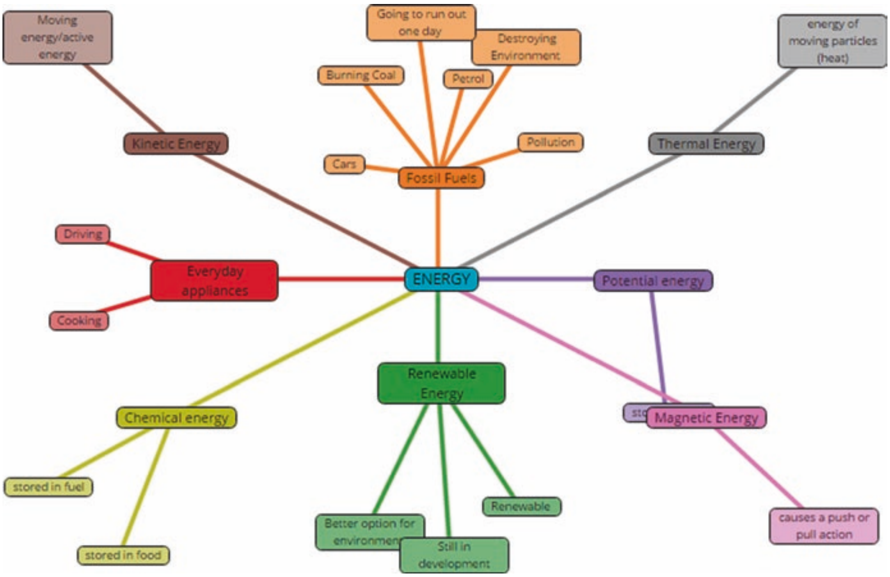


Fig. 5.4 Year 9 student's mind map connecting energy forms to their daily lives

5.4.2 Opinion Polls and Surveys

The use of a cloud-based platform accessible to all students in the class provides the teacher with ways to quickly gain formative data that can be put into various representational forms that can be fed back to the class to initiate discussion and inform the direction of further teaching (***Principle 4***). The following two examples relate to the use of opinion poll and survey strategies within the STILE platform.

The purpose for the opinion poll was to elicit Year 9 students' attitudes to climate change (***Principle 3b***) with questions that were part of an annual survey of Australian attitudes to climate change conducted by the Australian Government Commonwealth

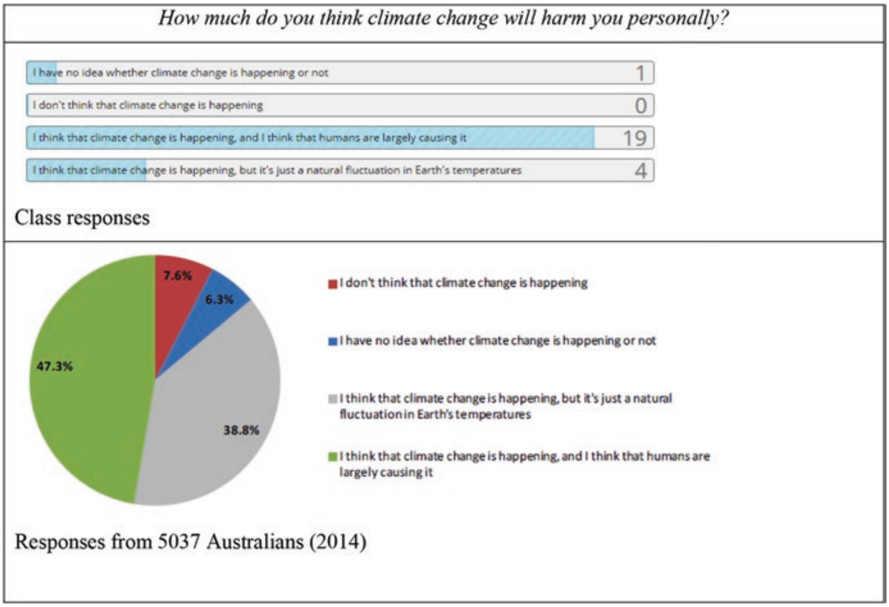


Fig. 5.5 Year 9 students' and Australian responses to an opinion poll/survey of attitudes to climate change (Leviston et al. 2014)

Scientific and Industrial Research Organisation (CSIRO) (Leviston, Price, Malkin, & McCrea, 2014). Questions included:

- Is climate change happening?
- What best describes your thoughts about climate change?
- How worried are you about climate change?
- How much do you think climate change will harm you personally?

After the class responded to a question, a graphical representation of the class results, automatically generated by the STILE platform, was shown to the students alongside a graphical representation of individual responses from the CSIRO survey. Figure 5.5 shows an example of the class and national results to one of the questions. The teachers reported that the class critique and analysis of graphical data were highly valuable in generating discussion about climate change from a personal and national perspective.

An online survey was used to determine the Year 9 students' prior knowledge of the particle model to inform the teacher in planning to teach energy transfer processes such as conduction and convection. Figure 5.6 shows a list of statements for which the student was to respond as either true or false. As with the opinion poll, the STILE platform immediately generated a graphical representation of the class results. A colour code is used in the representation with red indicating a non-scientific response and green indicating a scientifically correct response. The key affordance of this representational form was that the teacher gained instant feedback

When a substance freezes the temperature must always be less than 0 °C.	
It is possible to heat an object to +1000 °C but it is **not** possible to cool it -1000 °C	
When wax melts the molecules that make up the wax change from being hard and firm to being soft and 'gooey'	
A **closed** bottle with small amount of water at the bottom is left in the sun. After a while, when the water has evaporated, the mass of the bottle is now **less** than before.	
The molecules inside liquids and gases are moving but in solids they are stationary.	
In the spaces between atoms of an object there is air.	
A pie that heats up in a gas-fired oven can be explained by air molecules in the oven colliding with pie molecules.	

Fig. 5.6 Year 9 students' responses to a survey to elicit views about particle model

on students' thinking across several areas of the particle model at the same time. The teacher also used the representational form as stimulus to generate classroom activities and discussion about a topic the students had been taught in previous years.

5.4.3 Representational Challenges Employing Particle Ideas About Matter

Following the results from the survey (Fig. 5.6), the teacher engaged a review of the particle model and its role in science as a representation to explain properties of matter. Students were given the representational challenge to use particle ideas to represent the following properties of matter:

1. A lump of plasticine holds its shape.
2. A lump of plasticine can be changed into a different shape.
3. A piece of chalk can't change shape; it breaks easily (brittle).
4. A rubber band can stretch and return to its original shape.
5. Red cordial and water mix easily.
6. An iron cube is much heavier than an aluminium cube of the same size.

Students had the option of either creating a digital representation using a drawing tool embedded in the STILE platform, or they could draw on paper and take an image to then upload to the STILE platform. Figure 5.6 provides some examples of student-generated representations in response to the challenge. The evaluation of the student-generated representations was initially undertaken at the class discussion level with the teacher making references to specific representations.

