An exploration of how a drama-based pedagogy can promote understanding of chemical concepts in 11-15 year old Science students

This dissertation is submitted for the degree of Doctor of Philosophy

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Abstract

A growing body of evidence suggests that some Science teachers use drama-based strategies in order to promote understanding of abstract scientific concepts. These strategies employ action and imagination to simulate systems and processes that are too fast, too slow, too big, too small, too expensive or too dangerous to observe in the classroom. A small group of quantitative and qualitative studies over the past thirty years has suggested that these *physical simulations* enable learning in secondary students, by promoting discourse and by conveying concept features through a range of sensations. The field is as yet under-theorised, consisting of single case designs and unreplicated methodologies.

This multiple case study focused upon an intervention design based on a pedagogical model developed in my Masters research. This study aimed to explore the characteristics of students' interaction and the nature of their resultant conceptions over four months. Each case focussed upon one of eight Key Stage 3 and Key Stage 4 classes across a variety of UK schools. In each, a curriculum-based particle theory topic was taught in a double-period lesson. Data included video, participant observations, and interviews with three students from each class collected at pre, post and delayed intervals. Findings suggested that the pedagogy engendered engagement and self-regulation in group model-making tasks, and supported thought experiment-type visualisations of dynamic processes. Conceptual development was found to continue up to four months after the lessons. A model of learning was developed in which social interaction and multimodal discourse promoted the association of conceptual features with affective, visual and embodied images, which supported recall, discussion and further conceptual development in the longer term.

Declaration of Originality

This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except where specifically indicated in the text.

This dissertation is 79,732 words in total including headings but not including appendices, primary source material, footnotes and references.

Acknowledgements

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I thank my wife for providing a willing sounding board for my thoughts, much of the time without knowing what I was talking about, and for her support when I did not know either. I feel proud that I could also share my subject with my children, pilot my ideas for activities with them, and share my interest in how we learn.

I thank the teachers who have been a part of this study for their kind support, their open minds, and their eagerness to allow my work to inspire their own ideas for pedagogy in their classrooms. Finally, I am grateful to the students to whom I taught the interventions, whose enthusiasms fed my own and whose indomitable childishness (in the best sense) informed a continually interesting and exciting study.

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1.0

Contextualisation of the Study

1.1 Introduction

This chapter frames the investigation of physical simulations by initially recounting the experiences as a teacher and writer that inspired my interest in this field. It then provides an overview of this doctoral research, with a description of the key theoretical and methodological issues that arose as the study progressed from its design through to the data analysis. In doing so it foregrounds key themes and questions in the study, such as the utility of anthropomorphic teaching analogies in Science, the potential for drama-based activities to promote discourse and multimodal communication, and the impact of these features on students' conceptions of abstract scientific concepts over the longer term. Subsequent sections situate this study as focussed upon one of two key drama strategies in Science. Whereas one strategy aims to convey knowledge related to Science in Society, the strategy of physical simulations focuses upon the teaching of abstract scientific concepts. A rationale for this research is developed with reference to the increased interest in drama by Science practitioners, researchers, and academic institutions over the past thirty years, and findings that physical simulations promote meaningful learning in secondary Science.

1.2 Drama as a Classroom Resource in Science

The inspiration for this research came from my teaching of National Curriculum Key Stages 3 and 4 Chemistry and General Science in 1996. At the time, I had recently completed a postgraduate course in Modern Literature. This led me to consider the teaching of abstract scientific phenomena in Science as a similar process to the teaching of abstract concepts within the Arts and Humanities. Following this perspective, I employed drama activities in Chemistry, and devised and presented topics such as ionic reactions with student-enacted 'roving gangs of electrons' and particle theory with students shivering, dancing, and running randomly to indicate solids, liquids and gases. I perceived that these and other drama activities interested and motivated my students and seemed to support their conceptual development.

I maintained an interest in using drama-based activities in Science as I later became a Head of Drama and an English teacher, and I subsequently explored the subject while writing freelance education articles. During this time, I discovered a field of practice that was not reflected in the quantity or focus of academic studies. This observation was reflected too by Maria Odegaard, who, in a meta-analysis of drama in Science education, wrote that research in this field was 'neither highly theorized nor highly researched' (2003, p.77). No research had yet explored drama in respect to the objectives and strategies of 'typical' Science teachers who used drama-based activities in class. Based on my experience, I assumed that teachers' ad hoc use of drama-type activities was more common in UK secondary Science lessons than the literature suggested; this assumption led to my Masters study, an exploration into the characteristics of drama-based activities employed as a 'classroom resource' (Neelands, 1984) by five secondary Science teachers (§2.5). A central finding was that these teachers tended to use drama techniques to initiate and extend understanding of abstract scientific concepts, rather than, as the predominant literature suggested, as a means to promote understanding of social and cultural features related to Science in Society (§2.4). However, while there was evidence that drama may promote some learning, there was little research into the features by which this learning occurred. This provided the central question of my doctoral study.

An early question was the degree to which this pedagogy might promote, not only appropriate but, alternative conceptions: In the Masters study, the activities promoted anthropomorphic analogies in which human traits were implicitly and explicitly compared to scientific phenomena (§3.1). However, the wider Science literature had traditionally viewed such analogies as a potential hindrance to learning, in that they could lead to tenacious, teleological alternative conceptions. During this PhD study, I reviewed the literature on anthropomorphisms in Science Education and found that criticisms tended to be based upon findings of learners' *tendencies* to anthropomorphise, rather than upon evidence of a correspondence between anthropomorphic teaching analogies and subsequent conceptions (§3.1). Furthermore, recent research in this field suggested that at least some anthropomorphic analogies may support learning. In this context then, it was unclear whether drama activities enabled learning in spite of, or with help from, anthropomorphic analogies.

Another key research question, and a methodology with which to explore it, arose from the Masters research. It was evident that much of the communication of science concepts was modelled and negotiated through action, not words. To capture this, I found a Multimodal (§3.3b) perspective through which meaning is perceived to be created in the juxtaposition of signifiers across different sensations. For this PhD study, Multimodal Theory provided a lens with which to explore students' expressions, and interpret the potential conceptual features which they chose to foreground, to explore how these features were negotiated in groups, and to investigate expressions as markers of students' developing conceptions over time.

The multimodal approach promoted a view of highlighting modal signifiers as similar to highlighting key relations between base and target concepts within the topic analogy. This, and a suggestion within the Masters study that these activities may promote visualisation skills (§3.2), prompted me to review research in relation to the role of analogy for conceptual development in Science Education. I reviewed a range of analogical reasoning theories across Psychology and Language, and began to develop a design for the study based upon the dominant 'mapping' approach to analogy (§3.1a). I found that this theory of analogy was complementary with a multimodal lens, in that both tend to atomise a communicative act into units of signifier and meaning.

In this study, terms 'analogy' and 'metaphor', which are highly contested in their definitions (§3.1a), are used interchangeably unless noted otherwise. 'Model' refers to an analogy (or metaphor) expressed as an artefact within the classroom.

As the study progressed, the data suggested that while multimodal theory supported traditional mapping-type analogical theories, it could only provide data on some cognitive and affective features of students' developing conceptions; it did not sufficiently support analysis into the negotiation of these features, nor the motivation to use particular expressions. To question these issues of social dynamics, I drew upon discourse analysis that I had used in my Masters study relating to Mortimer and Scott's (2003) Communicative Approach (§4.8c), and of wider dialogic theory (which also underpinned the design of the research model), in order to describe social interaction in the interventions (§3.4).

Now with a range of lenses with which to explore features of conceptual development, the incoming data suggested two key emerging findings: First, that affective features related to social interaction appeared to give meaning to concept features, which played a major role in supporting the construction and retention of scientific concepts. This was of interest in that there is little theory available to inform conceptual development in relation to *affect*, and little research done (§14.0). Second, a central issue was that the evidence indicated holistic[1] features that were difficult to describe through multimodal and 'mapping' analogies. During analysis, I returned to an article by Heywood (2002) that I had initially come across during my Masters research. He advised a hermeneutics approach to conceptual development that, at the time, I could not relate strongly to my Masters findings. However, Wilbers and Duit subsequently promoted a similar perspective, contextualised within a Science Education response towards 'mapping' theories of analogy. They echoed Heywood's idea that teaching is a process of communicating heuristics, which are slowly developed into conceptions over time, through continual immersion in the topic. Wilbers and Duit's *heuristic analogy* (§3.1c) was attractive as means to synthesise the reductionist and holistic perspectives, in that it viewed the students' conceptual development as beginning with discrete perceptions, followed by a process of aggregation of these perceptions into a heuristic that was so individualised and complex as to be perceived as holistic in nature. In the longer term one's understanding of a concept coalesces over time. This view complemented my analysis by allowing me to telescope between a focussed exploration of how students' choices of signifiers suggested their focus on particular conceptual features, while also

[1] Holistic refers to the idea that the parts of an analogy or conception are explicable only by reference to the whole (adapted from OED, 2008).

explaining how more holistic processes within group interactions might inform the strength of these features within a developing conception (§14.3). The study ultimately found that students' resultant conceptions had developed through their social interaction while expressing visualisations across multiple modes of discourse.

1.3 A Problem: Describing the Unimaginable

The following sections provide a rationale for the study of drama in Science, a brief history of interest in the field, and a description of the central pedagogy of interest to this study. The learning of abstract scientific phenomena has proved a perennial issue in Science Education (Taber, 1996, 2001, 2009; Treagust & Harrison, 2000, Gilbert, 2008). Teaching these concepts is often an exercise in describing the unimaginable, requiring skills of expression more associated with poetry (Claxton, 1997). Science teachers have therefore tended to portray concepts through figurative representations: analogies, metaphors, and models (Gilbert, 2005). Traditionally, the dominant view in Science Education has been to simplify such representations by advocating adult-centric, consensus models and diagrams across concrete and visual modes (Bruner, 1974; Gilbert, 2005; Heywood, 2002). This approach has been criticised for promoting adult-centric base analogues and signifiers that are unfamiliar to students (Goswami, 2001; Taber, 2001b). Such analogies may demotivate learners (Bruner, 1974), and may limit their 'metaphorical imaginations' (Gilbert, 2005, p.134).

Research has shifted in the past thirty years towards a view of conceptual development as more complex than previously thought. Concepts are perceived to be constructed through cognitive and affective processes, employing 'multiple frameworks' (Taber, 2000) of science and social domain knowledge, and occurring over extended periods of time (Treagust & Harrison, 2000; Taber, 2000; 2002; Zemyblas, 2005; Gilbert, 2008). Meanwhile, Science Education has been informed by a growing body of Vygotskian-inspired research that has foregrounded collaborative talk and group work, and the co-construction of models (Lemke, 2001; Yerrick & Roth, 2005; Scott, Mortimer, & Aguiar, 2006; Mercer & Littleton, 2007).

