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Engaging students in learning science through promoting creative reasoning

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ABSTRACT
Student engagement in learning science is both a desirable goal and a long-standing teacher challenge. Moving beyond engagement understood as transient topic interest, we argue that cognitive engagement entails sustained interaction in the processes of how knowledge claims are generated, judged, and shared in this subject. In this paper, we particularly focus on the initial claim-building aspect of this reasoning as a crucial phase in student engagement. In reviewing the literature on student reasoning and argumentation, we note that the well-established frameworks for claim-judging are not matched by accounts of creative reasoning in claim-building. We develop an exploratory framework to characterise and enact this reasoning to enhance engagement. We then apply this framework to interpret two lessons by two science teachers where they aimed to develop students' reasoning capabilities to support learning.

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The student engagement problem and solutions

Enhancing students' interest in learning from school science experiences has remained a challenge for decades in many countries (De Witt et al., 2013; Duit, 2007). This challenge is variously attributed to: (a) too much didactic teaching that casts students as reluctant bystanders tasked with memorising expert claims (Lyons, 2006; Osborne & Dillon, 2008); (b) a disconnect between official science curricula and students' everyday worlds and interests (Aikenhead, 1996); and (c) lack of teacher familiarity with current scientific agendas, discoveries, and methods (Chubb, 2014). Proposed and enacted solutions include: changes to the content, purposes, and physical settings for learning (Duschl, 2008; Sadler, 2004); integration with other subjects, such as STEM (Scott, 2012); more links with practising scientists (Chubb, 2014); more use of virtual resources (Linn, Davis, & Bell, 2013), and an increased focus on students using these and other resources as reasoning tools for learning in this subject (Carolan, Prain, & Waldrip, 2008; Lehrer & Schauble, 2006; Tytler, Prain, Hubber, & Waldrip, 2013).

Science education researchers now broadly agree that quality learning entails students understanding, enacting, and valuing how scientists produce, judge, and share knowledge (Choi, Klein, & Hershberger, 2015; Duschl, 2008; Hand, McDermott, & Prain, 2016; Moje,

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2007). Students need first-hand experiences that reflect these scientific practices, where reasoning in science is understood as problem-solving processes to arrive at justified beliefs about natural phenomena (Peirce, 1931–1958). In this way students can learn how to integrate practical inquiry with visual, linguistic, and mathematical modes to reason about causal changes to phenomena. (Duschl, 2008; Lemke, 2016). When encouraged to construct and justify these claims using different forms of representation, including diagrams, drawings, models, and verbal explanations, students learn how to reason about scientific topics, advance their content knowledge, and practise the subject-specific ways to represent scientific processes and findings (Ainsworth, Prain, & Tytler, 2011; Liu, Won, & Treagust, 2014; Metz, 2011; Prain & Waldrip, 2006; Tytler et al., 2013; Waldrip, Prain, & Carolan, 2010).

Haste (2004), Lindahl (2007), Schreiner and Sjøberg (2007), and others note that students also need to understand and experience the creative, imaginative side of scientific reasoning. Scientists improvise, run intuitive thought experiments to imagine outcomes, and rework images to identify confirmatory or anomalous evidence. They make sketches to explore theories, create new representations to make and share new claims, and consider their representations' aesthetic properties (Dunbar, 1999; Gooding, 2004; Vertisi, 2014). In this way, creative engagement has both cognitive and affective dimensions. If students can come to understand that science is about rigorous evidence-based creative solutions and explanations, then they will experience identity work in this subject (acting and thinking scientifically) as inherently appealing, rewarding, and valuable. Students are also more likely to view science as meaningful if they can apply scientific methods and findings to everyday problems relating directly to their lives.

In this paper we report on a case study of two teachers' attempts to promote students' reasoning and enhanced engagement when the students were asked to construct and justify scientific claims about topics. We recognise that there are many perspectives on how to characterise and enable student reasoning in science, but here we are particularly interested in the initial claim-constructing phase. We first review relevant literature as a basis to develop an exploratory framework to interpret the teachers' approaches and the impact on student participation and learning outcomes in this initial phase of reasoning processes.

Characterising student reasoning in science

Traditional cognitive theorists tend to cast learners generally, and science students in particular, as adaptive information processors who reason through applying learnt rules or relevant criteria to case-building and case-judging in inquiry (Kuhn, 2015; Newell & Broder, 2008; Toulmin, 1958). We also recognise that sociocultural and embodied-cognition theorists tend to cast learners as active agents, who reason through participatory experiences, simulation, visualisation, rehearsal, practical engagement with tools, enactment, reflection, embodied understandings, and pattern-spotting (Barsalou, 2008; Klein, 2014; Lehrer & Schauble, 2006; Lehrer, Schauble, & Lucas, 2008; Prain & Tytler, 2012). We consider that both perspectives, including formal and informal reasoning processes, need to be incorporated into a comprehensive account of the many ways in which students reason in this subject. Both perspectives assume that students have relevant background knowledge, know how to apply rules of logic, and have enabling habits of mind to guide their reasoning.