The decision as to whether a representation is suitable depends on the nature of the property of the matter that is to be explained. For example, one might consider

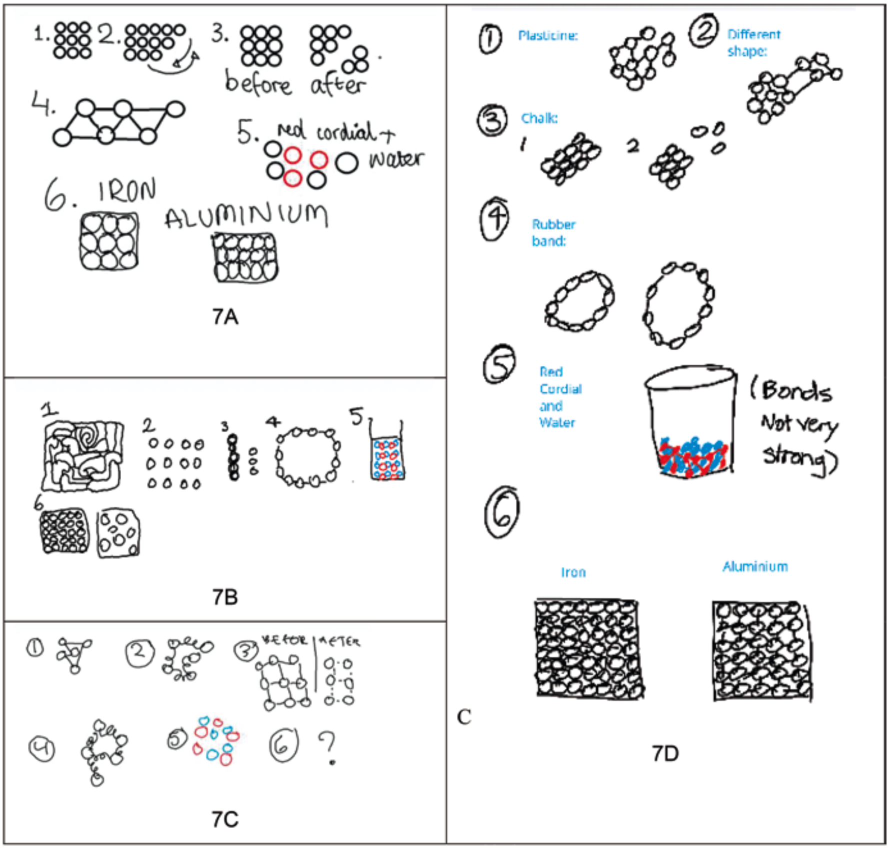
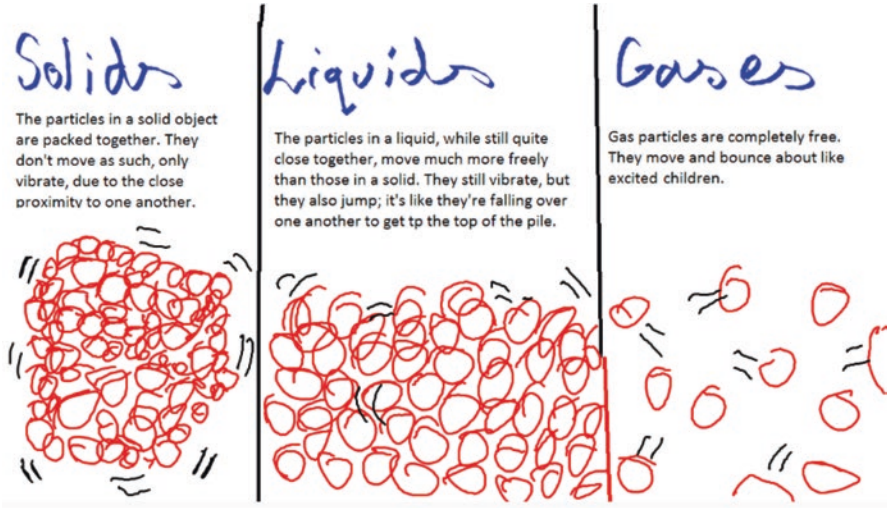


Fig. 5.7 Year 9 students' explanations of properties of matter using particle ideas

that a suitable representation for Challenge 1 listed above requires that the representation needs to show particles that are connected in some way to explain stability of shape of a lump of plasticine. Figure 5.7b–d successfully show this, whereas Fig. 5.7a does not show connectedness of particles. For Challenge 4 the representation needs to show particles, and connections between them can be maintained even though the particles move apart as occurs when the rubber band stretches. Figure 5.7d shows this with a before and after image, whereas Fig. 5.7c shows this through representing the connections as springlike.

These representation challenges described students engaging in the modelling process. Students are expected to take elements of the particle model of matter to generate in a drawing a model that explains the given property of matter. This replicates the work of scientists in creating scientific models to explain the observations they make of the world.

Having considered using the particle model to explain some physical properties of solids, the teacher introduced temperature and the idea that the temperature of an



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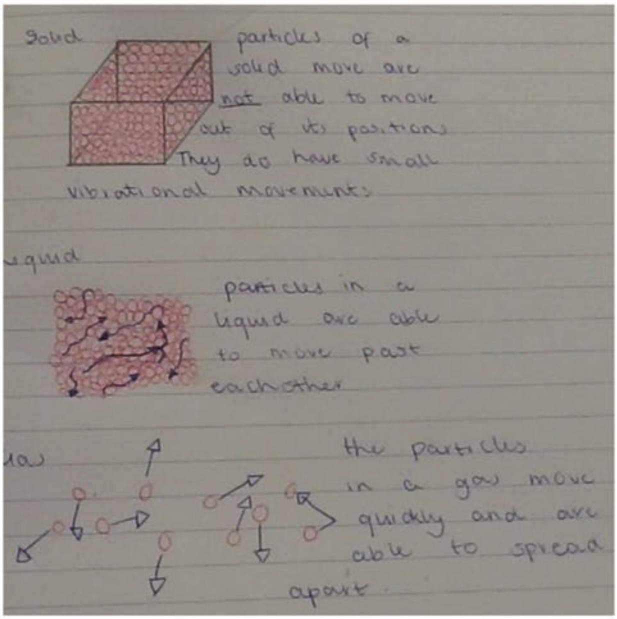

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Fig. 5.8 Year 9 students' re-representations of particle movement

object relates to the average kinetic, or motion, energy of the particles that make of the object. This led to the presentation of animations of particles in each state. The representational challenge was for the students to describe the motion of the particles in each of the states. Refer to Fig. 5.8 for student-generated representations to this task. Figure 5.8a describes very well the movement of particles in each of the states, whereas Fig. 5.8b makes effective use of arrows in representing movement of particles represented in a liquid state (curved arrows) and particles represented in a solid state (straight arrows).

For one of the classes that undertook this challenge, discussions of the student-generated representations led to a class convention as how particles might be represented diagrammatically. The class agreed that when representing matter in a solid state, particles would have bracket-type symbols to represent the movement (vibrations); when representing matter in a liquid state, particles would have curved arrow symbols to represent movement (moving around each other); and when representing matter in a gas state, particles would have straight arrows to represent movement (moving in straight lines). Coming to a class consensus view replicates the manner in which scientists undertake their work through generating and validating standard representational forms as a way to explain and communicate evidenced-based findings.

5.4.4 Interactive Simulations and Animations to Represent Dynamic Processes

One of the constraints associated with representations based on drawing is that it is sometimes difficult to show dynamic processes such as the movement of particles of matter in a particular state. In addition many of the dynamic processes that drive phenomena occur at the submicroscopic domain, and so animations and, in particular, simulations can assist the learner in developing an understanding of the phenomena. Animations and simulations can provide more insights into a dynamic process than drawings can, and so it can be beneficial for student learning if teachers use animations and develop students' skills in creating them (***Principle 2***). The following two examples relate to the teaching and learning of energy as part of the iSTELR project.

The first example relates to the use of an interactive simulation by the teacher. Figure 5.9 shows a snap shot image from an interactive simulation representing an energy system involving the sun, solar panel, heater and tank of water. The simulation is part of a high-quality set of freeware digital resources developed by the University of Colorado, Boulder (USA), and is known as Physics Education Technology (PhET) interactive simulations (https://phet.colorado.edu/).