These events coincided with, and supported, a widening view of what constituted useful representations in the classroom. Within and outside of Science Education, researchers advocated an emphasis upon social and cultural features (Treagust & Duit, 2008) and others upon action, gesture, and multisensory modes of learning (Roth, 2000; Kress & Leeuwen, 2001; Ihde, 2002; Bresler, 2004; Jewitt, 2006; 2007). Reiner and Gilbert argued for models that support embodied knowledge; and cited Clement (1988) who claimed that students and experts referred to their own senses of body movement in order to solve physics problems (2000, p.490). In Psychology, Gardner argued that students required a combination of kinaesthetic and spatial intelligence in order to solve problems involving abstract concepts (2006, p.48). Bresler, a researcher of embodied learning, argued for analogies which ostensibly engulf the learner:

> The new generation of learning environments improve the visual information by positioning the learner inside a virtual world. Yet most of the information is still visual only. There is a need to include more than one modality of sensory information in the learning environment. Not just visual imagery, but also force sensations…
>
> (2004, p.75)

It is within this context of analogy as a dynamic, multisensory heuristic, mediated through social interaction over time, that researchers have begun to redefine the utility of analogies in respect to their student-friendliness (Taber, 2001a), the richness and versatility of their metaphors, and their scope for promoting discourse (Heywood, 2002; Ritchie, Aubusson, & Harrison, 2006).

1.4 Physical Simulations: A Student-Friendly System of Representation

This openness towards non-traditional representations of abstract scientific concepts has coincided with an interest in cross-curricular drama in secondary Science, in particular, in the use of drama to develop 'virtual reality' simulations (Odegaard, 2003, p.132).

1.4a The emergence of drama in science

In 1989, the UK National Curriculum Council provided the following advice to Science teachers interested in using cross-curricular drama in class,

> If the technique of handling Drama in the classroom is unfamiliar to Science teachers they will be well advised to seek collaboration with colleagues in the English or Drama departments.
>
> (NCC, 1989, in Somers, 1994, p.104)

Implied in this advice was the assumption that there was *some* interest amongst Science teachers in using drama in their classrooms, and that the 'experts' were in another discipline. The latter suggestion seemed to be well-founded, as Odegaard's

(2003) literature review on drama in Science cited only two articles from before 1990 that described studies on the use of drama within the Science classroom.

Over the following twenty years the list of topics with which drama could inform Science had grown to cover objectives for cognitive, affective and procedural knowledge across Biology, Chemistry and Physics (Odegaard, 2003; McSharry & Jones, 2000). Activities ranged in diversity, from mime-based activities that focused upon the topics of meiosis (Odegaard, 2003), electricity (Aubusson, Fogwill, Barr, & Perkovic, 1997; Wilhelm & Edmiston, 1998), and particle theory (Tveita, 1997), to an inquiry about the ethics of mining (SATIS, 1986) and historical re-enactments of the Scopes Trial (Johnson, 1999). While the literature grew, so did interest across the wider educational domain; internationally (Sturm, 2009), but particularly in the UK, as evidenced by articles in the teachers' press (Littledyke, 2004), workshops and courses run through the Science Museum (2010), Science Learning Centres (2010), and Creative Partnerships (2010), and with events funded by industry, such as BAE Systems (Dorion, 2005b) and the Wellcome Trust (2002). The National Curriculum began to include guidance for specific drama activities in secondary Science (DfES, 2004; DfES, 2006). Such a range of information and events had informed my preliminary research for this study, as it suggested that there was now an increased potential for teachers to experience drama-based activities in action.

1.4b Meaningful learning of abstract concepts

Research has supported this increased interest. For example, two quasi-experimental studies have indicated that this approach enabled 'meaningful learning' of abstract scientific concepts within the secondary classroom (Metcalfe, Abbot, Bray, Exley, and Wisnia, 1984; Tveita, 1996), and a third suggested that these did so as part of a teaching approach that employed a mix of ‘untraditional models’ (Tveita, 1993). These findings have been supported by a small group of qualitative studies in secondary science, which have claimed that students had developed new concepts and had expressed them in their verbal responses to questions and in their construction of new models (Aubusson, 1996; Aubusson, 2006; Tveita, 1999; Wilson & Spink, 2005). These activities were seen to promote dialogic teaching (Edmiston & Wilhelm, 1998), ‘interactive dialogue’ (Wilson & Spink, 2005, p.6), student-centred discourse (Somers, 1994), and the development of positive, affective learning environments, which stimulated interest and motivated students (Tveita, 1997; Aubusson, 2006).

1.4c The development of two drama strategies for science classrooms

In the 1980s, following successes for cross-curricular Drama in the Humanities and Primary education, some UK researchers and institutions began to develop strategies for drama in the Science classroom. For example, the Association for Science Education provided lesson plans within their publication, *Science and Technology in Society* (SATIS) (Dorion, 2005a). One of the first lessons was *The Limestone Inquiry*, in which students and teacher took on roles of corporate, political, and civilian stakeholders within an inquiry into the fictional development of a quarry at the edge of a Lancastrian village (SATIS, 1986). Another ‘seminal’ (Altruz, 2004) publication described how researchers taught students through models of states of matter by acting in-role as individual molecules within a larger system (Metcalfe et al., 1984).

These two examples reflected the two predominant approaches by which drama would be used in the Science classroom for the next twenty years. Both strategies were driven by the objective of allowing students to observe the unobservable, i.e. giving concrete form to abstract concepts (Dorion, 2009). Both could be defined as *simulation* activities in which imagination and improvisation were employed to allow children to explore processes and systems, 'where the real things were too expensive, complex, dangerous, fast or slow for teaching purposes' (adapted from Jaques, 2000, p.132). However, the two activities also reflected a dichotomy related to whether the phenomenon was social or physical: *The Limestone Inquiry* aimed to develop students' understanding of social, ethical, and procedural knowledge in Science by focussing upon societal processes and systems. This *social* simulation strategy informed debates (Duveen & Solomon, 1994), historical re-enactments (Solomon, 1990; Johnson, 1999; Sturm, 2009), and inquiries (Butler, 1989; Solomon, 1989). The breadth of literature on social simulation-type activities (Odegaard, 2003) suggests that these approaches are the dominant form within the literature on Science through drama. Metcalfe's study (1984), by contrast, focussed upon simulating *physical* phenomena. In these, the teacher and/or students provided the modelling resource for describing chemical, physical, or biological processes (Wilhelm & Edmiston, 1998). It is this, less researched form, which this doctoral study explored.

1.4d Physical simulations introduced

The term, *physical simulations,* represents a collection of activities that resemble drama-based techniques known as 'drama machines' (Somers, 1994). These have been described variously as, 'drama models' (Tveita, 1997), 'simulation-role-play' (Aubusson et al., 1999), 'anthropomorphic metaphor' (Wilson & Spink, 2005, p.6), 'metaphorical role-play' (McSharry & Jones, 2000), 'drama analogy' (Wilhelm & Edmiston, 1998), 'imaginary demonstration' (Kress et al., 2001, p.65), and 'acting out' (Francis, 2007). These have tended to employ devised or improvised role-plays using mime and action (Odegaard, 2003; McSharry & Jones, 2000; Venkateswaran, 2006). Physical simulations incorporate participants as individual units within a complex system, where they may take on roles such as planets within the solar system, electrons within a circuit (Tveita, 1999), or cells and organs within the body (Johnson, 1999; Littledyke, 2004; Ross, Tronson & Ritchie, 2008). While following simple individual objectives, the participants' combined interactions create a dynamic model of the system, which they can experience from within. These models may be manipulated in order to aid discussion, for example, by pausing, fast-forwarding, or 'jump-editing' to a different period within the process. They therefore provide a controllable, 'virtual reality' (Jaques, 2000, p.132) through which the teacher and students can manipulate the representation of scale, time, and space, and can communicate scientific analogies via different senses (Dorion, 2009).

2.0

Key Studies in Physical Simulations Research

The field of research into physical simulations has produced a small number of studies over the past three decades. These have tended to be carried out by Science education researchers in collaboration with teachers (Metcalfe, Abbot et al., 1984; Tveita, 1997; Wilson & Spink, 2005) or with dramatists (McSharry & Jones, 2000; Altruz, 2004). The majority of these studies have focused upon secondary students (Tveita, 1999; Aubusson, 2006), but also primary (Altruz, 2004; Littledyke, 2004) and tertiary students (Sturges, Maurer, & Cole, 2009). In this chapter, key studies are presented. These suggest an increase in the breadth and scope of topics and techniques, and a shift in research focus, from the degree to which learning is promoted, towards a focus on how verbal and non verbal communication in these activities support conceptual development. The studies are argued to progressively foreground four key themes in relation to physical simulations which have informed this present study (these are developed further in the next chapter): the affordances of anthropomorphic analogies for promoting the visualisation of abstract science concepts, the scope for multisensory communication of conceptual features; the potential for discourse and collaboration between participants, and the potential for supporting the learning of concepts over time.

2.1 Metcalfe et al. 1984: a drama model of states of matter

Metcalfe's study (1984) was, to my knowledge, the first academic article based upon a physical simulation strategy. This was a small quasi-experimental study with two classes of 10-11 year old boys and girls. During a 300 minute unit of work, one of the two classes was taught through drama while the other class did practical investigations. The activities were designed to convey molecular behaviour in changes of state (Metcalfe et al, p.78). An exemplar model provided in the article suggested these were teacher directed, and that students were asked to pretend to be molecules and follow simple rules of behaviour:

> Pupils stood closely together in a group; chalk mark drawn around them—teacher (T) drew attention to the suggestion that each pupil *(P)* represented a single molecule, and that the whole group represented a solid (in this case a piece of iron); reference to molecules being close together, strong ‘bonds' between molecules—*Ps* instructed to move feet slowly in time with the beat of a metronome—explained that metronome represented heat, and that increase in beat-rate corresponded to increase in heat applied to iron—beat-rate increased gradually, with the result that pupils had to move out of the circle slightly—*T* commanded, "Stop"—pupils stood where they were, *T* drew a second chalk mark around the group—*Ps* moved to side of studio, and *T* pointed to the fact that the group had come to occupy a larger space—discussion, using question and answer technique, of relationship between temperature and space occupied by a solid
>
> (Metcalfe et al., 1984, p.78-79)

This activity revealed the basic, recurrent features of future physical simulations in the literature: Students pretended to be a single unit within a larger system, in this case, ‘a single molecule’ within a substance, and were given simple objectives to follow. An auditory signal was used to convey the relative speed of the particles. Through following the rules as individuals, the students collectively changed the global behaviour of the system, which in this case underwent expansion. The teacher's role, through drawing the chalk circle, explaining the metronome, and in structuring a question and answer session, was to frame and focus students' attention to features within the system.