Accounts of reasoning in science learning have generally drawn on the first set of theories around formal reasoning processes and critical appraisal of claims. For example, the Trends in International Mathematics and Science Study (TIMSS, 2007) characterises reasoning as a set of systematic logical applications and mental procedures. These include analysing and solving problems, integrating and synthesising evidence, hypothesising and predicting outcomes, designing and planning inquiry, drawing conclusions, generalising, evaluating, and justifying claims. Various frameworks have been developed to guide and assess these processes (Chen, Park, & Hand, 2016; Dolan & Grady, 2010; Erduran, Simon, & Osborne, 2004; Furtak, Hardy, Beinbrech, Shavelson, & Shemwell, 2010; Keys, Hand, Prain, & Collins, 1999). These frameworks tend to emphasise linguistic reasoning, where students make claims about phenomena, check for evidence, refine their claims, coordinate explanations, publicly communicate and justify claims, and reach teacher-guided consensus on the best or most adequate evidence-based explanation. This research tends to focus on tracking student learning gains from public appraisal of claim adequacy, where reasoning is understood primarily as argumentation (Chen et al., 2016; Jiménez-Aleixandre, 2014; Kuhn, Zillmer, Crowell, & Zavala, 2013; McNeill, Lizotte, Krajcik, & Marx, 2006). This focus on argumentation has tended to foreground the necessary study of student linguistic activity (talk and writing) in the claim-judging stage of reasoning. At the same time, some researchers have focused on multi-modal reasoning where students create, justify and refine non-verbal represented claims through the interplay of linguistic and non-linguistic representations (Dolan & Grady, 2010; Kozma & Russell, 2005; McDermott, Hand, Sturtz, & Mohling, 2016; Tang, Delgado, & Moje, 2014; Tytler et al., 2013). This research highlights the complexity of modal co-ordination to develop and organise persuasive scientific claims. For Dolan and Grady (2010, p. 40), this complexity is evident in the highest level of reasoning in inquiry, where students represent data in 'multiple ways including tables, drawings, graphs, or statistical representations, thoughtfully considering the meaning of representations'.

In our own research (Tytler et al., 2013; Waldrip & Prain, 2011; Waldrip, Prain, & Sellings, 2013), we claimed that students use both formal and informal reasoning processes, entailing both critical and creative thinking and problem-solving when they construct and evaluate their own representations. While these processes are often mediated through talk, they entail multi-modal reasoning where students integrate linguistic, visual, and embodied practical activity to build and justify claims. Through exploratory and extension activities, students speculate on key causal mechanisms, draw on perceptions from practical activity, past experiences, and analogies. They coordinate these perceived key aspects into a claim, often reasoning by association to re-represent 3D experiences and findings in 2D drawings and through talk. In constructing claims, students attempt to identify and organise a multi-modal integrated representation consistent with perceptible (or logically justifiable) features of the phenomena. Our research also confirmed that student reasoning varies markedly depending on purpose, context, available physical resources, and the particular stage or focus of inquiry. For example, assessing the emerging clarity, adequacy, and internal coherence of a represented claim entails different reasoning processes from checking if a resolved claim explains processes when applied to a new context.

However, both instances of reasoning will entail multi-modal text production, necessitating modal co-ordination.

Taking this complexity into account, we consider that reasoning should be defined broadly to encompass both student individual meaning-making around causal explanations to self and more public negotiation of claims of the kind reported in the literature on argumentation. This definition assumes that reasoning processes have multiple prompts and enablers, and entail both informal, tacit understandings, and imaginative speculation, as well as more formal linguistic logical case-defence and refinement. We concur with Sadler (2004, p. 514) that informal reasoning involves both 'the generation and evaluation of positions', and therefore occurs both in constructing as well as assessing represented claims. We also suggest that students assess claim viability as they individually or collaboratively build a case. Students are reasoning informally 'as they ponder causes and consequences, pros and cons, and positions and alternatives' (Sadler, 2004, p. 514). This reasoning can occur in the early stages of personally imagining a causal explanation, or in subsequent whole-class review. Attempts to characterise these creative reasoning processes, as they occur, are less established than reasoning requirements in argumentation. This is not surprising, given that these reasoning processes are often relatively tacit, fluid or less predictable, and given also that teachers are often eager to move discussion quickly to explicating and adjudicating claim adequacy as a key learning process. However, in conceptualising student engagement as deeper sustained interest, we consider that the initial claim-making phase is crucial in motivating and sustaining student interest. We also recognise that guiding this speculative student reasoning poses significant challenges for teachers in that they have to interpret accurately students' emerging ideas, and offer informed feedback, generative prompts and leads. In the next section, we review relevant literature as the basis for presenting an exploratory framework to characterise features and enablers of creative reasoning.

Creative reasoning

Research on how scientists reason creatively to make new discoveries provides some relevant insights applicable to the science classroom. Gooding (2004), Magnani (2010), Vertisi (2014), and others have highlighted the complex role of speculative manipulation of material and symbolic tools as key enablers of fresh insights. Vertesi (2014, p. 31) argued that selective attention in the act of drawing or image re-manipulation can make new areas of interest 'pop out' from apparently resolved findings, creating new research questions. Magnani (2010) highlighted scientists' practical reasoning in science discoveries, where they manipulate both symbolic and material tools and equipment to enable break-throughs. By implication, in reasoning with and from constructing their own representations, students need to be willing or encouraged to engage in this kind of speculative visual, spatial, and embodied thinking. From a cognitive perspective, Mercier and Sperber (2011) claimed that this reasoning entails a two-step mental process where the first stage of imagining and representing solutions is seen as automated, intuitive, and based on past knowledge and personal preferences. By contrast, the second phase of assessment or judgment is viewed as analytical, linguistic and evidence-based, and thus aligned with formal logical processes evident in the literature on argumentation. We think this version of a two-step process oversimplifies the kinds of reasoning that occur when students create possible solutions. Imaginative representation of claims based on perception and speculative inferences entails both analytical and non-linguistic reasoning. However, we agree that both creating and critiquing representations are crucial components in deeper science learning.