The PhET simulation was used by the teacher as part of a class discussion to explore key ideas associated with energy. As mentioned early in these chapter discussions about what the simulation shows about energy transfer in a system were had alongside discussions about what the simulation does not show. A key feature of the simulation is the way in which energy is visually represented which, from a

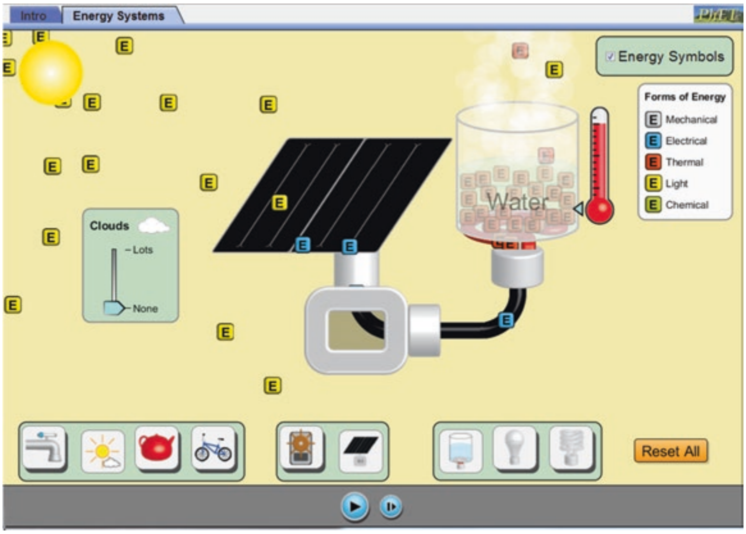


Fig. 5.9 PhET animation of an energy system (*Source*: PhET Interactive Simulations University of Colorado http://phet.colorado.edu)

scientific perspective, is a very abstract concept. Through the energy symbols interacting with the parts of the system, the student gets meaning to such ideas as:

- Energy is manifest in different forms – represented by different coloured symbols.
- Energy transformation – symbols change colour as they move through the various parts of the system.
- Conservation of energy – symbols might change colour but do not disappear as the simulation is run.
- Dissipation of energy – the energy symbols eventually spread out into the surrounding environment.
- Heating arises through the absorption of thermal energy – the simulation links the macroscopic observations of heating the water which are represented as rising scale of the thermometer and steam rising off the water surface with thermal energy symbols filling the water container.

Some aspects of energy transfer through the system that are not shown in the simulation include:

- The mechanism by which energy is transformed from one form to another such as light energy transforms into electrical energy at the solar cell.
- The heater attached to the solar cell is not explicitly represented.
- The simulation only shows electrical energy transformation to thermal energy at the water container.

The PhET simulation was also embedded in the STILE platform and therefore accessible to the students. The interactive nature of the simulation meant that students could explore energy transfer in other systems with components shown at the bottom of the simulation page (Fig. 5.9). In interrogating other systems, students were given a task to create energy flow diagrams.

The second example relates to a representational challenge given to the students that involved them creating an animation using PowerPoint that uses a particle representation to represent how solar radiation from the sun can interact with Earth in different ways. They were to choose one of several scenarios to represent as a PowerPoint animation. Two such scenarios include:

- Solar radiation enters Earth's atmosphere, reflects off Earth's surface and returns to space.
- Solar radiation enters Earth's atmosphere and gets absorbed at the surface. Thermal radiation is emitted that either:
  - Enters atmosphere passes through into space
  - Enters atmosphere, gets absorbed by carbon dioxide and radiates back to Earth to then be reabsorbed by Earth and then reradiated to the atmosphere then into space

Students were given a template, shown in Fig. 5.10a–c, to construct their PowerPoint animation. Through the STILE platform, they were provided with a short video screen cast that outlines the procedures to construct an animation.

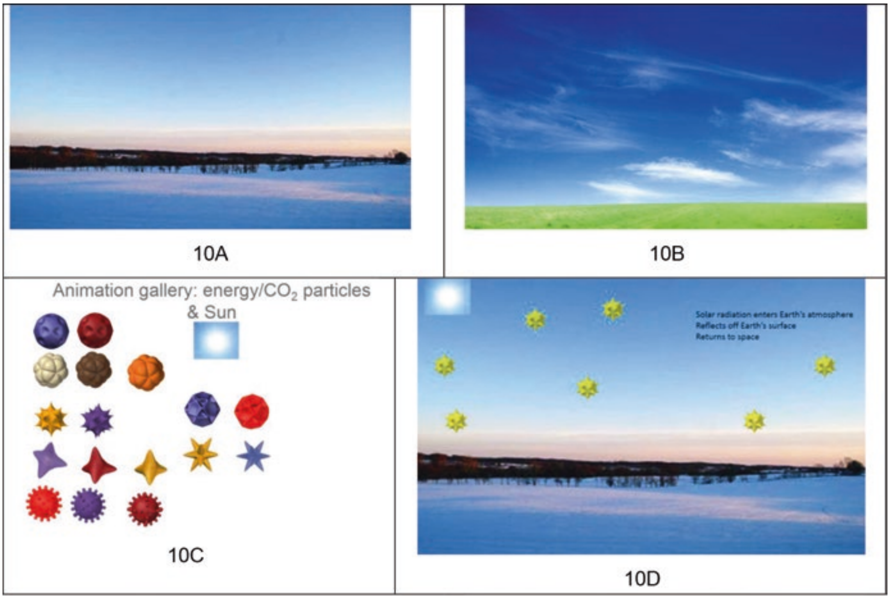


Fig. 5.10 Year 9 challenge to create an animation representing the Sun's radiant energy interactions with the Earth

Figure 5.10d is a snap shot of a student-generated animation representing one of the first scenarios listed above. The animation challenge explored key ideas that formed the basis of understanding the warming of Earth through the greenhouse effect.

5.5 Drawing to Learn in Science

As will be apparent from the illustrations of student work in the previous sections, much of the representation construction involves student drawings of a variety of types, either iconic or symbolic. We have found that drawing has much to offer in terms of student engagement, focus on learning and collaborative construction of explanation. Much of the research on the impact of drawing on learning has come from the cognitive science literature and characterizes drawing in terms of its support of cognitive processes. There is, however, growing interest from a sociocultural perspective in drawing as an important discursive practice mediating learning (Vygotsky, 1981). A recent review of the literature that combines both traditions (Ainsworth, Prain & Tytler, 2011) identified five reasons for a renewed focus on drawing as a classroom activity:

1. Drawing to enhance engagement
2. Drawing to learn to represent in science
3. Drawing to reason in science
4. Drawing as a learning strategy
5. Drawing to communicate

Researchers argue that students, when generating their own representations such as line graphs, can come to a deeper understanding of the conventions of specific representations, as a form of meta-representational competence (diSessa, 2004; Gilbert, 2005). Other researchers have focused on the benefits of collaborative drawing, in which the explicitness of drawings provides opportunities for students to exchange and clarify ideas (Schwartz, 1995). The public sharing of representations, a key component of our own approach, has been argued to allow students to productively critique the clarity, coherence and content of drawings (Linn, Lewis, Tsuchida & Songer, 2000). Hackling and Prain (2005) found, in an evaluation of a large-scale literacy-based Australian science programme, that teachers perceived a positive motivational benefit when students drew to explore and justify understandings in science. Van Meter et al. (2006) argue that the strength of drawing to support learning occurs when students are required to translate between modes, thus enriching understanding.

Other studies (Stieff, 2011; Zhang & Linn, 2008) have shown marginal effects of coupling drawing with dynamic visualizations of complex molecular structures in high school chemistry. Similarly Stieff and DeSutter (2016) found only marginal learning gains when students made observational, then reflective sketches of a dynamic simulation of molecular behaviour. Van Meter and Garner (2005), in a review of the literature, argue that interest in research on drawing has fallen off because of a history of inconsistent results, which relate to variation in the way drawing is conceived of and used in different studies.

In our own research, we position student drawing as an important aspect of students generating representations in response to challenges. For us, the key question is how the act of constructing and collaboratively negotiating ideas through drawing can support enriched reasoning and learning as the task is engaged with. In order to further explore how students collaboratively reason through the construction and coordination of multimodal representations, we conducted research in a specially constructed classroom with multiple cameras and radio microphones, in order to capture a comprehensive record of student activity, including talk, gesture, experimental exploration, drawing and modelling and embodied interactions, in response to representational challenges. Within the analysis we were able to focus particularly on students' drawing activity, and in this chapter we provide illustrations of some of the conditions, and learning affordances, associated with learning through drawing.