2.1a Empathy with an atom

Metcalfe suggested that his particle model promoted a novel point of view for the student: the viewpoint of a particle within the system, similar in perspective to Einstein's imagined ride on a beam of light (Reiner & Gilbert, 2000, p.490). However, Metcalfe's perspective was argued to be more than visual. In his conclusion he mooted that through drama students can 'empathise with an atom' (Metcalfe et al., 1984, p.78), suggesting that they could adopt an affective or embodied sensation as they take on the role of another.

> Drama can be used in an additional way: it can be used to enable the learner to 'take on the role of another', to cast off an egocentric perspective—and the 'other' can equally be an animate or an inanimate object.
>
> (Metcalfe et al., 1984, p.78)

For Metcalfe, a key feature was the use of role as a mechanism for framing (through empathy) the visualisation of the target 'other'. The importance of experiencing abstract concepts through imagination would be echoed in descriptions of thought experimentation by Gilbert (2005), but would be challenged by Aubusson and Fogwill (2006), for whom *role* would be seen to carry less importance than dialogue **(**§3.4b**)**.

2.1a.i An improvement in meaningful learning

In Metcalfe's study, written tests were given to both his classes, with assessment focused upon factual recall, explanation and interpretation. It found that while both groups tested equally for factual recall, the drama group scored significantly higher in explanation and interpretation:

Table 2.1 Factual Recall vs. Meaningful Learning

	Class A (control group) $n=26$	Class B (experimental group) $n=21$
Factual recall	$\bar{X}$ 9·00 sd 3·66	$\bar{X}$ 8·52 sd 3·06
Explanation and interpretation	$\bar{X}$ 2·42 sd 1·77	$\bar{X}$ 5·19 sd 2·11

N.B. The circled figure is the drama group's score. (Source: Metcalfe et al., 1984, p.79; oval circling is mine.)

Metcalfe therefore concluded that students developed 'meaningful learning' (1984) in the way they would 'synthesize and apply learned material' (Altruz, 2004, p.38). The groups were not randomly assigned, although a baseline was established with mean scores in the National Foundation for Educational Research (NFER) mathematics, English, verbal reasoning, and reading experience age tests. Mean scores were higher for group A, therefore if the hypothesis were to be supported, it would be in spite of lower attainment scores on standardised tests, Metcalfe concluded (p.80).

With this study, Metcalfe introduced to the literature a new form of teaching through analogy in the Science classroom. In doing so drew attention to the potential for an anthropomorphic teaching analogy to promote meaningful learning of a science concept. Furthermore, the study suggested that this learning may be due to the promotion of non-verbal communication and affective features (i.e. empathy). These aspects of the pedagogy continued to be explored in the literature below. In this study they underpin research questions related to anthropomorphic analogies (§3.1), multimodal discourse (§3.3a), and longer term conceptual development (§3.5).

2.2 Johannes Tveita: simulations of gas and solids within a study of 'untraditional models'

Between 1993 and 1999 Johannes Tveita published findings related to two quasi-experiments with Norwegian students. In the first study (Tveita, 1993), two Year 7-8 (ages 12-14) classes of twenty-nine students and two Year 6-7 (ages 11-13) classes of twenty-nine students were taught a unit of 'untraditional models' including simulation strategies. The study followed a longitudinal approach with a pre, post and delayed test (at twelve months). The findings are problematic in relation to claims for learning, since the drama activities were just two of several teaching strategies, including concept maps, using concrete models, writing in-role as particles, and asking students to describe particle theory to their parents. However, the study was useful in expanding the range of simulation activities and forms, and in introducing a research focus on *affective features* in the learning environment and their role in aiding conceptual development.

As with Metcalfe, Tveita used a simulations approach to teach kinetic particle theory. However, whereas Metcalfe used an 'ideal' simulation, Tveita framed his in reference to a real-world Science situation, the compression of gas in a syringe. Tveita designed a model for gas in which students 'played particles' (1997, p.6) by moving and colliding with one another while confined between two rows of desks as if they were in a syringe. One end was blocked; at the other end the teacher held a 'log' (Tveita, 1999, p.134) which he moved towards the entrance of the desks as if he were pushing against a piston. Through changing the tempo of recorded music, the teacher signified a temperature change.

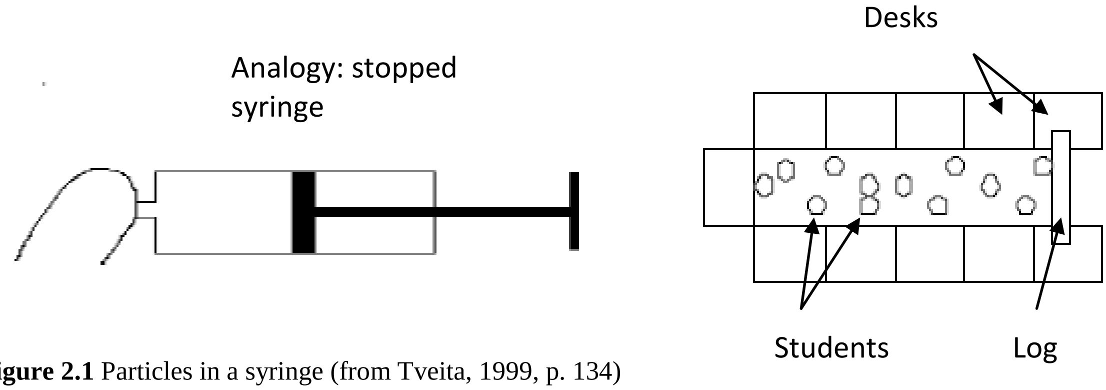

Figure 2.1 Particles in a syringe (from Tveita, 1999, p. 134)

As with Metcalfe's teacher, Tveita used auditory information to convey a sense of particle speed, and also used props (the desks and the log) in order to mediate the students' behaviour. As with Metcalfe, students were units with individual objectives; their individual behaviours were simple and rule driven.

2.2a Arms-as-bonds

In Tveita's second simulation, students 'dramatis[ed] a solid by holding onto each other's shoulders' (1997, p.7). Students were asked to apply this model to explain macro phenomena, such as:

- Melting ice
- Conduction of heat in a metal rod
- Tearing a thin metal wire

- Expansion of a warmed metal wire

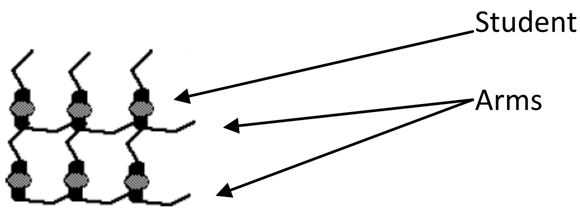

Figure 2.2 Arms-as-bonds to convey bonding in a solid (source: Tveita 1997, p.8)

This use of arms as ‘bonds’ between participants, had been described previously in the UK, in Peter Warren’s *Physics for life* (1988). What was novel was that Tveita had now asked students in groups to take the teaching model and then change and apply this to explain a series of phenomena.

Tveita framed his work within a constructivist paradigm, citing two problems with present representational forms. First, he argued that learners actively construct knowledge based upon what they know, but that their experiences of phenomena can conflict with scientific knowledge. Second, he argued that teaching models were often based upon machine analogies that were not familiar to students: such as the planetary model for atoms and the water model for electricity (1997, p.5). Unlike Metcalfe, Tveita did not focus upon empathy and visualisation, but rather upon students’ access to familiar social metaphors and human interaction as an analogy for particle movement (1997). Unlike Metcalfe, Tveita investigated students’ *interest*, which he did with a Likert scale survey and post intervention interviews. Tveita also investigated other affective affordances of the simulations. For example, in a conference paper on the study, Tveita noted students’ comfort with the models:

‘These phenomena with solids were easy and popular to dramatize and even easy for the students to explain using the drama analogy!’ (1997, p.8).

2.2b Tveita’s ‘drama model’ of electricity

Tveita’s second study was focused upon a single physical simulations pedagogy, rather than a general interest in ‘untraditional methods’. This 1997 study employed a similar quasi-experimental design in order to assess conceptual development. Students were taught with a previously trialled physical simulation: Inspired by the train analogy of electricity (Dupin & Joshua, 1989), Tveita developed the ‘drama model of electricity’. In this model, students engaged in-role as electrons within a circuit and stood with one hand on the shoulder of the person in front of them. They signified voltage by pushing on the student in front of them. They signified current through forward movement and resistance by creating friction as their free hands pressed against the ‘resistance table’ (Figure 2.3).

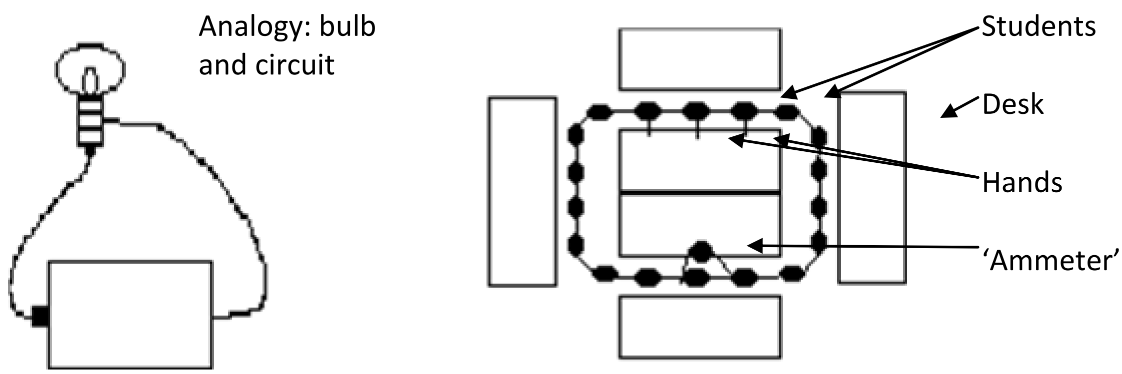

Figure 2.3 Tveita's drama model for electricity (from Tveita, 1999, p.137)

It is worth noting that self-regulation[2] was required by the activity: the proximity of students and the potential misbehaviour in cramped lanes, with students directed to push one another, entailed a high degree of student complicity in the successful running of the simulation.

2.2c Good for girls

The sample in this new study was larger in scale than Tveita's previous study, with 122 students in five classes in Year 7 (ages 11-12) and Year 8 (ages 13-14). The intervention lasted eight lessons. Students received post and delayed tests at one and twelve months. Results were compared with the Norwegian part of the Third International Teaching in Mathematics and Science Study (TIMSS). Tveita concluded that the drama model for electricity enabled learning that compared favourably with traditional teaching methods, in respect to conservation of current, concepts of current and voltage (Tveita, 1997, p.18). Tveita also included interview evidence that the teachers who used the drama models with their students for the unit perceived that the model was more effective than a more traditional, 'water model for electricity' (Tveita, 1999, p.135) in helping students to distinguish between current and voltage.