While not directly addressing creative reasoning in school science, Lucas, Claxton, and Spencer (2013, pp. 16–17) propose that students demonstrate creativity when they enact and value five key dispositions. Creative students are inquisitive, persistent, imaginative, collaborative, and disciplined, with distinguishing traits instantiating each disposition. For these researchers, being inquisitive entails a willingness to question, be persistent, investigate, explore issues in depth, and challenge assumptions. Persistence entails daring to be different, and tolerating uncertainty. Imagination is shown in playing with possibilities, making connections, and using intuition rather than analytical thinking alone. Collaborators willingly share their products, give and receive feedback, and learn from others. Creative students are also disciplined in that they apply domain-specific methods and knowledge to shape and refine products and develop expertise. They devote time and effort, reflect critically on what they have achieved, and take pride in success. While construing these characteristics as dispositions casts them in traditional cognitive terms as essential traits, we were more interested in looking at teaching and learning contexts where these 'dispositions' can be recast as potential and actual student responses to particular teacher guidance and prompts. From this perspective, these responses can be elicited and encouraged, or stifled, depending on the roles and tasks required of students. We also acknowledge that these generic categories may need further refinement to capture the distinctive attributes of scientific norm-disciplined creativity. As noted by Bailin (2002), critical and creative reasoning are norm-based and must meet relevant standards and criteria, and draw on and contribute to disciplinary knowledge. However, we consider that this framework provides a generative exploratory lead to investigate how teachers might elicit these creative habits of mind in students' reasoning in initial claim-making.

Research aims and methods

In this case study approach we aimed to:

(1) develop a descriptive framework to characterise students' creative reasoning processes in engaging with claim-making in science.
(2) apply this framework to interpret teachers' practices to support student reasoning in their claim-making.
(3) identify the effects on students' engagement with learning science.
(4) consider broader implications for teachers engaging students in learning in science.

We developed a descriptive framework that incorporated both Lucas et al.'s (2013) five student creative attributes (Table 1), and informed by insights from our past research that student creative reasoning entails integrating linguistic, visual, spatial reasoning as well as embodied practical activity to build and justify claims (Tytler et al., 2013; Prain, Waldrip, & Lovejoy, 2015). We recognise that while linguistic contributions are important in enacting creativity in the process of case-building, as noted by Nickerson (1991) and implied by the Lucas et al. (2013) framework, this mode is often used in tandem with other modes of exploratory reasoning. Through video data capture of whole-class and student sub-group interactions, we aimed to identify students' creative reasoning, including the percentage of time spent by participant teachers in facilitating creative responses. We assumed our focus would be mainly on the purposes of student talk, but that some analysis might also focus on students' participation in practical activity incorporating embodied, spatial, and visual reasoning.

Two video cameras were used in each classroom, with one focused on the teacher and the other on a different student group for each class. Students soon ignored these cameras and were not distracted from normal interactions. The video-taping included records of talk, drawing, and student activity. Students were told that they could view these interactions, and that the video was to enable subsequent stimulated recall to help us re-create the lesson and request clarification of student intentions. We analysed the recorded processes for common themes, highlighting sequences that appeared important to the students, the teachers or to us. The teachers were consulted about our intentions of focusing on reasoning. Although the teachers discussed with us what was observed, they maintained complete autonomy over the content, teaching and learning methods. When the students were working on teacher-assigned tasks, we asked them to explain what they were doing and/or how what they were learning related to past classes.

Participant teachers and students

The two participant teachers, Ben and Wendy, have collaborated with us over the last few years in guiding students to generate and assess their own represented claims. They normally taught middle school classes (about 25 students per class), and were asked to plan

Table 1. Percentage of time on creative student responses.

	Ben		Wendy	
	Elements and compounds		Atomic structure and radioactivity	
	Class 1 %	Class 2 %	Class 1 %	Class 2 %
Inquisitive responses				
a. Wondering and questioning	13.1	7.3	10.8	6.8
b. Exploring and investigating	6.9	9.1	12.0	12.4
c. Challenging assumptions	4.5	4.4	1.9	8.5
Persistence				
a. Sticking with difficulties	6.1	4.2	5.7	4.9
b. Daring to be different	2.1	2.1	0	3.2
c. Tolerating uncertainty	2.3	1.3	2.5	5.3
Imaginative responses				
a. Playing with possibilities	12.0	16.1	5.1	13.7
b. Making connections	8.0	9.4	1.9	7.1
c. Using intuition	3.3	2.9	4.4	3.0
Collaboration				
a. Sharing the product	2.9	7.8	16.5	5.6
b. Giving and receiving feedback	8.0	14.8	13.9	3.0
c. Cooperating appropriately	2.0	5.2	12.6	10.3
Discipline-based responses				
a. Developed techniques	2.4	6.0	1.9	9.0
b. Reflecting critically	6.7	3.6	8.2	3.0
c. Crafting and improving	3.5	5.7	13.9	4.3

each lesson, optimising active roles for learners to engage in individual and collective reasoning. We did not explain our creativity framework to the teachers in advance, because (a) we were uncertain about its practicability for distinguishing creative student responses in a science class, (b) we did want to distort the teachers' normal pedagogical processes with perceived additional requirements, and (c) we wanted the teachers to focus on student engagement through disciplinary reasoning. We provided feedback on our perceptions of students' developing understanding of topics. The students were accustomed to traditional didactic approaches where the teacher tended to demonstrate evidence for claims, and where practical work was used for further claim illustration. By contrast, in these classes, the students were challenged continually to explore, speculate, represent, and justify their understandings, and to make their reasoning explicit through ongoing commentary around their own and other students' claims.