The research involved the planning, execution and analysis of six single science lessons on the topics of levers, toys and energy, plant reproduction and astronomy, conducted in the Science of Learning Research classroom at the University of Melbourne. The Year 7 classes (students age 12) were taught by their own science teachers, with the activities developed jointly by the research team and the teacher based on the representation construction inquiry approach. The broad lesson outline involved an introduction to the topic, a preliminary challenge engaged with by pairs of students, reporting back and then a more advanced challenge tackled first by pairs of students and then shared within groups of four students to negotiate resolution. Most activities involved drawing, either using pen and paper or using markers on a portable whiteboard, or both in sequence. The analysis of the video record was undertaken first by selection of groups to illustrate a variety of levels of engagement and production and then transcription of the audio and video record to identify sequences that provided insight into processes of collaborative reasoning through exploration and representation construction. From these analyses a number of principles were constructed concerning the roles of drawing in supporting reasoning and learning (Tytler, Ferguson, Aranda, Gorur, & Prain, 2016). In this chapter we describe a number of these insights into the way drawing supports reasoning and learning in science.

1. *Drawing can play an active role in framing student exploration and reasoning*

The lever task required students to explore, using a set of small weights and a see-saw constructed from a ruler with an attached fulcrum in the centre, what combinations of weights would create a balance. They were to draw a representation of their findings.

Students used the drawings sometimes as predictive and then tested their hypothesis using the see-saw and in other cases first tested using the see-saw and then noted through drawing (Fig. 5.11). The drawings thus ranged from generative of ideas to consolidating, but the distinction is not clear-cut. The drawings in either

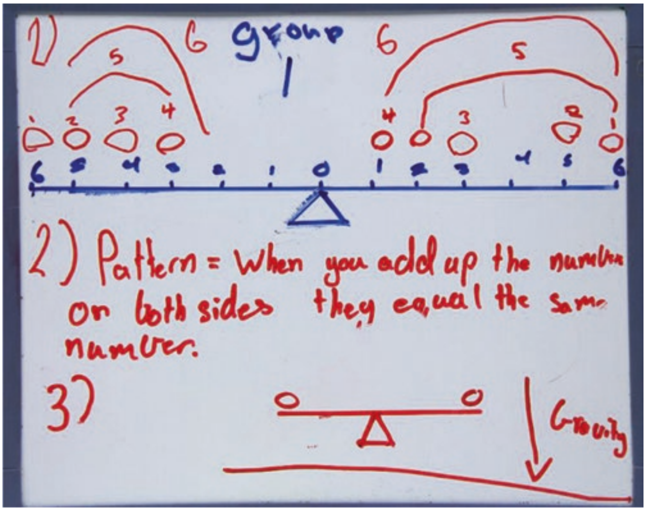


Fig. 5.11 Group drawing on a whiteboard of patterns of lever balance, showing abstracted representations of patterns of weights for balance

case served to structure the experimentation to some degree, making apparent the patterns of distance and weight through mathematical abstraction.

2. *Symbolic drawings were used to establish key ideas*

In a subsequent lever task, students were asked to provide advice to the owner of a donkey and cart, shown in a photograph where the donkey is raised in the air because of too heavy a load on the back of the cart. The drawings in the most productive cases were used to abstract the problem to lever principles with explicit reference to fulcrum and load. The affordance of the drawing in these cases is to help make apparent and force choices regarding the spatial and numerical features of the situation and to establish common meaning amongst students in the group. Figure 5.12 shows the abstraction involved in approaching a solution. The group had debated whether to draw an actual donkey or a symbolic representation.

3. *A key distinction is between the generative and consolidating roles for drawing*

One of the key distinctions we made in the analysis was that between generative and consolidating roles for drawing. In some cases students were challenged to draw in a task where the real exploration best took place with the physical exploration. For instance, students were challenged to work out the mechanisms and energy pathways for small toys such as wind-up cars, a jack-in-the box, a spring-loaded helicopter launcher, a balloon rocket or a mousetrap car. In many cases the students explored the toys to work out the mechanisms, but the drawing, with some exceptions, tended to be an after-the-event activity, and students did not have sufficient access to the hidden mechanisms to speculate on the spatial arrangement of cogs or springs that would give drawing its power. In other cases, however, for the astron-

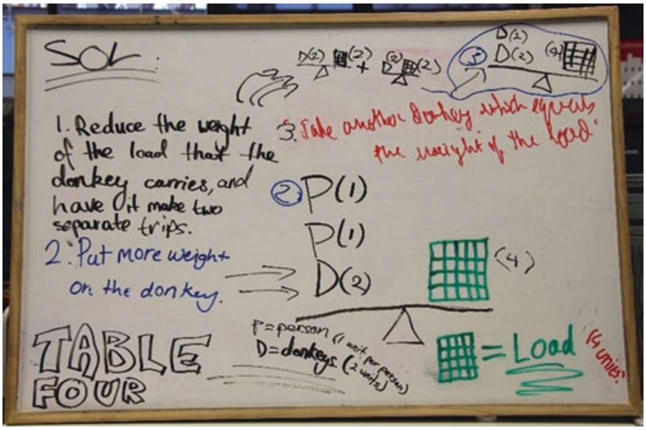


Fig. 5.12 Abstracted drawing of a donkey and a cart, making reference to lever principles

omy lessons, for example, the drawings were the site for collaborative problem-solving as students negotiated their understandings of the spatial arrangements that would explain night and day, or sun elevation, for instance (see below).

4. *Drawing was effective in framing/constraining student attention to relevant details of phenomena.*
5. *Drawing engaged students in focusing and maintaining attention on the task.*

In a task involving drawing and writing about a balloon-powered car, the act of drawing raised for the pair of students the question of the relative direction of the air coming from the balloon and the movement of the cart. The drawing required specificity and led the pair back to exploring with the car itself. It thus triggered attention to noticing of details, and the resolution was reflected in the final drawing. Similarly, in drawing a mousetrap car mechanism, a pair of students became intensely focused on the details of the mechanism layout, occasioned by a need to frame the drawing to illustrate this clearly. In this and other cases, the act of drawing led to deeper engagement with the phenomenon.

6. *Drawing acted as a common ground through which groups of students revealed their ideas and negotiated agreement about the visuospatial aspects of interpretations/explanations*
7. *Drawing can be powerful when coordinated with other representational modes*

Two boys were challenged to construct a drawing that might be shown to a 7-year-old to explain how it could be different times in London and Melbourne. One student drew and talked his partner through the specifics of his drawing. His partner responded with his own account, illustrating with pointing to features of a small earth globe, and then negotiated drawing his own account on the basis this would be clearer for a 7-year-old (Fig. 5.13).