Girls at the time tended to do worse than boys in Science in Norway (1999). A subsidiary question within the research of the drama model for electricity was the impact upon girls' achievement. Tveita concluded that the girls achieved at an equal level to the boys, and that in the delayed tests the girls achieved higher percentages

[2] Depending upon the discipline or field, researchers tend to emphasise self-regulation as a process associated with metacognition, by which students organise thought, feeling and action in an effort to achieve personal objectives (Boekaerts, 1999). This study uses the term to emphasise students' regulation of the latter two features, in particular with respect to cues from other students, and the teacher (Jarvenoja & Jarvela, 2009).

than other Norwegian girls and boys, based on the Norwegian part of TIMSS (Tveita, 1999, p.139). In a later publication he informed these findings with a revised intervention for a group of twenty student teachers. Here he noted the striking level of comfort for the modelling form that female students seemed to show,

> Several student teachers, mostly girls, asked if this unit of electricity really is physics. It was too easy to understand! (Tveita, 1999)

Tveita had previously argued that these models may particularly help girls and reluctant learners (1996, p.8), and that this success was in relation to their comfort and enjoyment of the modelling form.

As with Metcalfe, Tveita concluded that his students gained and retained a greater understanding of the taught concepts than through traditional teaching. However, Tveita foregrounded the importance of interest and motivation over role and empathy. In his design of the physical simulations, Tveita extended the range of approaches; he introduced props, superimposed macro and sub-micro level objects, and included touch sensation as a signifier for a specific feature of the phenomenon. In Australia, two small qualitative studies would extend these approaches further.

2.3 Aubusson, Fogwill, Barr, and Perkovic (1997): biology and physics simulations

In 1997, Aubusson et al. described an exploration of three student teachers' 'simulation-role-play' activities (p.566). This study, and the subsequent study by Aubusson and Fogwill (2006), brought research closer to the practice of 'everyday' teachers; this focus would be developed further in my masters research, which produced a pedagogical model (§2.5c) used in this doctoral study. The sample consisted of their three mixed ability classes in a New South Wales secondary school, with a Year 8, Year 9 and an 8/9 split (ages 13-15). The student teachers had initiated the study when they came to Aubusson, their supervisor, expressing dissatisfaction with their Chemistry, Biology, and Physics students' understanding via traditional theory lessons. Together they decided to explore the affordances for role-play.

An interpretive study was designed, with video data, observations, field notes and interpretive commentary, analysed jointly by the three student teachers and Aubusson, the head researcher. The study followed three interventions. These are briefly summarised below.

2.3a Reg's class: gas exchange in the human lung

- A devised, teacher-led demonstration in which students assumed roles of lungs, alveoli sacs, red blood cells, plasma and body cells. They used coloured balloons to represent oxygen and carbon dioxide. The balloons were exchanged between participants as the 'blood cell' and 'plasma' students moved through the system.

2.3b Linda's class: electricity

- An impromptu teacher-led demonstration, initiated by the teacher out of 'sheer desperation' at students lack of understanding during a question and answer session on electricity after a theory based approach (p.570). The students, in-role as electrons, walked in a closed loop to signify a circuit. Chairs, as resistors, were added so that students had to slow down to climb over them. One student took on the role of an ammeter, and counted the number of electrons that passed a point in a set time.

2.3c Stephen's class: electricity

- A two-day lesson: On the first day, the teacher directed the students to act in-role as electrons in a parallel and then in a series circuit. In the next lesson they were asked to form groups and co-construct role-plays based on their previous simulations in order to explain their observations in an experiment with a light, a switch and an ammeter. The simulations were performed to the class, with subsequent discussion that led to a whole class role-play which used the 'best features from each group' (p.571). Stephen's lesson contrasted with previous simulations as he first modelled the simulation approach, by directing the students on the first day. The students co-constructed group simulations in the subsequent lesson. In this respect, they applied their modelling knowledge to a new problem, similarly to Tveita's students' with the particle model (1999).

2.3d Aubusson et al., findings: visualisation and motivation

The authors noted that a central objective of the lessons had been to support visualisation of the microscopic world, and that this seemed, 'to have been realised' (p.570). Furthermore, they proved to hold heuristic value for the students after the interventions, as Linda found that in future lessons she could return to the role-plays to review and extend the students' understanding of electricity (p.570). The simulations also supported students' personal expressions of the taught concepts: for example, students in discussion in Linda's class could describe the function of the lungs in their own words (p.569).

The simulations appeared to enhance learning through promoting a sense of autonomy and ownership that improved the classroom atmosphere (p.570). The teachers even reported surprise at students' willingness to work together. Finally, in an echo of Tveita (1997), they noted of the students' motivation,

> Most convincing of all the findings was that the students were motivated during the lessons when they participated in the role-plays and thought they were fun activities in which to be involved. (Aubusson et al. 1997, p.574)

Along with Tveita (1997), Aubusson et al., here emphasised that students perceived these activities as fun, and that this seemed to support motivation and complicity.

2.3e Mixing macro and sub-micro level representations

An interesting feature of the electricity simulations was the superimposition of macro level objects, such as light bulbs, resistors and ammeters, in the same representational frame as the sub-micro level 'electrons'. This superimposition was also a feature in Tveita's syringe of particles (1999). The researchers appeared to assume that such mixing of representational levels did not hinder learning. It presents the question of whether students actually did delineate these two levels of representation in their resultant conceptions of electricity. This has not been discussed in the physical simulations literature to date. This issue inspired the design of the activity *'The Spy's Perfume'* (see Appendix 1), in this PhD study.

2.3f Do they know it is an analogy?

The authors hypothesized that simulations may be optimized if students developed their own role-plays. However, a constraint that these authors identified was that it was not always clear whether students could differentiate 'the analogy from the content being learned' (p.576). Therefore, they argued, the teacher needed to promote self reflexive talk among the students.

2.4 Aubusson and Fogwill (2006): Chemistry Simulations

The issues above were explored further by Aubusson when, almost a decade later, he revisited 'role-play simulations' with one of the teachers, Stephen, from the previous study (Aubusson & Fogwill, 2006). This too was an interpretive study based on teacher observations and discussions with the lead researcher, Aubusson. The teacher, Fogwill chose to teach an intervention on the process of extracting copper from copper ore. He had perceived that his students had poor understanding after four theory lessons, using concrete models, so over the course of the next three lessons, students in groups devised and performed physical simulations in order to provide sub-micro level descriptions of copper carbonate and sulphuric acid, and the electrolysis of copper sulphate. The students' resultant simulation of copper carbonate was described in the passage below,

> The students made the copper carbonate molecules (sic) with five students. They put labels on themselves, for example, the copper ion students wore a "Cu^{2-}" label. Four students represented the carbonate ion (CO_3^{2-}), one was carbon and three others were oxygen atoms. They represented the covalent bonds between carbon and oxygen by linking

arms. One oxygen student linked both arms with the carbon atom representing a double covalent bond. The other two oxygen students formed a single covalent bond by linking one arm with the carbon student. These two also held a book in their other hand, representing an "extra electron". The students explained that they were trying to show not only that the carbonate group was negative but also the location of the "extra electrons". (Aubusson & Fogwill, 2006, p.98)

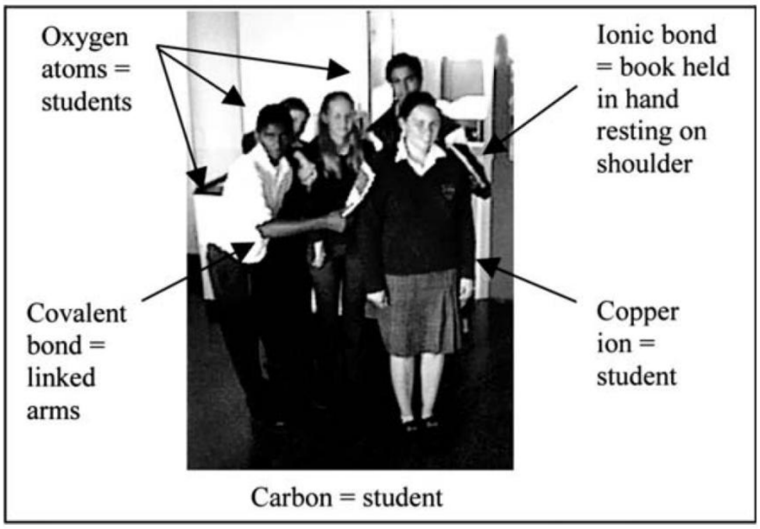

Figure 2.4 Copper carbonate simulation (From Aubusson & Fogwill, 2006, p.98)

In Aubusson and Fogwill's study, the passage above suggested the most complex simulation yet, with older students, in groups, and with representations across the sub-micro and also symbolic levels: with the bodies-as-particles and the copper ions described with formula labels. The simulations were re-visited over three lessons, explored through discussion, performance and evaluation. The findings supported previous claims that the simulations aided students' visualisation at the sub-micro level. As with their 1997 study, Aubusson and Fogwill concluded that there was a high degree of student autonomy and interest (2006).

The authors focused upon discourse as a means of mediating the interaction 'of ideas and representation' (2006, p.102) during the devising process, and then again during the evaluation of performances. Aubusson and Fogwill went so far as to argue that,

> … Much of the learning that occurs is brought about by the discourse associated with the analogical reasoning rather than by the role-play per se. (Aubusson & Fogwill, 2006, p.103)

The authors appeared to have suggested that the act of being in-role was not integral to the cognitive process of visualising abstract phenomena. This contrasted with Metcalfe's supposition that a key aspect for learning through his drama model was to, 'take on the role of another' (1984, p.78). The utility of role for learning in role-play is a highly debated topic (O'Toole, 1992). Aubusson's perspective reflected the predominant view in Games and Simulations theory, that it is not the act of pretending but the participant interaction and discourse that engenders learning (Jones, 1995). By contrast, Metcalfe's perspective resonated with Drama in Education theory, that viewed role as an integral mechanism for learning (O'Toole, 1992; Bolton & Heathcote, 1999).

2.4a Criticisms of previous studies' designs

The studies here reflect the wider literature into drama in Science, in which the designs tended to be single case, or employed complex intervention which were not sufficiently clear to be replicable, which made comparison difficult (Conard, 1998; Harvard-Project-Zero, 2001). A further issue with drama-based activities, exemplified in Tveita's and Metcalfe's studies, was the mixing of physical simulations in combination with other teaching techniques. This made their claims of meaningful learning difficult to ascribe solely to the simulations themselves. As Tveita noted in his study of ‘untraditional models’, ‘[they] are probably more powerful in combination than they are in isolation (1997, p.11).

These studies reflected a tendency within physical and social simulations research to focus on *what can* be done, rather than *what is* being done within Science classrooms. Drama-based activities were driven by the researchers’ objectives: until my Masters study, there had been no investigations, for example, of the work of ‘everyday’ Science teachers’ use of physical simulations. This suggested a potential gap in our understanding of teachers’ background, their role-play choices, their objectives, their topics of interest, and the characteristics of student interaction and discourse when these activities were employed as a classroom resource. These issues were addressed within my Masters study, below.