Data selection and analyses

Data analyses were carried out in two phases: (a) video analysis by each researcher independently (and then through mutual agreement) about identified categories, time spent on each, and non-linguistic components of reasoning processes (Tytler et al., 2013), and (b) further case interpretation. We viewed all the classroom videos in which students or teachers used creative prompts or actions. For example students were asked to construct and explain workable models of ions, demonstrate their understanding of a concept to a person who did not understand it, explain why substances dissolved or not, and to speculate about what was happening in a radioactive decay process. In this way they were prompted to apply current knowledge to reason about a new context or generalise from past experiences. We noted students' use of representations as tools to show emerging reasoning and understanding. We compared the two case studies to identify similarities and differences in teacher attempts to elicit students' creative reasoning, and to identify possible explanations for these patterns. Four students from each class, based on the teachers' view of representativeness of the classes' abilities and interests, were interviewed to identify perceptions of the extent to which the lessons were engaging and why. These students reflected high and low achievement scores, motivation, interest, and engagement as perceived by their teacher. The analysis of the video was conducted by one senior researcher who was experienced in video analysis. There was not an opportunity for co-analysis because of the unavailability of appropriate software at the other sites. No one else at the analysis site had the experience to code and analyse the data.

Findings

In applying our proposed framework, we found that student inquisitiveness and imagination were often linked, in that inquisitive responses led to imaginative claim-making, but that each category was broadly distinguishable (see Table 1). By combining the three component of each category, this table shows that Ben and Wendy regularly prompted student inquisitiveness (20–25% and 24–28%), with Wendy's class exploring and investigating to a greater extent than Ben's class (~12% compared to 7–10%). Inquisitive responses were evident each time as a starting point for students to make claims. When refining their claims, the teachers also prompted further imaginative or inquisitive responses that entailed linguistic and non-linguistic reasoning (see following case studies).

While both teachers had clearly defined student learning goals, they responded very flexibly to student responses, often demonstrating their own creativity in adapting resources or inquiry to guide students' emerging understandings. This meant that there was no stable pattern of reasoning processes across or between classes, but rather both teachers adjusted their prompts to particular purposes. While we had not directed the teachers to address the five areas, we noted that all areas were covered in their attempts to elicit student engagement. Ben focused strongly on eliciting student inquisitiveness (23–28%) and collaboration (13–28%), but his students also often influenced the direction of learning by making suggestions, challenging peer claims and comments, and asking questions Ben had not anticipated. We found that students reason in multiple ways in response to both teacher and student prompts. They proposed explanations, trialled imaginative options for assessing explanatory credibility, checked for visual or other confirmatory or anomalous evidence, and responded individually and collectively to their teachers' ongoing demands for justified beliefs.

First case study

Atomic structure and electron shells: isotopes and half-lives

Ben's class involved Year 10 students taking a non-preferred compulsory subject. They took this class because they had to take a science subject. Each class was scheduled for 90 minutes twice a week for three weeks. This classroom had sufficient room for students to choose where they sat. Knowing his students were unwilling participants, Ben sought to increase student engagement through continually asking students to explain and justify their claims. He often started a lesson with a question and brought everyday materials for students to use to experiment with and prompt speculative thinking. Ben commenced his teaching by seeking student current understanding of a concept and then asked clarifying questions that required student to justify their views with additional evidence.

He often set student group work to build understandings, and this class had a high degree of observed student–teacher and student–student interactions. He invited multiple creative solutions, encouraging students to attempt different approaches with the everyday materials, and continuously elicited student claim-making supported by evidence. Students were expected to propose claims, develop inquiries, trial practical tests of their ideas, check for supportive evidence for their claims, and attempt subsequent revised experiments and refinements.

The class had been discussing genetics in a previous topic and this led to the topic of radioactive materials. Many students came from farms with genetic breeding programmes, where they had observed and experienced labelling of radioactive materials. One of the terms that students raised was half-life in the discussion about genetics. Ben would deviate from planned learning goals if he felt that it was appropriate to deepen student understanding. Ben asked them to show what they thought this meant, with verbal responses revealing mixed understandings of what half-life meant. Ben then consciously chose questions, activities, and possible scenarios that challenged students' current understandings to deepen engagement. To facilitate class description of their understanding of half-life, students were asked to demonstrate models of probability in half-life decay using M&Ms (a coloured confection with the letter M on one side). The students were not told how to do this but were expected to devise an explanatory model through which to make a claim. Some students mistakenly placed their M&Ms in a linear fashion, alternating marked and unmarked sides, assuming an orderly pattern. They could not describe how their explanation illustrated half-life. A few students chose to tip the M&Ms onto their tables and removed any M&Ms that did not have the lettering facing upwards, in an attempt to enact probability (Figure 1). The M&Ms that faced downwards were considered as decayed and removed from the packet of M&Ms. They repeated this activity with the remaining M&Ms and plotted results (Figure 2). The other students, after some discussion linked to previous experiences where they had seen half-life graphs, adopted a different approach. Drawing on these imaginative responses, Ben probed students further to justify their understandings in relation to authorised views, as shown in science books. Finally, students collaborated to compare the general shape of their graphs from this activity with published half-life graphs to determine how these different graphs supported the concept of half-life and the differences between the graphs. They then talked about how the shape of the graph differed if the isotope had a longer or shorter half-life. The teacher had accustomed these students to explain their ideas, challenge one another, and justify

Figure 1. Students sorting labelled from non-labelled M&Ms indicating radioactive decay showing half-life.