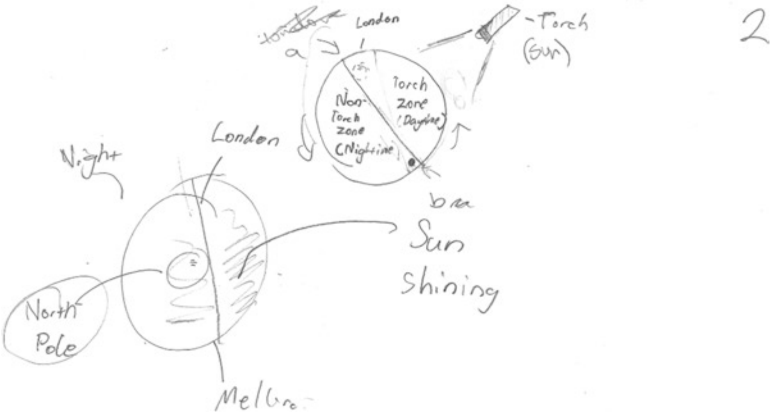


Fig. 5.13 Drawings to explain why London and Melbourne experience different times. The drawing on the right is the second of the two

8. *Drawing acted as a common ground through which groups of students revealed their ideas and negotiated agreement about the visuospatial aspects of interpretations/explanations*
9. *Drawing on whiteboards was advantageous in allowing preliminary thoughts to be rendered and refined and in allowing joint construction*

Figure 5.14 shows a whiteboard drawing designed to show how the sun can be at a higher angle in the sky in summer. This drawing was the result of considerable collaborative discussion between the two students, involving rubbing out and redesigning text, frequent exploration through a torch and model of the globe and discussion in which one student would illustrate a point using the drawing, and gesturing, and the other would exclaim 'yes, I've got what you mean!'. The drawing thus grew by degrees with each student contributing and refining their ideas of what about the geometry of the orbit and axis tilt was important. The whiteboard allowed this constant refinement and shared production and thus became an effective site for negotiation. We found generally that students were more ready to commit ideas on the whiteboard, because of this capacity to erase. The drawing in these cases often was used for, first, unrefined thoughts and was progressively modified through collaborative discussion and shared control.

10. *Drawing exposes visuospatial aspects of student conceptions that were accessible to teachers and provided an opportunity for negotiation of meaning*

During the lessons it was clear, as the teachers circulated round the class checking students' work and engaging with their ideas, that the drawings were a powerful focus for conceptual discussion through their specificity in visual, spatial and symbolic aspects. Teachers and students were able to focus their discussion through features of the drawings in ways that would not have been possible with text or talk alone.

These vignettes of student drawing illustrate the central role of representation construction in collaborative reasoning in science and show the central role of draw-

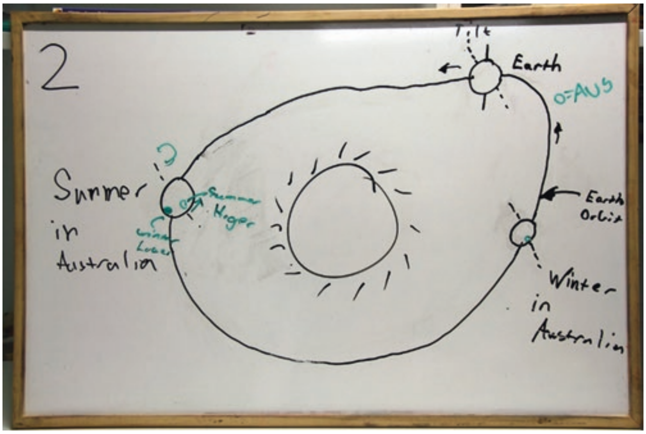


Fig. 5.14 Whiteboard drawing to explain why the sun is higher in summer than winter, in Australia

ing, alongside other modes of representation, in collaborative inquiry processes that focus on conceptual explanation. We argue that inquiry processes in science classrooms that include drawing as a central process engage students in approximating scientific discovery processes and support reasoning and learning in powerful ways. We further argue that these representation construction processes are central to scientific problem-solving within transdisciplinary contexts. These findings are consistent with a body of research that places representing and drawing as central to modelling processes in mathematics (Lehrer & Chazan, 1998) and engineering (Johri, Roth & Olds, 2013) as well as science. Thus, developing capability to represent and draw needs to be central to teaching and learning in each of the STEM disciplines, if students are to operate effectively in transdisciplinary contexts.

5.6 Further Development of the Representation Construction Approach

Since developing the representation construction inquiry approach, we have worked with many teachers and quite closely with a number of schools to refine and extend the approach and expand the range of topics for which we have generated resources. One school that has been particularly generative in this regard is Salsa College,[1] a metropolitan boy's school, where a group of dedicated teachers worked with Years 7 and 8 students over 3 years in collaboration with the research team. The experience and innovations of teachers Alice, Jaz and Kate[2] are described below under particular features of their approach.

[1] Pseudonym for the school

[2] Pseudonyms are given for all teacher names.

5.6.1 Student Record-Keeping

The teachers introduced learning journals for science, which were project books that were larger than A4 in size and were formatted so that when opened the left-hand page was lined and the right-hand page was blank. The use of these project books was new to the students who previously used fully lined A4-sized workbooks.

The project books facilitated the use of drawings in recording what they learned (see Fig. 5.15 for some examples). Drawings were often used in addressing the representational challenges (see Fig. 5.16 for some examples). The blank page encouraged visual forms of representations. The visual representations provided the teacher with ready insight into students' thinking:

> *Immediately by looking at their representations, I know, okay those boys have got it and those boys are on the right track but those haven't fully kind of understood. (Alice)*
>
> *But the books just having the blank page, I think sometimes, it's just all text that we kind of forget how much the use of those representations and diagrams can really help in Science, so it was a good reminder. (Alice)*

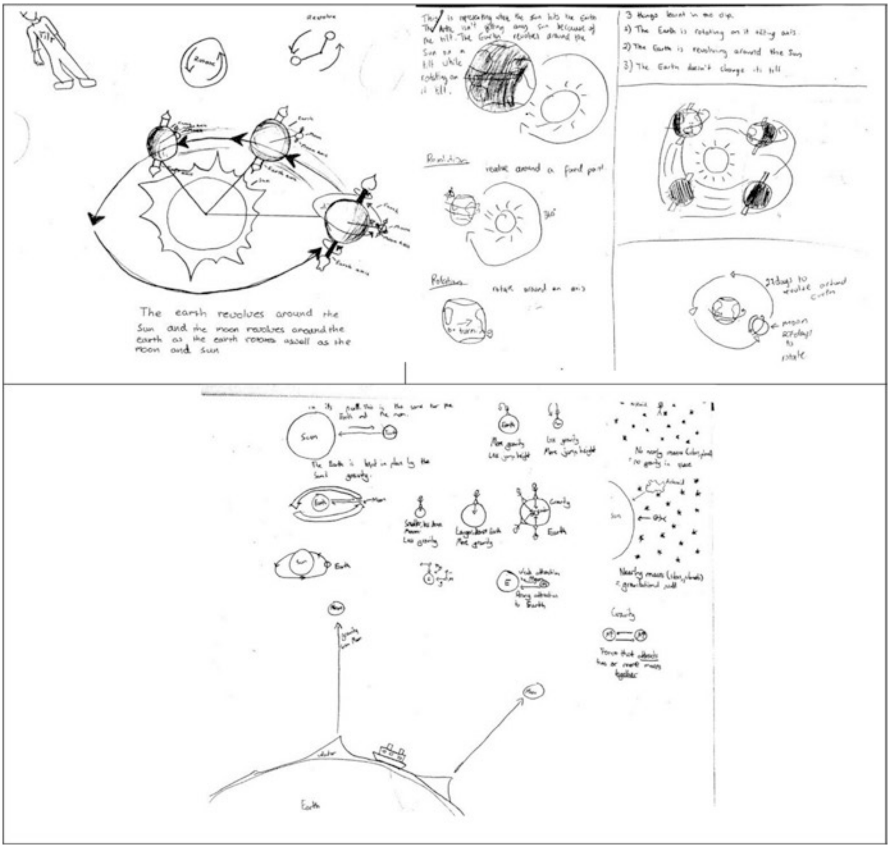
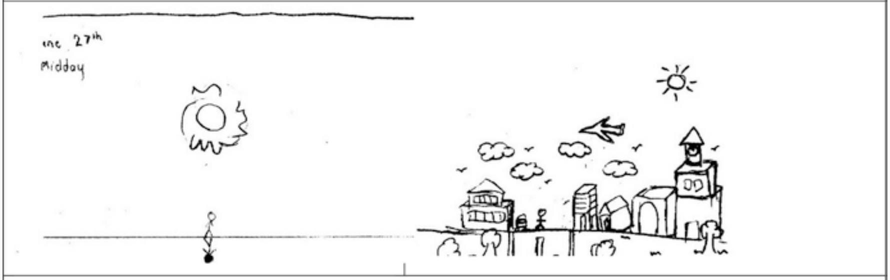
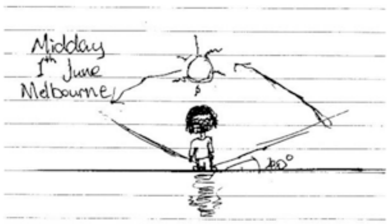