2.5 Dorion (2007): Everyday Teachers’ Use of Drama in Chemistry, Physics, and Biology

This was a multiple case, ethnographic exploration of drama in Secondary Science. It used a purposive sample of six secondary school teachers who believed that they used role-play regularly. The teachers were asked to invite me in when they next used an activity that they thought might be role-play. Before the lesson, the teachers participated in semi-structured interviews in order to explore their backgrounds and teaching objectives for the upcoming lesson. Naturalistic observations of the lesson were followed by further semi-structured interviews with teachers and a sample of three students from each class, with an aim to triangulate perceptions of interaction and learning in the lesson. The six lessons were analysed individually and then across cases.

The teachers ranged in age, gender and experience, but all of them tended to reveal a strong belief in presenting students with an objective base of Science knowledge (p.110). They tended to perceive a need to control the learning environment when concepts were introduced, in order, they argued, to mitigate misconceptions. In this context, the teachers had traditional views on learning. However, these teachers echoed the dissatisfaction for traditional pedagogy that was displayed by Aubusson's co-authors (1997). For them, traditional representational forms did not sufficiently promote and enhance affective and social aspects of the learning environment. Motivation, ownership, autonomy and a sense of community were perceived as key affective features, both by the teachers and the students.

The study did not focus upon physical simulations *per se*. Rather, this classification emerged out of the analysis. Four of the five teachers used physical simulations in the lessons and the fifth described previous physical simulations activities that he had used. In total the study identified fifteen physical simulation activities which had not, to my knowledge, been recorded within the academic literature (Table 2.2 on the following page).

Table 2.2 Observed and reported physical simulations activities in a multiple case study of secondary Science teachers who used drama as a classroom resource

Topic	Subject	Age	Corresponding physical simulation form
Electronic structure of ion	Chemistry	13-14	Human Analogy Model
Car crash forces	Physics	16-17	Bodies as Units
Limestone decomposition	Chemistry	14-15	Bodies as Particles
Young's Modulus	Physics	16-17	Human Analogy Model
Reactivity	Chemistry	13-14	Teacher-in-role/ Human Analogy Model
Bioaccumulation	Biology	13-14	Bodies as Units
Zeolites	Chemistry	14-15	Bodies as Particles
Mass Spectrometry	Chemistry	16-17	Bodies as Particles
Electrolysis	Chemistry	14-15	Bodies as Particles
EMF	Physics	16-17	Human Analogy Metaphor
Wavelengths (Demonstration)	Physics	16-17	Gestural Metaphor
Wavelengths	Physics	16-17	Gestural Metaphor
Nephron	Biology	15-16	Bodies as Units
Hydrocarbons	Chemistry	15-16	Bodies as Particles
Electro-magnetic wavelengths demonstration	Chemistry	16-17	Teacher in role/ Gestural Metaphor

(Source: Dorion, 2007, p. 105) N.B. the terms in the final column have been changed to correspond to the three physical simulations approaches within this study (section 4.4a); for the previous terms, see Dorion, 2007.

2.5a Dialogic episodes and non verbal discourse

An emergent theme was that the teacher's activities supported dialogic discourse. Analysis of this feature included Scott's communicative approach (CA) (4.8c) to categorise student and teacher discourse into dialogic and non dialogic forms. Devised performances were interpreted to be non-interactive/non-dialogic: performers tended to perform these in a rote fashion, having already rehearsed the scenes. By contrast, the preparation and evaluation sessions were interpreted as interactive/dialogic. This suggested that preparation and performance tasks were complementary: engagement in the extended science-related dialect of the preparation was motivated by the common goal of the performance, which heightened a sense of community and autonomy. This tandem aspect of dialogism and heightened emotion informed the design of the subsequent pedagogical model (and the research model for this PhD study).

2.5b Teachers employed, ad hoc, features from previous studies

The resulting activities employed many of the features of the previous studies, including the use of props (Dorion 2007, p.106), teacher-directed demonstrations (p.58), student-centred simulations in groups (p.93), impromptu (p.86) and devised improvisations (p.107). Rather than having participants acting in-role as objects, they acted in-role as humans within an explicitly anthropomorphic analogy of a scientific phenomenon. The study provided, to my knowledge, the first examples of teacher-in-role within a physical simulation, within the academic literature. For example, in the following example, the teacher stood on a chair and said that he was the nucleus of an atom,

> He then told the girl on his left to stand three feet in front of him. He asked another girl to get up and stand six feet in front of from him. Robert explained that the girls were electrons in different electron orbits; and said that the further out they were, the less attracted they

> were to him, and vice versa. He asked the students to pretend that a reaction had just begun. He told the furthest girl to leave her position and walk away. As she stepped towards the back of the room Robert declared, 'She's not bothered at all [about leaving me].'
>
> …
>
> Finally Robert asked the girl he was holding to go. As she began to walk he pulled her back beside him, and melodramatically bellowed that she couldn't leave. Over the students' laughter, he lowered his voice, stepped out of role, and explained to the class that the electron was attracted to him as he was to it. (p. 86-87)

The importance of this teacher-in-role approach was that it afforded scope for him to manipulate and foreground signifiers for conceptual features across a range of modes of communication. The teacher employed humour, voice and action, as he emphasised an affective analogue (human desire) for a cognitive concept (electrostatic attraction). The other teachers in the study also used multiple modes in their demonstrations; I described them as employing a 'multimodal toolkit' from which to describe difficult abstract conceptual features (Dorion 2007, p.115).

Extending Aubusson et al.'s (2006) focus on discourse, the findings suggested that communication occurred across all of Kress and Leeuwen's (2001) list of external (sight, sound, touch), and internal sensations (spatial, affect, imagination). Students' interviews suggested the potential that particular modes of discourse might have conveyed particular perceptions of conceptual features. This theme is raised further in section 3.3, and has informed the research questions (RQ) for this study which sought to explore how students' multimodal expressions supported their resultant conceptions (RQ 1, §4.1).

2.5c A physical simulations pedagogical model

The study produced a pedagogical model that incorporated three pedagogic routes by which the teachers used drama in their lessons (Dorion 2007, pp.127-128). One route consisted of a lecture-based approach that focused on one mode of communication (i.e. voice); one was a teacher-led multimodal approach using action-based demonstrations, and the final route was a student-centred multimodal, dialogic approach (p.124). The model aimed to progressively build a dialogic learning environment in which students engaged in group thought experiments, and then expressed their answers in performance to the class (Figure 2.5). The intervention followed an iterative structure, beginning with authoritative/non-dialogic demonstration (Label A, Figure 2.5), and progressed towards interactive/dialogic, group thought experiments (Label B). The structure gave the teacher the freedom to extend or break the cycle according to their assessment of the students' progress (Label C). A detailed description of each stage in the model is below in Table 2.3. A sample lesson plan can be found in Appendix 1.

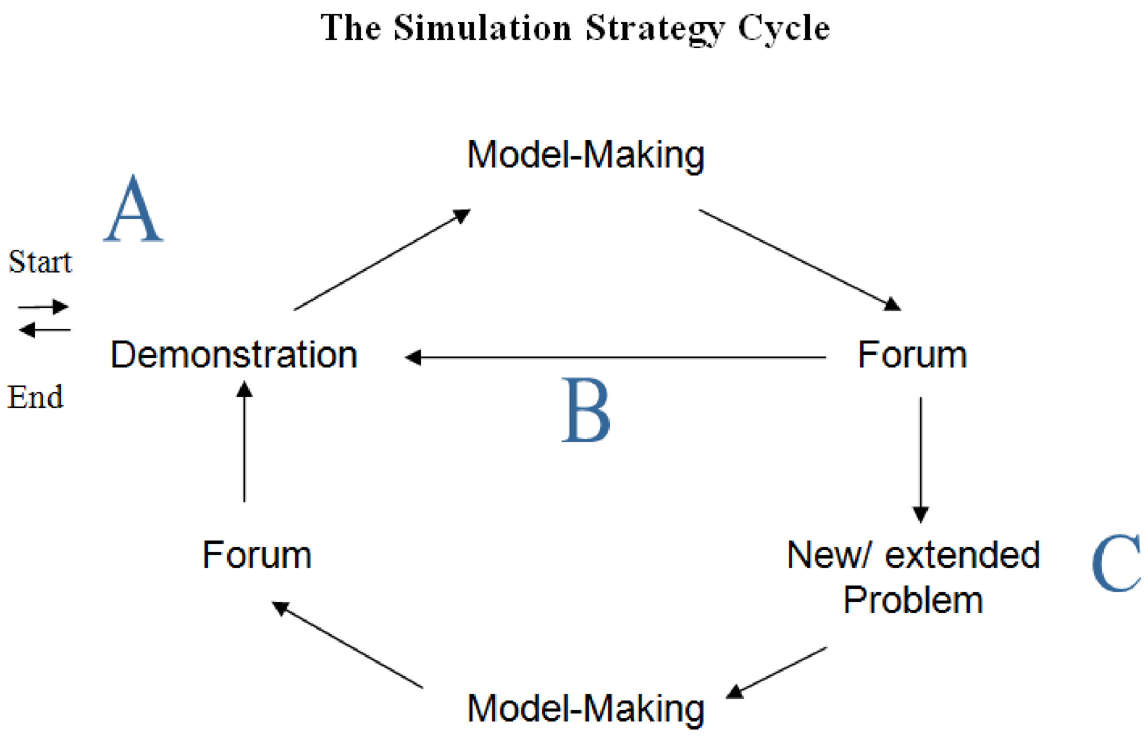

Figure 2.5 The simulation strategy cycle (Dorion, 2007, p. 128)

Table 2.3 A Drama-Based Pedagogical Model to Convey Abstract Scientific Concepts in Secondary Science

Phase	Instructions
1	The activity would begin with a teacher-led demonstration. The modality is not prescribed, but should be a creative response to the drama resources of role and action within a fictional situation. The teacher should justify to students their reasons for using particular modes in conveying the concept, making a multimodal perspective explicit to the students.
2	The students should be placed into small groups and engage in preparing a replication of the teacher's model. This should be a brief activity aimed at introducing participation, and providing an element of formative assessment: with an opportunity to observe all students, and if need be, to ask questions. This phase introduces a dialogic element and an opportunity for developing a sense of community through praise and support.
3	From this stage until the demonstration, the teacher should attempt to maintain dialogic/interactive talk despite temptations to correct misconceptions. The analysis of the case studies suggested that misconceptions are inevitable, but they are appropriate at this stage, as long the dialectic is maintained.
4	After the initial modelling phase, a brief sharing phase should occur in which students should have the opportunity to see each others' models. Anomalous models which are encountered as part of ongoing formative assessment should be challenged for justification, but not corrected from a position of authority; the perception of dialogism should be maintained.
5	The students should be asked to extend their modelling through application to a problem posed by the teacher.
6	After this stage, the cycle continues with further model-making, problem and forum stages.
7	The cycle can be broken after any forum. At this point, the teacher will present an authoritative, consensus version of the concept, using formal modes of expression.