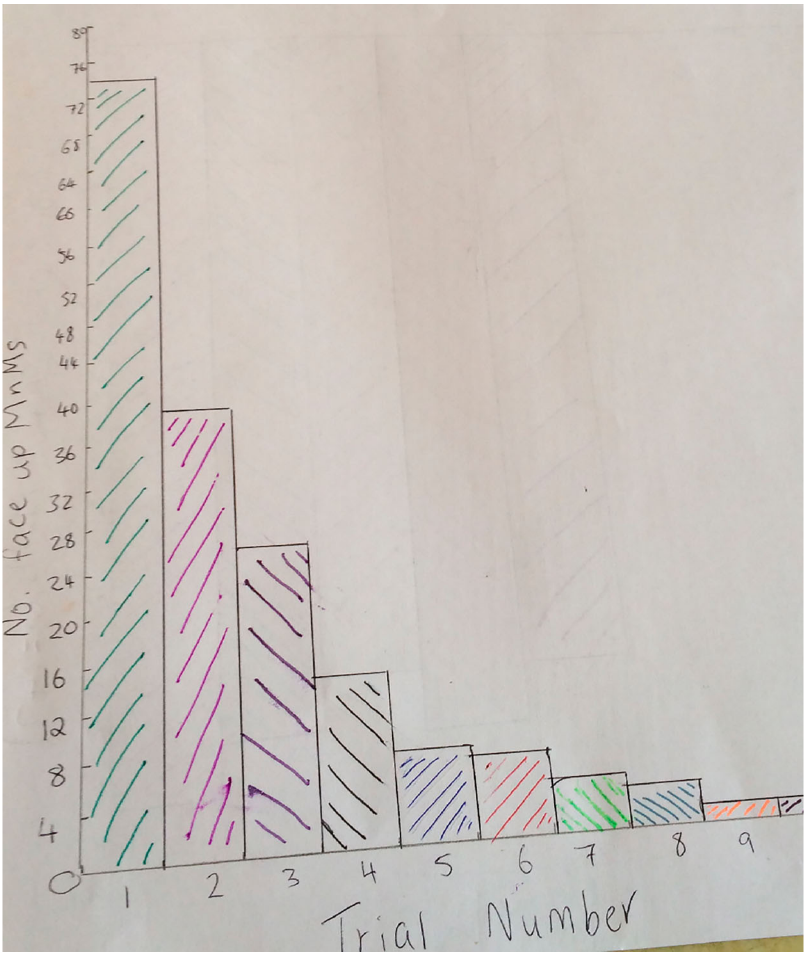

Figure 2. Student half-life graph.

claims and understandings. For these students, it was natural for lessons to conclude with discussion about the part that chance had played in the process. In this way, students built explanatory shared accounts that connected past and current experiences:

Teacher: *Will your rate of decay ever become zero?*
Student: *Yes. Because you will have none left.*
Teacher: *Can you show me why?*
Student: *Find 24 decay, we have 28 left. If 13 decay, we have 15 left. If 8 decay, we have 7 left … . eventually one decays and we have none left.*
Teacher: *Is this what happens in real life?*

The resultant discussion explored the concept of large numbers of atoms decaying. Ben wanted the class to understand whether their results applied to larger scale situations and what happened when the radioactive component becomes very small. The group eventually concluded that the rate of decay would decrease so much that it might be difficult to detect:

Teacher:	*What patterns did you find in your graph?*
Carl:	*Mine was fairly even*
Eva:	*Mine wasn't. It wasn't even because it involved chance.*
Megan:	*Mine halved every time.*
Ben:	*That's different from what we got.*
Teacher:	*What would happen in real life?*
Pause	
Teacher:	*What could affect half-lives and how they decay?*
Ben:	*The temperature. It can't decay if it is frozen.*
Carl:	*In areas where it is frozen, there is no radioactivity decay.*
Gwen:	*But there is always background radiation.*
Teacher:	*You mean that in Antarctica that there is no radio-active decay?*
Carl:	*There is always background radiation. It is found everywhere. It is just another chemical.*
Teacher:	*How does this affect how isotopes decay?*
Steve:	*It mixes with another element. If they have different half-lives, what would be its half-life?*
Gwen:	*Would it affect its half-life?*
Ben:	*They would keep their own half-life.*

This discussion indicated students' collaborative responses as they justified their ideas from their observations, past experiences, and logical inference. They modified their explanations as evidence was provided and showed how their ideas were viable for the initial claim. While some students dominated classroom discussion, over the whole lesson almost all students participated. Some initially quiet students became more involved as the lessons progressed until a new concept was introduced where this hesitancy was again apparent. Subsequent interviews confirmed that the students wanted to raise questions and pose problems.

Ben worked at prompting ongoing inquisitive responses. For example, he would ask for evidence of patterns, challenge assertions, ask for other explanations and model his own inquisitiveness and reasoning through speculation and applying concepts to processes during the teaching of the topic, and encourage students' speculation. Table 1 shows that imaginative (5%), collaboration (15%) and discipline (3%) contributions increased, while inquisitiveness (4%) and persistence (3%) fell. While some creative responses were more or less dominant, there was no consistent pattern in creative responses across all categories between classes. Claim-making was generally facilitated when the teacher encouraged inquisitive responses through practical investigation. When the students checked claims, the video analysis showed that the teacher tended to elicit students' collaborative or imaginative responses. Student collaboration was evident when the teacher prioritised evidence-checking. When all the lessons were examined, there was considerable variation in the use of creative prompts within and across lessons. These differences relate to stages in topics, that is, introduction, exploration, consolidation, reviewing, etc. Student learning appeared, at times, to move forward and at other times to regress, reflecting resistances and shifts in students' reasoning. These patterns indicate that creative reasoning is very context-dependent, and not easily reducible to a set of teacher procedures. What can be reasoned about creatively also depends on the knowledge base of the students, as well as their understandings of how scientific knowledge is claimed, justified, and shared.