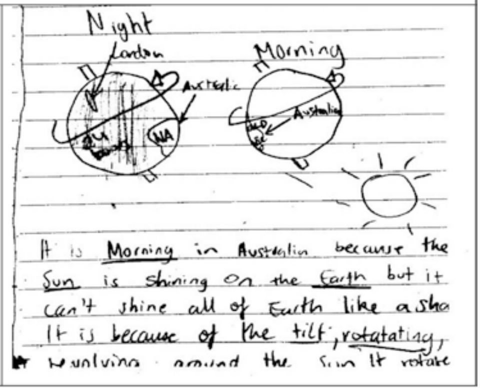
Fig. 5.15 Examples of students' entries into their learning journals

Representational Challenge: Represent in a drawing the height of the midday sun in winter from Melbourne





Representational Challenge: Why when we were watching the opening ceremony for the Olympics was it night in London, but morning here in Melbourne?



It is morning in Australia because the Sun is shining on the Earth bit it can't shine all of Earth like a shadow. It is because of the tilt; rotating, revolving around the Sun it rotate

Fig. 5.16 Examples of students' responses to two representational challenges

The teachers found that students were more willing to use their journals to reflect on their learning:

> *…they seemed more willing to go back over their work and look back at their past stuff as well…And I don't think they do it very well if it's just written stuff and they had a sense of ownership over it which was good. (Kate)*

The entries the students' made in their learning journals were seen by the teachers as a vehicle for discussion:

> *And I think …that while they're doing their representations you can have conversations with them and be active with them but it's not such a threat, it's not give me the correct response, it's more about why have you done it that way. (Alice)*
>
> *But I found that the discussions were a lot more sophisticated that they were having, around the topics than usually with the textbook. (Alice)*

5.6.2 Pretesting and Alternative Conceptions

A pretest for each topic was developed by the research team. Whilst the administration of pretests was not common practice at Salsa College, the teachers agreed to implement it. They initially viewed the pretest as part of the research rather than integral to the teaching sequence, but subsequently came to view it as an important part of the teaching approach: 'It just should be teaching practice; it should just be what we do [Kate]'. The prevalence of alternative conceptions was surprising for Jaz who commented, 'I didn't realize. I just thought once kids learn things that they keep a hold of it, but they don't'.

The teachers used the information gained from the pretests in their teaching as the illustrated by the following comments:

So I would say that, in that question [taken from the pre-test], what did we think and I'd get them to talk about it. And then at the end of the lesson, we'd say "Okay, so if we saw that question again, how would we be changing our answer to be more representative? …we weren't pretending like they had this blank slate and they'd never seen astronomy before. They already had ideas, that we kind of – half the battle was challenging them, more so than teaching them new content. [Alice]

I did deal with the topics that they had the most trouble with. [Jaz]

…and the misconceptions we knew where the majority of the class were thinking so you could direct your teaching to that…it highlighted for me the numbers in the class who don't get it, don't get a concept. (Jaz)

5.7 Summative Assessment

The teachers at Salsa College had a long-standing practice of administrating pen-and-paper-based tests as a final summative task to the topics that were taught. This practice continued in the astronomy unit. However, a key insight the teachers gained from the students learning journals was the power of the multiple modes of representation that the students generated. This prompted a change to open-ended questions given on the final test, challenging students to construct representations and providing a space rather than the traditional lines for student to respond. Figure 5.17 shows the use of this expanded space for student responses to a test question asking, 'An astronomer investigating the motion of *Europa*, which is a moon, or natural satellite, of the planet *Jupiter*, found that it *revolved* as well as *rotated*. Use the space below to clearly explain what each of these motions mean'.

The teachers commented on the value of having these multiple representational responses to the test questions:

In their test answers if we gave them the space they would perhaps do a diagram to help with explanation or we might say use representation, they didn't just stick to the words. (Jaz)

And it valued those boys that do like to draw. (Alice)

The science team subsequently adopted this approach to assessment more widely:

And even with our year 8 exam last semester [outside of the Astronomy topic] like in our extended response more inquiry based we opened it up that they could represent that knowledge in multiple ways. (Alice)

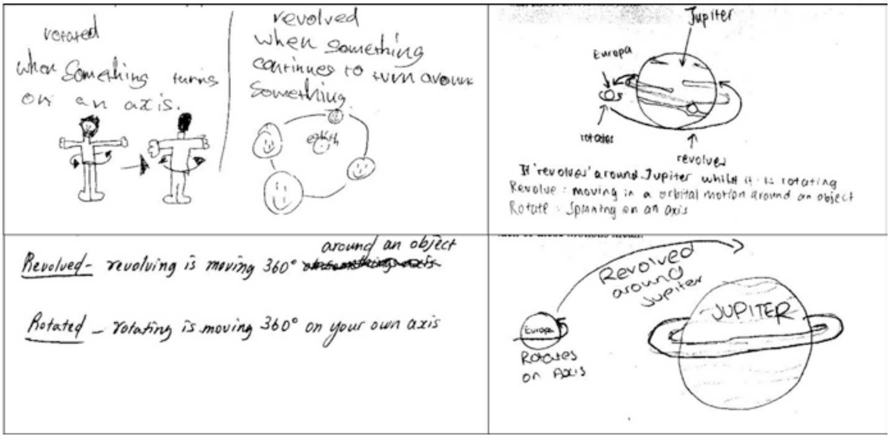


Fig. 5.17 Student responses to a test question

5.7.1 Teachers Focusing on Meta-Representational or Representational Competence

The Salsa teachers who have worked with us in developing and implementing representation construction over several years indicate that a key change to their teaching revolves around a more targeted need to develop students' meta-representational competence (diSessa, 2004) or representational competence (Kozma & Russell, 2005). Kozma and Russell (2005) point out that representational competence allows students to think, communicate and conceptualize about science concepts and includes the abilities to:

(a) Use representations for describing scientific concepts
(b) Construct and/or select a representation and explain its appropriateness for a specific purpose
(c) Use words to identify, describe and analyse features of representations
(d) Compare and contrast different representations and their information content
(e) Connect across different representations and explain the relationship between them
(f) Realize that representations correspond to phenomena but are distinct from them
(g) Use representations in discourse to support claims, draw inferences and make predictions

We have found that teachers who are new to implementing representation construction also point to representational competence as a new area of focus for their teaching. The following case refers to a Sydney metropolitan girl's school where Year 7 teachers were introduced to representation construction. They then trialled

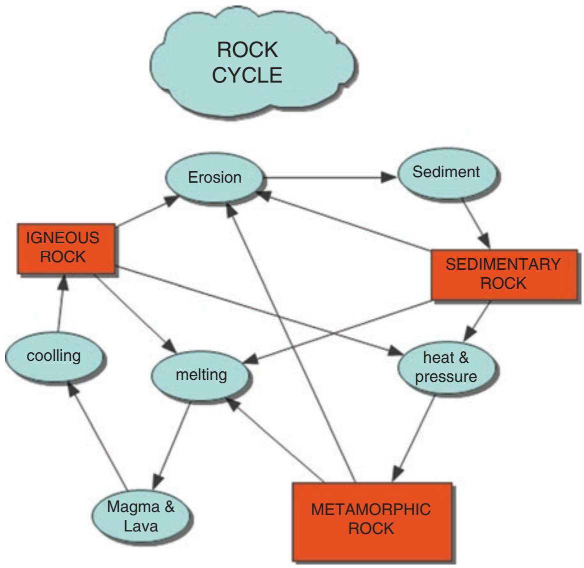


Fig. 5.18 Small group critique of diagrammatic forms of the rock cycle

the approach in the classroom sometimes taking classroom video to share with colleagues and researchers.