(Source: Dorion, 2007, p. 127)

2.6 Three Physical Simulation Forms in the Literature

Across the activities, three physical simulation forms have emerged. The first resembled drama machines, a rehearsal technique whereby participants enact simple objectives using sound and action, and are choreographed together, usually with the aim to express abstract themes (Neelands, 1984). These approaches constituted the majority of activities within the literature. Within the interventions, I have termed these as bodies-as-particle simulations (BAPs), in order to highlight the focus on body language and movement as the central signifiers for meaning (§4.3a).

The second simulation form resembled drama analogies in the discipline of Drama in Education (DIE), whereby participants enacted the behaviour of humans in society as analogies for the behaviour of scientific phenomena. An example is the teacher and students in section 2.5b who enacted nucleus and electrons as a courtier and his courted ladies. Within the context of physical simulations, these analogical models were termed human-analogy-model simulations, (HAMs) (§4.3a).

A third form used mime to simulate dynamic phenomena in space, such as electromagnetic waves (Dorion, 2007, p. 31). For these gesture-based analogies, this study adopted the term, *metaphorical gestures* (Roth & Lawless, 2002), which defines these gestures as embodying a concrete image for an abstract concept. In the interventions, a formalised form of this was termed a Gestural Teaching Model (GTM) (§4.3a; Table 4.2).

3.0

Theoretical Framework: Key Themes Emerging from the Literature

To date research has been isolated and largely lacking in theory (Odegaard, 2003; Aubusson & Fogwill, 2006). The nascent research programme into physical simulations is still primarily descriptive. Although quantitative studies have suggested that these promote meaningful learning, we have, as yet, made little progress in mapping out the breadth and scope of teaching objectives, simulation techniques, learning behaviours, and the scope for conceptual development afforded by this pedagogy; nor has there been much indication of its constraints. Within this context, I considered Stebbins' suggestion, that when a field is dominated by narrow prediction and control designs, and a lack of theory, one should use a 'wider lens' consisting of an inductive, exploratory approach which would maintain an open perspective, and allow theory to emerge out of the data (2001, p.5).

Exploratory studies are not wholly open, but are rather framed by the researcher's epistemology, and by the chosen methods of data collection (Yin, 2003; Simons, 2010). In order to provide a clear explication of the underlying theoretical framework for this study, the following chapter bridges the review of Key Studies and the Study Design chapters by expanding upon key issues raised in previous research, and drawing implications for theory and methodology within this study.

This review was drawn from the wider literature in Science Education, Drama in Education, Linguistics, Semiotics and Psychology. The first section explores the value of anthropomorphic analogy within the model-making perspectives in Science Education. Next, scope for promoting visualisation and thought experimentation skills is suggested, and then the multisensory nature of these activities is described through multimodal theory. Then key issues of dialogic and interactive discourses within physical simulations are discussed. The final section considers the issue of how to define conceptual development, and suggests potential methods of data collection.

3.1 Anthropomorphic analogies for scientific concepts: do they lead to anthropomorphic concepts?

Physical simulations have been described as anthropomorphic analogies (Tveita, 1999; Wilson & Spink, 2005). Anthropomorphic analogies employ human behaviour as the base analogy for describing scientific phenomena (Taber & Watts, 1996). A traditional view in science education assumed that these representations obscured, rather than conveyed, features in the target concept (§3.1a). Anthropomorphic analogies have traditionally been viewed with caution, as they were perceived to be likely to engender tenacious misconceptions in Science (Gilbert, 1982; Solomon, 1983). The bias against these analogies was such that Zohar has described them as 'taboo' among science education researchers (1998, p.679). However, claims that these analogies hinder learning have been largely unsubstantiated by the evidence, and have been challenged by research which has indicated that anthropomorphic teaching analogies may in fact enable learning at secondary (Zohar, 1998; Hellden, 2003; Kallery & Psillos, 2004) and also university level (Treagust & Harrison, 2000).

Wilson & Spink (2005) argued that these 'anthropomorphic metaphors' (p.6) make 'science palatable' (p.9) and complement the use of accepted teaching models in illustrating scientific concepts. Taber and Watts (1996) suggested that some types of anthropomorphic analogies are useful in teaching, whereas Treagust and Harrison

(2000) argued with reference to freshman college students in Physics, that all analogies have utility when used by experienced teachers.

Anthropomorphic analogies may support students' own mental tactics when confronted with new concepts. In a longitudinal study of twenty-three students, Hellden concluded that students' own, 'anthropomorphic explanations seemed to play an important role in the students' conceptual development' (2003, p.2). Certainly, students seem prone to anthropomorphic thought: studies have suggested that the tendency for students to use anthropomorphic reasoning is extensive, to the point of constituting an 'emergency' (Jungwirth, 1974). In contrast to Jungwirth's alarm, however, Kelemen and Rosset (2009) presented evidence of a potential affordance for anthropomorphic thinking. They recently studied college students whom they showed questions to on a monitor for brief durations and found that students tended to use anthropomorphic explanations when they were given less time to consider the answer (3200ms as opposed to 5000ms). This suggested that students may tend towards anthropomorphic thinking as an intuitive form of reasoning. Whether it hindered or helped in learning new concepts was suggested elsewhere, when, commenting upon students' initial explanations of an investigation into a chaotic pendulum, Wilbers and Duit (2006) noted that 'a remarkable number of students use animistic dictions' (p.46), and that, 'However, [the animistic analogies] do not appear to hamper understanding but merely serve as first heuristics'. Given such evidence, this suggested the question as to whether anthropomorphic features in physical simulations may help conceptual development by bridging initial knowledge gaps. This question, and the debate over the utility of anthropomorphic analogies in Science Education, inspired the inclusion of a specific research question (§4.1a) which asked whether anthropomorphism promoted alternative conceptions (RQ2c). This issue also informed other research questions that explored the possible affordances of students' resultant conceptions during and after the interventions (RQ1b; RQ2a; RQ3a, b and c).

3.1a Three perspectives on learning through analogy

The issues above inspired a review of the literature related to the teaching and learning of concepts through analogy. Traditionally, in Science Education, analogies of scientific phenomena have tended to be seen to be most appropriate for teaching when there is agreement amongst science experts that the analogy/model is *scientifically accurate* (Gilbert & Boulter, 2000, p.25). The most successful analogies were perceived as those which incorporated a clear, simple and formalised proposition of a phenomenon's features (Boulter & Buckley, 2000; Heywood, 2002). This approach was exemplified in a seminal theory by the science philosopher, Mary Hesse, who argued that most analogies fall between two boundaries: *positive analogies* that have exact correspondences between their base and target analogues, and *negative analogies* that have no exact correspondences (1970). Most analogies reside in the middle of these extremes: Within a billiard ball model of particles, for example, the particle 'mass is part of the positive analogy and colour is part of the negative analogy' (Brown, 1986, p.292). Hesse contended that all analogies could be improved through *a reduction of inexact correspondences* (Hesse, 1970). In this view, therefore, analogies could be improved by paring-down extraneous features. Hesse did not propose her approach for teaching children; her heuristic was meant to aid scientists in developing hypotheses in their work (p.57). Nonetheless, the belief in the educational power of the consensus model has remained a feature in Science

Education, which has at times resulted in typologies of models that tended towards a hierarchy, with 'valid' scientific analogies at the top, and 'less valid' alternative analogies at the bottom (Heywood, 2002, p.237; Gilbert & Boulter, 2000), (Figure 3.1, below).

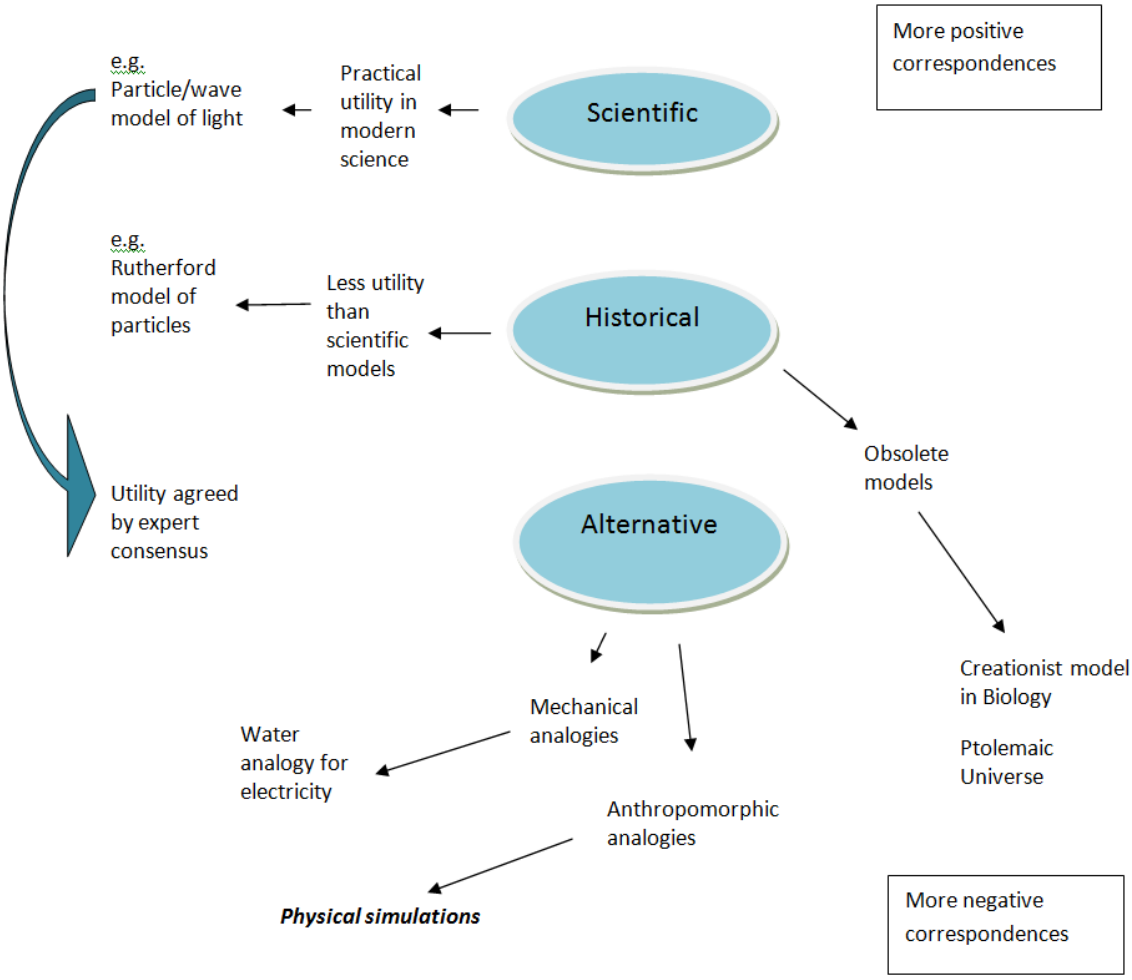

Figure 3.1 A hierarchy of analogy in science education (informed by Gilbert & Boulter, 2000).