In a follow-up interview, Ben claimed various gains from his approach. He felt the students were more engaged and their learning improved:

> I got a lot out of it [teaching this way]. I gained more in terms of questioning and listening carefully to what they were saying and learning. There was more this year of students saying "If we do this then does that mean … ? They were more "why" questions. There were more "what if" questions. It helped students when they listened to each other.

He claimed he had attempted strategies he had never used before, like asking students to list three things they knew about a number of elements. He believed that compared to other classes 'there was more students at the higher level and they were more insightful, on track and more complex responses'. He claimed that there was more detail in the drawings, and that they all knew how to draw electron shells. He noted that 'being asked to reason frustrated some kids. It was confronting for some to start with. The emphasis on reasoning pushed them to think more about the topic'. Some students expected that the teacher would provide a response and found the lack of an immediate response frustrating, especially if they had to wait for a subsequent class. He claimed that at first they could not do it, but that by the end they could explain and justify their thinking. 'Even if their justification was wrong, this allowed me to address their understanding.' Ben viewed teaching as necessitating careful planning, where each activity, set of questions, discussions, served particular purposes for student conceptual understanding, and that this understanding needed to be tracked closely. However, he also recognised that he had to be adaptive to unplanned learning opportunities. For him learning involved mutual student and teacher understanding and student–student dialogue, where the teacher facilitated reasoning whereby students meaningfully linked their background experiences, practical demonstrations, and their evidence-based claims.

Second case study

Wendy wanted to teach a topic that challenged both her and her students (Waldrip & Prain, 2011). Wendy's class was slightly larger than Ben's class. The 26 students were first-year secondary (13–14 year old) students undertaking a unit on chemical bonding in a regional Australian high school. For many of these students, it was the first year of extended exposure to science, with science receiving only cursory treatment in many elementary schools. In Australia, all junior high school teachers are expected to teach all areas of science, including astronomy, biology, chemistry, geology, and physics, irrespective of academic background. The classroom had traditional seating rows with little room for movement for either the teacher or students. The unit consisted of two 50-minute theory classes and one 100-minute practical class per week for four weeks. It was novel in this Australian state to teach atoms, ions, and compound formulation at this year level. Wendy wanted to see whether teaching this topic to this level of students was achievable. She intended to pose a sequence of representational challenges to extend their thinking as they attempted to show how compounds were formed, first using a 2D format (where she guided students to identify limitations to their representations), and then using a 3D format. She planned that each lesson should contribute to either challenging or reinforcing students' understanding, where students needed to justify their explanations. She listened carefully to students to monitor their learning and adjusted learning and teaching approaches to dealt confusions and unexpected opportunities as they arose.

Overview of teaching sequence

Wendy decided to plan a series of lessons that explored how students understood particles and elements, and how compounds were formed, starting with 2D representations to ascertain their current knowledge. Initially, students were asked to discuss with each other and then the class, what were things made of and to draw what they thought these particles looked like, enabling the teacher to identify the students' prior topic understanding. The students described what some displayed artefacts were made of and what they would see if the object was observed under a very powerful microscope. The students discussed their ideas in small groups. During the discussion, a number of students called these particles atoms, a name adopted by the class as the smallest particle of a substance. The term 'atom' had not been specifically taught to this class but appeared to have come from extra-curricular reading or multi-media (e.g. television) viewing. After the structure of an atom was explored, including the role of electrons, protons, and neutrons, the teacher explored atoms with either an excess or a deficiency of electrons through her own whiteboard representation, and labelled these as ions. Most student drawings were strongly influenced by their past reading or viewing, with reliance on circular or ball-like shapes. Students stated this was how they had previously seen drawings of atoms in books or visual media. Wendy perceived the need to extend these broad students' understandings to more detailed accounts of compound formation processes, through some practical experiments and a spatial, visual representational challenge.

Later, in practical classes, students explored what happened when two substances (aqueous) were allowed to contact one another, with the students introduced to chemical reactions. They observed that various changes with some combinations (a precipitate formed, a colour change, a gas released, or energy absorbed or released). By comparing different sets of combined aqueous solutions, students began to realise that some ions were more likely to be involved in these changes while others were not critical to the change. Students asked what were the ions doing if they did not seem to be part of the precipitate, gas, or colour change. Wendy told them that these ions were like spectators – *at the game but not the main players*. They were asked to develop their own 2D-generated representations to show how two or more ions (Figures 3 and 4) formed a chemical compound (see Figure 5). After they had generated their own representations, they were asked to check to see whether their representation was useful in forming recognised examples of compounds, in line with diSessa's (2004) focus on developing students' understanding of representational effectiveness (clarity, coherence, and adequacy to observed or imagined referent). The class then discussed whether particular representations satisfied the criteria for forming recognised chemical compounds. Wendy guided the discussion to identify limitations to the 2D representations once the students started talking about the shape of the molecules that resulted in a chemical reaction, and the need for a 3D representation to show the process. A number of representational forms were modified or rejected because they could not explain how some chemical compounds were formed. In this way the representations functioned as revisable claims, tools for clarifying ideas,

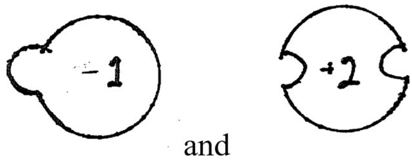

Figure 3. Student drawings of single and double charged ion.