The following transcript is taken from a video clip one of the teachers shared with colleagues. The task involved small groups of students who were to critique a set of seven different rock cycle representations. For each representation the students were to answer the questions, 'What does it show well?' and 'What it does not show well?'. Figure 5.18 shows a particular rock cycle that is referred to in the following transcript of the teacher and students:

Teacher (T): *Looking at the cycle what can you tell me about it?*
Student (S)1: *It shows how everything is formed and connected.*
T: *When you say everything what do you mean?*
S1: *The types of rocks.*
S2: *And it is colour-coded too.*
T: *Does that help?*
S2: *Yes because if you follow the arrows you find what you are looking for.*
S1: *For example, both sedimentary and igneous rocks have similar processes that they can through heat and pressure form the metamorphic rocks* [pointing to the dark red arrows]*…it shows how they are connected to the metamorphic rock.*
S3…*it gives you options about where to go.*
S1: *The second example is sedimentary rocks can melt to form magma, which when it cools becomes igneous rocks; the igneous though can become a sedimentary rock once again through erosion [tracing the path with a pen].*
T: *So erosion is leading from that one* [pointing at igneous].
S1: *Connected to sediments to sedimentary…*
S2: *Its like a never ending cycle* [point out various cycle on the diagram].
T: *Does it show weathering?*
S1: *It shows erosion but doesn't show weathering.*
T: *So does this help explain the ideas?*

S2: *Looking at it first it was kind of confusing but once you had time to look at it and follow the arrows it makes a lot of sense.*

Following this activity a class discussion ensued as to the affordances and constraints of the rock cycle presentations. A key point expressed by the teacher was:

It is always important to acknowledge the fact that when you are making decisions about representing things compromises have to be made as to the level of detail wanted.

The next tasks for the students in one of the classes, as expressed by the teacher, were:

They made a poster of the rock cycle each from an initial critique and then peer assessed each others…this lead to a challenge to construct a stop-motion animation of a rock story; each pair were given a random sequence of rocks in pairs of students e.g. sedimentary to metamorphic.

In reflecting on any changes to their practice through the implementation of representation construction, the following views were expressed by the teachers:

I think getting them to try and represent something or I think particularly critiquing, comparing two different representations was useful when we did the rock cycle one, comparing two different ones.

Usually I would give them what I thought was the best diagram for what I was trying to explain…but getting them to compare two diagrams and pick out the best and draw their own version is better, because they've had to process that to put it into a diagram.

But the thing that I've changed the most is critiquing the representations…I think critical evaluation is probably the biggest change I've seen in myself… the kids would see this explicitly.

I think getting them to try and represent something or I think particularly critiquing, comparing two different representations was useful when we did the rock cycle one, comparing two different ones…getting them to compare two diagrams and pick out the best and draw their own version is better, because they've had to process that to put it into a diagram.

The students are now more critical of the representations that they find…before they would grab the first google image without critically analysing it for what it shows.

Because they had done it earlier – they were used to the language, used to critiquing and yes there are different ways to represent things…and then they would comment why are things like this represented in this textbook and not in another.

5.8 Conclusion

This chapter has introduced representation construction as a directed inquiry pedagogy approach that requires students to interpret and construct representations of scientific concepts, claims and processes. By representing some aspect of the world about them, students engage in the processes of knowledge construction of science as well as gaining scientific knowledge. The approach maps well with the creative processes in which scientists explore nature and construct new knowledge. The adoption of representation construction approaches addressed call for school science to better represent the epistemic practices by which knowledge is built in science.

Representation construction supports a more active view of knowledge than traditional structural approaches and encourages visual as well as the traditional text-based literacies. This is illustrated with the visual nature of the student-generated representations given as examples throughout this chapter and, in particular, the section related to drawing to learn in science. The examples of student-generated representations emphasize the manner in which students grapple with conceptual challenges in exploring, generating, evaluating and refining representations. Representation construction show promise in not only engaging students in inquiring into the world about them but supporting students to develop scientific literacies to a high level.

The representation construction approach places demands on the pedagogical skills of the teacher beyond those needed for transmissive approaches, for example, the skills to provide a representation-rich environment and opportunities for students to negotiate, integrate, refine and translate across representations. Teachers require good subject content knowledge that entails an understanding of the key representational resources underpinning science topics and an understanding of the role of representation in teaching and learning science. The approach requires of teachers a capability to run open discussions and develop the insights needed to guide the classroom tasks and conceptual negotiation.

The adoption of representation construction approaches does open up new directions and emphases for teachers to pursue in their teaching. For example:

- A change from students using their notebooks as repositories of distilled scientific knowledge provided by the teacher to use their notebooks as learning journals
- The affordances of the student-generated representations to provide insights into their thinking and formative tools that inform the teacher in addressing issues such as the prevalence of alternative conceptions
- A new emphasis in not only developing students' conceptual understanding of science but also developing students' meta-representational competence

Representation construction as a guided inquiry approach was born from extensive research in science classrooms. However, we feel that many of the ideas inherent with the approach have synergies with inquiry-based approaches in other disciplines. Certainly, the basic premise that representations are things that individuals use to understand the world as well as communicate meaning to other individuals applies to other disciplines to science such as the creative arts and, in particular, other STEM disciplines. For example, Dreher, Kuntze and Lerman (2016) point out that representations and their connections play a key role for experts in the creation of mathematical knowledge and for learners to build a conceptual knowledge in the mathematics classroom. Mathematical objects are abstract, and so experts as well as learners must use representations when dealing with them (Duval, 2006). Similar views are expressed by Johri, Roth and Olds (2013) for the discipline of engineering. These authors note in a special issue in the Journal of Engineering Education focused on 'Representations in Engineering Practice' that representations are central to engineering professional practice as well as learning about engineering design processes in the classroom.

Engaging with multimodes of representations in teaching and learning is important for each of the STEM disciplines. However, when considering the demands on the learner for integrated STEM education experiences, Honey, Pearson and Schweingruber (2014) indicate that, 'Students need to be competent with discipline-specific representations and be able to translate between discipline-specific representations thereby exhibiting what some scholars refer to as *representational fluency*' (p. 71). Representational fluency is synonymous with meta-representational competence. The role of the STEM teacher becomes one of not only introducing students to the individual disciplinary representations but also guiding them in constructing their own representations and developing their skills in representational fluency that allows them to move flexibly with and across disciplinary representations. It is therefore a worthy path for future research in representation construction to explore its efficacy in the teaching and learning within and across the STEM disciplines. Our current project is a Victorian Department of Education-funded project, Secondary STEM Catalysts: professional learning programme (2016–2018), which aims to build STEM engagement of Year 7 and 8 students in 30 government schools across the state of Victoria. Whilst we are early days in the project, teachers from all STEM disciplines initially find representation construction an appealing approach to pursue further in their teaching.

References

Ainsworth, S. (2006). DEFT: A conceptual framework for learning with multiple representations. *Learning and Instruction, 16*(3), 183–198.

Ainsworth, S. (2008). The educational value of multiple representations when learning complex scientific concepts. In J. K. Gilbert, M. Reiner, & M. Nakhlel (Eds.), *Visualization: Theory and practice in science education* (pp. 191–208). New York: Springer.

Ainsworth, S., Prain, V., & Tytler, R. (2011). Drawing to learn in science. *Science, 333*(26), 1096–1097.

Chi, M. (2009). Active-constructive-interactive: A conceptual framework for differentiating learning activities. *Topics in Cognitive Science, 1*, 73–105.