This hierarchy can be highly delineated, with levels evident even *within* the set of alternative analogies at the bottom of the hierarchy: both Tveita (1997) and Wallace (2002) have observed that machine or mechanical analogies, such as cells-as-factories or the solar system model for the atom, have been preferred by some teachers over anthropomorphic models due to their perceived clarity and transparency. This view resonates with the traditional perception that anthropomorphic analogies lead to more tenacious alternative conceptions than conceptions drawn from consensus analogies (Gilbert et al., 1982; Solomon, 1983; Kallery & Psillos, 2004).

3.1b All analogies are equal

A hierarchical perspective seems to have been particular to Science Education. In Psychology (Gentner & Gentner 1983; Goswami, 1992) and Cognitive Science (Holyoak, Gentner, & Kokinov, 2001), a competing view has emerged in the past thirty years that the success of any analogy should not be dependent on paring down inexact correspondences, but rather, should be based on making clear the important correspondences or relations between the base and target; students must know to look for relations between the analogical base and target concept, and be motivated to do so. Furthermore, the comparison must use a *familiar* base analogue (Goswami, 1992; Holyoak & Thagard, 1996; Wallace, 2002), i.e. students must have some knowledge of the domain from which an analogy is constructed.

In this theory, the important pedagogical issues are not related to removing negative correspondences. Rather, they are the level of a students' domain knowledge, the degree to which they understand that an analogy is a representation, and the degree to which they can make connections between the analogy and the target concept. This perspective ultimately suggests that *any analogy* is potentially useful, if the teacher and student understand the context in which it is given.

3.1c Non-propositional analogies

This 'mapping' theory of analogical reasoning shares with Hesse (1970) the view that propositions can be clearly identified when comparing the target and base analogy (Gentner, Bowdle, Woolf & Boronat, 2001). A competing viewpoint that has begun to emerge is of a non propositional perspective in which the student's perception of an analogy is unique, and does not convey the same meaning as it does for the teacher.

Wilbers and Duit (2006) have posited that students learn to acquire analogies through a series of mental images or intuitive schemata, rather than by a series of logical propositions. When students are presented with an analogy, they initially interpret the analogy according to their own schemata; Wilbers and Duit do not presume a shared understanding between the students and the teacher. It is only over time, by testing their understandings of the analogy in relation to their experience of the phenomena (principally in discourse with the teacher) that they eventually construct an analogical understanding that is similar to the teacher. In this context it is the analogy that is learned initially, not the intended scientific conception, which will subsequently develop over time as the heuristic is progressively accessed.

Wilbers and Duit have argued that this perspective explains evidence of the non-linear acquisition of analogies in Science students (2006, p.47). This associative view of analogy is echoed in linguistics, as Cameron (2003) claimed that learning through analogy begins necessarily with a rather chaotic mixture of misconceptions but that over time, patterns of predictable conceptual understanding may occur (2003, pp.45-47). In Science Education, Reiner and Gilbert (2000) have noted that non propositional logic may be a central mode of thought in the analogical constructions of thought experiment visualisations.

3.1d How can we describe the effectiveness of physical simulations?

These theories reflect a move away from a perception of analogy as effective or ineffective, and towards a perception in which such dichotomy is moot. In their introduction to Metaphor and Analogy in Science Education, the editors observed that, 'Even as we reviewed the chapters, we realised that there were no 'right' and 'wrong' analogies and metaphors…' (Aubusson, Harrison, & Ritchie, 2006, p.7). Their view corresponds with Psychology researchers, Kokinov and Petrov (2001), who had previously written, 'There are no true and false metaphors, and each metaphor could be useful in certain contexts' (p.68). Without this dichotomy, the value of analogy must be defined in some other way. The following sections suggest that the value of physical simulations analogies may be perceived in their promotion of visualisation skills within dialectic, multisensory learning environments that support conceptual development over the longer term.

3.2 Visualisation

The evidence from my Masters research for this PhD suggested that physical simulations might help develop students, 'spontaneous operation of structured imagination' (Gilbert, 2005, p.65) i.e., the visualisation skills used in developing thought experiments (TE). A prime aspect of visualisation in science, as exemplified in studies of expert scientists, is the ability to think at a macro (approx. human scale), sub-micro (approx. atomic scale), and symbolic level, and to translate ideas between them (Treagust & Chandrasegaran, 2009). Gilbert described this as a metacognitive skill, which he calls, ‘metavisualisation’ (2005). Students, even at university level, may tend to find metavisual thinking difficult across these multiple representations (Justi, Gilbert, & Ferreira, 2009), and initially tend to focus upon macro visualisations of scientific phenomena. The development of students’ ability to think on these levels, and to apply this thinking in TEs, has been a growing field of interest (Gilbert, 2004). Gilbert and Reiner have laid out three criteria for a TE:

- That the design must support the attainments of a particular goal
- That it must be based on prior experience and concepts
- That it is internally coherent

(Gilbert 2005, p.65)

I interpreted these to be present within one physical simulation in my Masters study (2007). The lesson concerned a Physics topic about the forces that act upon a car and driver during an accident. Students were asked to simulate a car crash, and to narrate the crash with reference to these forces. The teacher had implemented the activity with a view to supporting their visualisation and reasoning skills. Furthermore, the teacher’s expected *outcomes* for this activity revealed her aim that students’ developing mental models were meant to be applied during a later thought experiment during national exams:

> So they're sitting in the exam, and they've got a question saying, you know, ‘Why have seat belts? Why do we have airbags? Why do we have crumple zones?’ And they can think, ‘Right, I'm in the car, I've got my seatbelt, I've got to start over this long distance’, and you sort of see it in

> your head: 'Oh the airbag, right I'm being stopped here where the steering wheel...'
>
> (Dorion 2007, p.72)

This passage appeared to meet all three of Gilbert's criteria for a TE: Gilbert's *goal* was evidenced by the teacher's 'Why do we have…' questions. *Experiential knowledge* was indicated by the technical supposition, 'I've got to start over this long distance,' and the *internal coherency* was evident through the credibility of the image she described. This description also showed evidence that the teacher expected a process of visualisation, with 'embodied force' suggested by, 'Right, I'm in the car', and a visual-pictorial image in, 'You sort of see it in your head.' In this particular case, I concluded that this physical simulation appeared to be an effective medium through which to teach the skills of thought experimentation (2007, pp.72-73).

Evidence from a second TE suggested the potential for physical simulations to provide a scaffold for visualising a phenomenon across multiple representations. In a simulation of the decomposition of calcium carbonate, it seemed that individual students perceived the process with a global view of the whole system but also from the point of view of themselves as single ions and atoms within the system (p.101). This suggested that they may have perceived their simulations as outside observers and also through Metcalfe's 'particle' viewpoint (1984).

To my knowledge, there is no literature which has explicitly investigated TEs and TE-type visualisation within role-play or drama. TEs themselves have received a lack of attention within Science Education to date (Gilbert, 2008). This issue is explored through a research question that asks whether the pedagogy can enable thought experiment visualisation in relation to the topic concepts (RQ2b).

3.3 How might we investigate the meanings generated across multiple sensations?

Previous studies have suggested that teachers have promoted different senses through which students have focused on a concept: Tveita used the friction of hands on a table to simulate the heat in a resistor (Tveita, 1999, p.137), and Aubusson's teacher, Linda, made students climb over chairs, exerting extra energy, as if in a resistor (Aubusson et. al, p.570). In the limestone decomposition activity within my Masters study, I interpreted students' visualisations as gestalt-like, and with a particular focus on a 'force feeling' (Bresler, 2004). One student seemed to corroborate this interpretation when he noted,

> …you realise what happens, instead of seeing what happens. And instead of the knowledge of what happens, you feel what happens; and you understand the concepts…
>
> (Dorion, 2007, p.97)

This focus on 'feel' was intended by the teacher, who aimed for an holistic 'appreciation' of the dynamics of movement:

> You want them to follow through a set of instructions and then stand back from what they're doing and then feel it.
>
> (ibid)

Such embodied sensations, described primarily through action, tended to draw students' attention to space, movement and interaction in their resultant conceptions (2007, p.115). By contrast, teaching through diagrams and traditional modelling forms seemed to focus students on the colour and shape of objects within a described system or process (Treagust & Harrison, 2000).

Authors from different disciplines have argued that the mode through which a concept is conveyed mediates the receiver's perception of that concept (Lemke, 1990; Kress et al., 2001; Ihde, 2002; Scott, 2004; Bresler, 2004). Lakoff and Johnson have even argued that any particular expression of a metaphor 'entails very specific aspects of [the] concept' (2003, p.109). Even anthropomorphism and humour, for example, may be seen to influence the meaning that a student confers to a scientific concept (Tveita, 1997; Wilhelm & Edmiston, 1998; Odegaard, 2003). The question of to what degree physical simulations foregrounded particular meanings for particular features of topic concepts informed the research questions into students' expressions (RQ1b), the incorporation of multisensory data to analyse their resultant conceptions (RQ2a-c) and the utility of these conceptions in the longer term (RQ3b). The question of how to observe and make sense of such complex and often non-verbal discourse has inspired my use of a theoretical and methodological approach called Multimodality, or Multimodal theory.

3.3a Multimodal theory: making thought visible

Multimodal theory is supported by a perspective shared across Semantics, Linguistics, Drama, and research into gesture, that students' verbal and physical interaction can reveal the features of their conceptual understanding and the progression of their learning when these features are compared over time (Franks & Jewitt, 2001; Kress et al., 2001; Roth, 2002; Cameron, 2003; Odegaard, 2003). In short, students' actions provide a lens for investigating conceptual development as both a verbal and a visible process**,** which can be investigated through observing the actions of students and teachers in the classroom (Franks & Jewitt, 2001; Cameron, 2003).

To perceive a classroom as not just a verbal but a multimodal environment opens up a range of data sources for investigating the expression of concepts within drama-based activities. Multimodal theory views classroom communication as conveyed across several *modes* of sensation (Jewitt, 2008). These modes may consist of external or internal sensations including sight: sound; touch; spatial awareness; affective awareness; imagination; and social interaction (Kress & Leeuwen, 2001). Multimodality draws attention to these features, as Jewitt notes,

> Examining multimodal discourses across the classroom makes *more visible* the relationship between the use of semiotic resources by teachers and students and the production of curriculum knowledge, student subjectivity, and pedagogy. [italics added]
>
> (Jewitt, 2008, p.357)

Here, learning is perceived as a complex combination of complementary and competing perceptions, an ongoing discourse between teacher and students, students and students, and the surrounding texts and artefacts within the classroom (Kress et al., 2001). Within this environment, students are assumed to develop a variety of individual interpretations (Jewitt et al., 2001). Multimodal research attempts to identify these interpretations based on observations of the students' expressions, and then situates the interpretations in relation to the original teaching and the key modes through which it was mediated. For example, Figures 3.2 and 3.3 are two primary students' expressions of an onion cell through the visual mode, drawing. These expressions were influenced by the students looking through a microscope at onion cells. Although both looked at exactly the same slide, their responses differed 'markedly' (p.9). Through multimodal analysis, a key mediating mode was the teachers' verbal description that the slice would look like a 'brick wall' (Jewitt et al., 2001, p.11). After looking at the slide, 'Child A' was found to frame his subsequent drawing and description based upon a perception of a brick wall as highly regular, i.e. symmetrical. 'Child B' focused upon asymmetrical features such as, 'cracks and bubbles' in the brick wall.