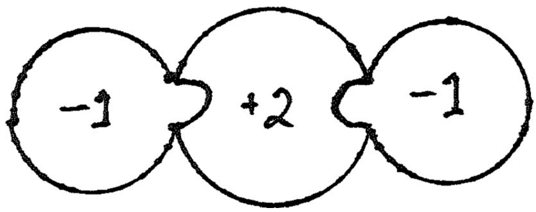

Figure 4. Student drawing of compound formed.

Figure 5. Student drawing of double and triple charged ion.

communicating explanations to others, organising and reporting results, and resources for further reasoning. Because many original drawings (e.g. Figures 3–7) did not reproduce adequately for publication, the presented drawings are re-constructed representations of student and teacher drawings.

Initially in a 2D format, students proposed rounded shapes of atoms of an ion. Two selected shapes were:

T: I would like you to make an ionic compound of these two elements to make a neutral compound. Call it models of ions. After some deliberations, a student produced the following figure.

T: Are there limitations to this [pointing to a self-generated representation] that prevents you from drawing or showing the things the way you want?

S: You can't connect all the points up

S2: yes you can

T: If you stuck exactly with this representation, it is difficult to link up all the notches with the grooves. It can be difficult to match the parts. [draws self-generated diagram of a unknown compound].

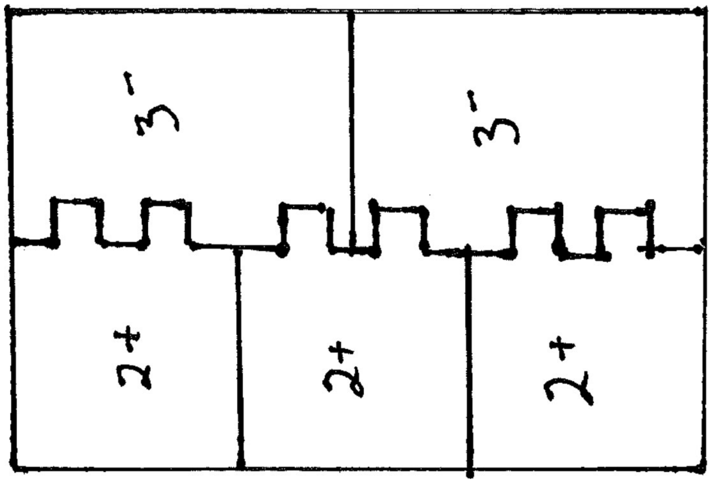

Figure 6. Peta's solution to drawing a resultant compound.

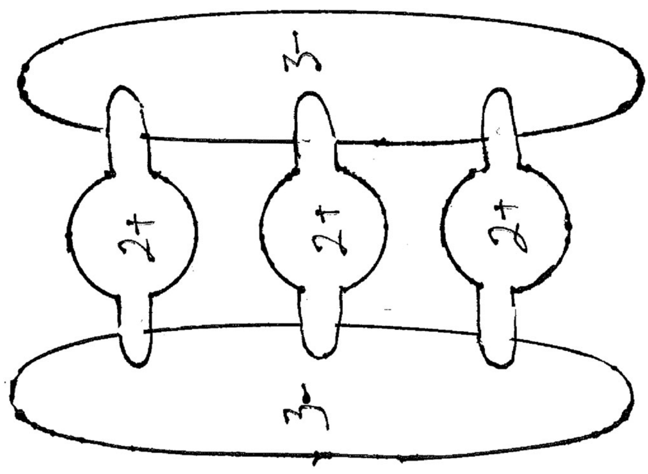

Figure 7. Jack's solution to drawing a resultant compound.

He then challenged them to construct a compound that contained these two elements. Many students found that combining the +2 with the −3 was difficult. Students were asked to use their imagination to develop element shapes that would help them to develop new drawings that would work with any compound that combines +2 and −3.

After some time, Wendy commented:

> Somehow, some people have rearranged this and come up with something that works. The reason I like that is that you realise that we want the same number of positive and negatives. You have remembered about what you have learnt about ionic compounds. There are other ways you could have done this. Peta can you put yours ion the board?

Peta drew her claim for how this could be achieved:

T: Jack, can you please draw yours?
T: Have a look at what these students have done. They have changed the original way of representing the ions so that they fit together. Why have circles, why have squares?
S3: It has been modified to make it more applicable.

After the class had constructed possible representations of ions, the teacher pointed to some of the drawing on the board (Figures 6 and 7) and asks:

T: Are there any limitations in drawing these ions that prevent you from drawing or showing things the way you want?
S: You can't tell where the points are?
S: It can be difficult to match the points with the holes if you stick exactly with this and that (pointing to particular diagrams)
S: Can we split the atoms so that we can combine them differently?

The following discussion canvased the uniqueness of each atom and what it meant if the number of protons changed. This process was designed to enable students to check whether their current understandings stood up to challenges. Some students then drew their ideas as to how atoms could be combined to form a molecule. These students modified their previous drawing so that they could draw the molecule that resulted from a $^{+}3$ and a $^{-}2$ ions.

T: Have a look at what these gentlemen have done? They have changed the original way of drawing ions so that they could join together like a jigsaw puzzle. They allowed for correct parts sticking out for elections and holes for missing electrons and they allowed for the correct number of electrons. They have modified this (old drawing) to make something that works.
T: What about the placement of the charges?
S: They need to be opposite because they could repel each other.
T: Good point. Which drawings then show this?

Some students point to an older drawing (Figure 4).