Chubb, I. (2014). Office of the Chief Scientist: *Science, Technology, Engineering and Mathematics: Australia's Future*. Australian Government, Canberra, Australia. Retrieved from http://www.chiefscientist.gov.au/wp- content/uploads/STEM_AustraliasFuture_Sept2014_Web.pdf

Cox, R. (1999). Representation construction, externalized cognition and individual differences. *Learning and Instruction, 9*, 343–363.

diSessa, A. (2004). Metarepresentation: Native competence and targets for instruction. *Cognition and Instruction, 22*(3), 293–331.

Dreher, A., Kuntze, S., & Lerman, S. (2016). Why use multiple representations in the mathematics classroom? Views of English and German preservice teachers. *International Journal of Science and Mathematics Education, 14*(2), 363–381. doi:10.1007/s10763-015-9633-6.

Duval, R. (2006). A cognitive analysis of problems of comprehension in a learning of mathematics. *Educational Studies in Mathematics, 61*, 103–131. doi:10.1007/s10649-006-0400-z.

Elkins, J. (2011). Visual practices across the University: A report. In O. Grau (Ed.), *Imagery in the 21st century*. Cambridge, MA: MIT Press.
Furtak, E., Seidel, T., Iverson, H., & Briggs, D. (2012). Experimental and quasi-experimental studies of inquiry-based science teaching: A meta-analysis. *Review of Educational Research, 82*(3), 300–329.
Gibson, J. (1977). The theory of affordances. In R. Shaw & J. Bransford (Eds.), *Perceiving, acting, and knowing: Toward an ecological psychology* (pp. 67–82). Hillsdale, NJ: Erlbaum.
Gilbert, J. K. (2005). *Visualization in science education*. New York: Springer.
Gooding, D. (2004). Visualization, inference and explanation in the sciences. In G. Malcolm (Ed.), *Studies in Multidisciplinarity* (Vol. 2, pp. 1–25). Elsevier.
Gooding, D. (2006). From phenomenology to field theory: Faraday's visual reasoning. *Perspectives on Science, 14*(1), 40–65.
Goodrum, D., Druhan, A., & Abbs, J. (2012). The status and quality of year 11 and 12 science in Australian schools. Canberra, Australia: Australian Academy of Science. Retrieved April 2016 from http://www.science.org.au/publications/research-reports-and-policy.html
Greeno, J. G., & Hall, R. P. (1997). Practicing representation: Learning with and about representational forms. *Phi Delta Kappan, 78*(5), 361–368.
Hackling, M., & Prain, V. (2005). *Primary connections: Stage 2 trial*. Canberra, Australia: Australian Academy of Science.
Honey, M., Pearson, G., & Schweingruber, H. (Eds.). (2014). *STEM Integration in K-12 education: Status, prospects and an Agenda for research*. Washington, DC: The National Academies Press.
Hubber, P., Tytler, R., Chittleborough, G., Campbell, C., & Jobling, W. (2012). *Evaluation of delivery of the switched on secondary science professional learning (SOSSPL) program (2011–2012)*. Waurn Ponds, Victoria: Deakin University.
Hubber, P., Tytler, R., & Haslam, F. (2010). Teaching and learning about force with a representational focus: Pedagogy and teacher change. *Research in Science Education, 40*(1), 5–28.
Johri, A., Roth, W., & Olds, B. (2013). The role of representations in engineering practices: Taking a turn towards inscriptions. *Journal of Engineering Education, 102*(1), 2–19. doi:10.1002/jee.20005.
Kapur, M. (2008). Productive failure. *Cognition and Instruction, 26*(3), 379–424. doi:10.1080/07370000802212669.
Kozma, R., & Russell, J. (2005). Students becoming chemists: Developing representational competence. In J. Gilbert (Ed.), *Visualization in Science Education* (pp. 121–145). Springer.
Latour, B. (1999). *Pandora's hope: Essays on the reality of science studies*. Cambridge, MA: Harvard University Press.
Lehrer, R., & Chazan, D. (1998). *Designing learning environments for developing understanding of geometry and space*. Mahwah, NJ: Lawrence Erlbaum Associates.
Lehrer, R., & Schauble, L. (2006a). Cultivating model-based reasoning in science education. In K. Sawyer (Ed.), *Cambridge handbook of the learning sciences* (pp. 371–388). Cambridge, MA: Cambridge University Press.
Lehrer, R., & Schauble, L. (2006b). Scientific thinking and science literacy. In W. Damon & R. Lerner (Eds.), *Handbook of child psychology* (6th ed., Vol. 4).
Lemke, J. L. (1990). *Talking science: Language, learning and values*. Greenwood Publishing Group.
Lemke, J. (2004). The literacies of science. In E. W. Saul (Ed.), *Crossing borders in literacy and science instruction: Perspectives on theory and practice* (pp. 33–47). Newark, NJ: International Reading Association/National Science Teachers Association.
Leviston, Z., Price, J., Malkin, S., & McCrea, R. (2014). *Fourth annual survey of Australian attitudes to climate change: Interim report*. CSIRO: Perth, Australia.
Linn, M., Lewis, C., Tsuchida, I., & Songer, N. (2000). Beyond fourth grade science: Why do U.S. and Japanese students diverge? *Educational Researcher, 29*(3), 4–14.

Moje, E. (2007). Developing socially just subject-matter instruction: A review of the literature on disciplinary literacy learning. *Review of Research in Education, 31*, 1–44.
Osborne, J. (2006). Towards a science education for all: The role of ideas, evidence and argument. In *Proceedings of the ACER research conference: Boosting science learning –What will it take*? (pp. 2–5). Retrieved from http://research.acer.edu.au/cgi/viewcontent.cgi?article=1000&context=research_conference_2006
Prain, V., & Tytler, R. (2012). Learning through constructing representations in science: A framework of representational construction affordances. *International Journal of Science Education, 34*(17), 2751–2773.
Schwab, J. J. (1962). *The teaching of science as enquiry*. Cambridge, MA: Harvard University Press.
Schwartz, D. L. (1995). The emergence of abstract representations in dyad problem solving. *The Journal of the Learning Sciences, 4*(3), 321–354.
Stieff, M. (2011). Improving representational competence using molecular simulations embedded in inquiry activities. *Journal of Research in Science Teaching, 48*(10), 1137–1158.
Stieff, M., & DeSutter, D. (2016, June). *Drawing from dynamic visualisations*. Paper presented at the International Conference of the Learning Sciences, Singapore.
Tytler, R., Ferguson, J., Aranda, G., Gorur, R., & Prain, V. (2016, June). *Drawing within experimental exploration as part of core epistemological and epistemic practices in science*. Paper presented at the International Conference of the Learning Sciences, Singapore.
Tytler, R., Haslam, F., Prain, V., & Hubber, P. (2009). An explicit representational focus for teaching and learning about animals in the environment. *Teaching Science, 55*(4), 21–27.
Tytler, R., Peterson, S., & Prain, V. (2006). Picturing evaporation: Learning science literacy through a particle representation. *Teaching Science, the Journal of the Australian Science Teachers Association, 52*(1), 12–17.
Tytler, R., Prain, V., Hubber, P., & Waldrip, B. (Eds.). (2013). *Constructing representations to learn science*. Rotterdam, The Netherlands: Sense Publishers.
Van Meter, P., Aleksic, M., Schwartz, A., & Garner, J. (2006). Learner-generated drawing as a strategy for learning from content area text. *Contemporary Educational Psychology, 31*, 142–166.
Van Meter, P., & Garner, J. (2005). The promise and practice of learner-generated drawing: Literature review and synthesis. *Educational Psychology Review, 17*(4), 285–325.
Vygotsky, L. (1981). *Thought and language* (Rev. and Ed. by A. Kozulin). Cambridge, MA: MIT Press.
Waldrip, B., Prain, V., & Carolan, J. (2010). Using multi-modal representations to improve learning in junior secondary science. *Research in Science Education, 40*(1), 65–80.
Zhang, Z., & Linn, M. (2008). Using drawings to support learning from dynamic visualizations. In *Proceedings of the 8th international conference on the learning sciences* (Vol. 3, pp. 161–162).