Students used these ideas on to how to draw compounds to construct examples of Barium chloride and aluminium oxide using their representation of a compound. They then considered what new compounds would form if these two compounds reacted to make a new substance. If they had difficulty with the structures that they designed, then Wendy told them they needed to look for new shapes that would work for any relevant compound.

When interviewed subsequently, Wendy claimed that she planned what she wanted students to know and how this would happen, but always had contingency plans to respond to unexpected student feedback and learning opportunities. In practice, her plans were constantly modified as students become more involved in the learning process. She claimed her planning focused more on how to get students to know rather than telling them. She used

> multiple ways to probe student thinking', looking more at what they needed to know rather than what she needed to tell them. She claimed that the students were 'thinking more about what they are doing and how things fit together to create a coherent whole.

Student engagement

Student engagement was based on the results of a student survey that measured cognitive, emotional, and behavioural engagement. As seen in Figure 8, engagement increased, particularly cognitive engagement.

The survey was not administered in Wendy's class and in follow-up interviews, but students broadly agreed about the value of this approach, as indicated in the following responses:

> Ben gets us to get involved and draw on the board.
>
> Watching others draw on the board helps me to understand better.
>
> We get to explain it ourselves.
>
> The teacher doesn't always tell us that we are right or wrong. We don't get given answers but have to figure it out.

The students saw that they learnt from each other and the process of explaining and justifying claims challenged and clarified their thoughts. They recognised that their teachers was making increased demands on their thinking and reasoning. As one student put it, 'she doesn't always tell us the answer but we think about it overnight and continue talking a about an idea in the next class. I prefer if she told me the answer'. This comment is a reminder that students sometimes have to experience the frustration of challenging tasks to appreciate the value and satisfaction of subsequent successes. Their comments indicate that they saw reasoning through representations as both sustaining their engagement and supporting their learning.

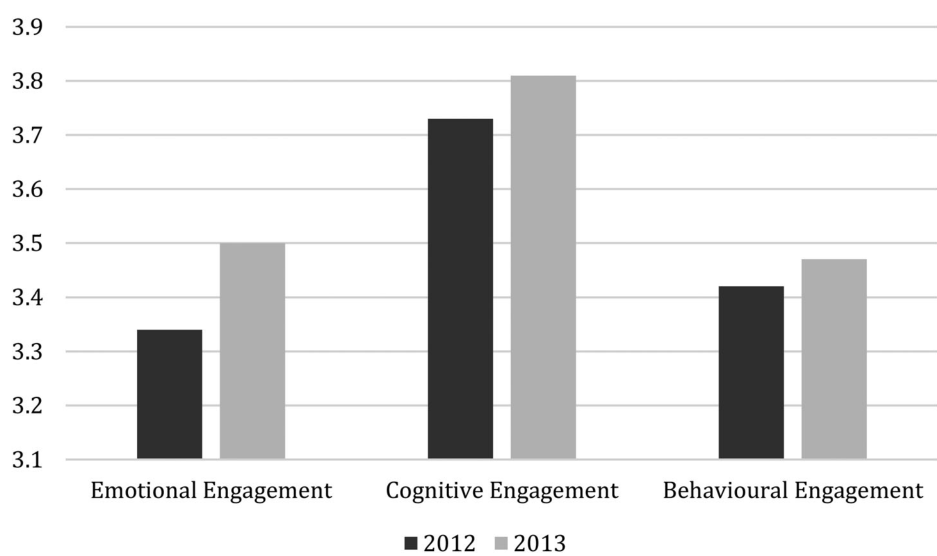

Figure 8. Student engagement in Ben's class during subsequent years.

Teacher strategies to elicit student creative reasoning

Our case studies show that the participant teachers were able to promote student cognitive engagement through eliciting students' creative reasoning processes in case-building and claim-making. While not easily reducible to a planned set of teacher and student procedures, eliciting these processes entailed a range of teacher expectations, prompts, demands, guided activities, and invited roles for students. Both teachers expected students to play an active role in collective knowledge production. They expected students to apply imaginatively some past relevant knowledge to make and justify a claim about a new topic or context. Both teachers continually prompted students to explain their reasoning further, to question one another, to use emerging insights derived from manipulating resources, timely feedback, teacher-generated representations, speculative suggestions, timely counter-claims to prompt further student knowledge consolidation. Both teachers guided consensus-building around the adequacy of student-generated multi-modal explanations. Throughout, the teachers cast the students as active claim-makers, where guided inquiry processes led to verbal and multi-modal representations to be judged against disciplinary criteria. Our experienced participant teachers understood that to engage the students effectively they needed to elicit student questioning, inquisitiveness, persistence, collaboration, and imaginative student-owned problem-solving.

Concluding remarks

As noted earlier in our paper, we recognise the complex range of influences on student engagement in science, including learner prior experiences of this subject, perceived content remoteness from students' lives, and uninviting classroom roles for learning. In putting a case for why and how cognitive engagement can be promoted in the early phases of claim-building in a topic, we have focused on conditions to encourage students' creative reasoning. We consider that there is practical value in developing a shared teacher language for planning, enacting, and reviewing attempts to elicit this reasoning. We consider that scientific norm-disciplined forms of creativity can be enabled in the classroom by a focus on guided representational challenges, provided this is accompanied by teacher-led processes of rigorous judgement of claim adequacy. As noted in our past research, these challenges also need to be framed by judicious teacher introduction of relevant representational conventions and generic resources for particular topics, thus also aligning students' creative reasoning with scientific conventional norms. Further research is needed into identifying, enacting, and reviewing generative representational challenges within and across science topics to contribute to enriched conditions for student sustained cognitive engagement in science learning.

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