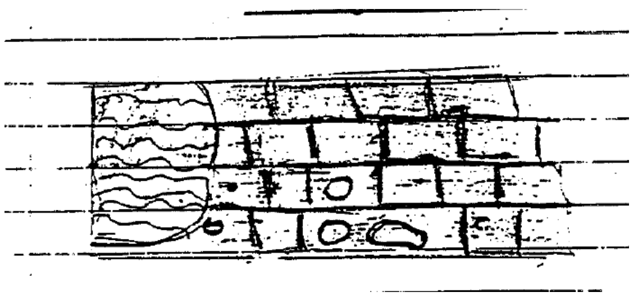

Figure 3.2 Pupil A drawing (from Jewitt et al., 2001, p.9)

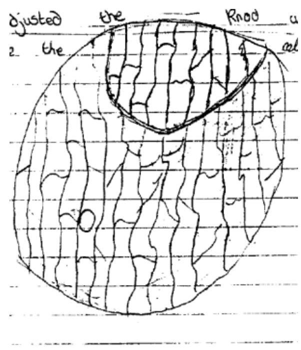

Figure 3.3 Pupil B drawing (from Jewitt et al., 2001, p.9)

Although both students shared the 'brick wall' analogy, the analysis suggested that they foregrounded different features, which in turn influenced their resultant expressions. In this case, a multimodal approach suggested that a seemingly clear verbal description may lead to dramatically altered conception of an onion cell. An important feature of this research has been to emphasise that actions can modify, or even contradict the teacher's *intended* explanations of the taught concept (Kress et al., 2001, p.3).

3.3b Multimodal methodology in practice

Multimodal theory informs a methodology for investigating how meaning is expressed, how expression is constructed, and what the expression may indicate about the originator's initial conception of a topic. Originally developed as a semiotics-based method for investigating texts (Jewitt, 2008), it has since focused upon students' creation of artefacts (Kress et al., 2001), and upon action within the Science classroom. It has been used to explore a Biology teacher's demonstration of blood circulation as he superimposed layers of meaning by choreographing gestural metaphors simultaneously with concrete models, diagrams and speech (Kress et al., 2001). In another demonstration, a Chemistry teacher used action and anthropomorphic analogy to augment traditional particle models, with which to 'imagine the invisible' (Jewitt, 2006). Note how the following passage illustrates the non verbal aspects of the teacher's performance:

> In the lesson (originally observed by Ogbourne, [Kress, Martins, & McGillicuddy], 1996) the teacher stood at the front of the classroom and talked about the arrangement of the particles in a solid, liquid and a gas, pointing at the images she had drawn on the blackboard. She then captured a handful of air in her hands. The teacher sprung open her hands releasing the gas particles into the classroom and through her talk imagined them moving around the room: going all over the place

filling up the room. The teacher then picked up a board rubber to bring the inertness of solid particles into being.

(Jewitt, 2006, p.145)

A key feature of this passage is the emphasis on the extra meaning afforded by the addition of gesture and imagination. The teacher had traditional models of particles in the classroom, but she needed, 'to make the models move, and … ascribe this movement to the 'inert' balls' (Jewitt, 2006, p.145). Through gesture and props the teacher provided an 'imaginative demonstration' of the gas particles 'moving around… all over the place' (Jewitt, 2006).

3.3c The multimodal lens for analysis

Studies with multimodal analysis have so far tended to focus upon teachers' actions. Jewitt, however, has observed secondary student pairs interacting with computer modelling software in Science (Jewitt, 2006). She began with video and naturalistic observations of the lessons; particular episodes of interest were chosen, from which she produced rich, interpretive descriptions. She then *speculated* upon the range of meanings that may be conveyed by the available semiotic resources, in an effort to describe a 'semantic landscape' (p.37). Once the data was produced, it was explored with respect to sampling criteria, and then the data was explored again with respect to patterns across semiotic resources, language, and social interaction.

Some researchers within Science Education may be cautious of an interpretive approach that includes speculation upon potential meanings of student expressions. For example, if one compares Jewitt's description of the teacher in the passage above with Aubusson's description of Fogwill's copper carbonate simulation (§2.4), they may notice a difference in the level of inference; Aubusson described only what one might see, whereas Jewitt included potential meanings such as, 'to bring the inertness into being' in her description. Jewitt defended her approach, as one drawn from textual and linguistic analysis methods, that uses triangulation to improve validity, and only makes local claims that are situated within the given circumstances:

> A criticism sometimes made of multimodality is that it can seem rather impressionistic in its analysis. How do you know that this gesture means this or that that image means that? In part, this is an issue of the linguistic heritage of multimodality. …It is perhaps useful to note that this problem exists for speech and writing. The principles for establishing the security of a meaning or a category are the same for multimodality as for linguistics ... It is resolved by linking the meanings people make (whatever the mode) to context and social function. Increasingly, multimodal research looks across a range of data (combining textual/video analysis with interviews for example) and towards participant involvement to explore analytical meanings as one response to this potential problem.
>
> (Jewitt, 2008, p.363)

Although the idea of 'speculation' implies a subjective process, Jewitt describes this as a form of discourse analysis, supported by triangulation between different sources of data. Furthermore, claims are idiographic and situated in the local context. These characteristics are not unfamiliar to qualitative case study research methods (Stake, 1996; Cohen, Manion, & Morrison, 2000).

3.4 Dialogic discourse evidenced within physical simulations

In my Masters research, the use of a multimodal lens provided evidence to suggest the nature of students' resultant conceptions, by reducing the meaning-making process to the interaction of a few key signifiers, similar to a 'mapping' analogy process in which only a limited number of relations are made between the base and target concepts. However, experience of this methodology in my Masters suggested that it was less effective in describing the influence of the social and affective environment within which conceptual meaning was generated, i.e. through the *negotiations* of individual mental models and the *tactics* of the learners within a group. What was missing was a means of augmenting multimodal methods with a theory of discourse.

The study of physical simulation strategies through discourse analysis has employed large-grained measurements to date, through naturalistic observations of whole classes, and interviews of students and teachers (Aubusson et al., 1997; Aubusson and Fogwill, 2006; Wilhelm and Edmiston, 1998). Findings have reflected those within the wider field of drama in Science, which describe highly dialectic learning environments in which discourse is often argued to be dialogic, and which develops a sense of autonomy, ownership, a sense of community, and complicity in students' support of imagined situations (Butler, 1989; Odegaard, 2003; Christofi & Davies, 1991). Within this context, it was the aim of this study to incorporate an analytical tool which would aid the exploration of physical simulations in respect to their promotion of dialogic learning environments.

The concept of dialogism has received a great deal of interest in Science Education over the past two decades (Scott and Amettler, 2006). Among the topics of study has been the investigation of group work situations and student-centric work (Mercer, 2006; Alexander, 2008). Dialogic-type behaviour has been found to be an indicator for student learning (Howe & Tolmie, 2003). However, as yet there has been a disjoint between theory and practical instruction in the classroom. Scott and Amettler observed that,

> Despite this widespread interest in dialogic discourse, the fact of the matter is that dialogic interactions are notably absent from science classrooms around the world (Alexander, 2001; Fischer, Reyer, Wirz, Bos, & Hollrich, 2002; Wells, 1999).
>
> (Scott & Amettler, 2006, p.606)

Scott and Amettler argued that the implementation of dialogic teaching may be hindered by a Science-specific issue: the need to convey a bank of knowledge which must at some point be accepted as authoritative. As a Science-specific but drama-based pedagogy, physical simulations seemed to provide an interface, or a crucible, for exploring the tension between Science and drama objectives, the latter of which have traditionally aimed to promote multi-voicedness and reduce authoritative control over meaning: Edmiston and Ensico write,

> As Bakhtin (1986) argued, 'in the act of understanding, a struggle occurs that results in mutual change and enrichment' (p.143) Thus, a dialogic

> approach to classroom drama positions the student to experience multiple discourses and assumes that there will be resulting struggles for meaning.
>
> (2002, p. 871)

Dialogism is described within drama as a forum for multiple and oppositional perspectives (O'Toole, 1992) in discourses that may have an open-ended and democratic quality (Bolton, 1995). However, in Science Education, dialogism narrows the frame of the dialectic, which is facilitated by the teacher (Scott, 2003; Alexander, 2008; Mercer & Scott, 2006), towards what Scott has called, 'the teaching narrative' (2003).

3.4a Dialogic discourse evidenced within physical simulations

My Masters research suggested that physical simulations pedagogy revealed examples of tension between dialogic and non-dialogic discourse. In that study I investigated discourse using Mortimer and Scott's c*ommunicative approach* (CA) (2003). The CA focuses upon two dimensions of discourse: dialogic/authoritative and interactive/non-interactive, which may be combined into four categories:

- Interactive/dialogic – Teacher and students consider a range of ideas with a high level of discourse with students
- Interactive/authoritative – Teacher focuses on one point of view but with a high level of discourse with students (i.e. rapid-fire Q and A)
- Non interactive/dialogic – Teacher considers a range of ideas, in front of, but without discourse with, students

- Non interactive/authoritative – Teacher focuses on one point of view but with little or no discourse with students

(Scott and Mortimer, 2005, p. 397)

In using the CA, it was evident that the observed lessons of the ‘everyday’ Science teachers included dialogic activities, in spite of the traditional view of the teachers towards a need to control the conveyance of ‘static, objectified knowledge’, an attitude described by Mercer and Littleton as the antithesis of dialogic teaching (2007, p.69). Nonetheless, the teachers appeared to be drawn into dialogic teaching due to the physical simulations *structure*, as emphasised after one lesson in which both the teacher and one of the interviewees conflicted in their perceptions of whether the teacher or students were in control of the learning (Dorion, 2007, p.74). Dialogic discourse was a feature of one of the three pedagogic routes that teachers used (§2.5a), which informed the construction of the subsequent pedagogic model, and the research model for this study.

3.4b A challenge to drama: is role useful?

Drama, in respect to social simulations strategies, has long been seen to promote a continuous dialogic learning environment, due to an entailment for acting and reacting in-role with others (Bolton, 1985; O’Toole, 1992). In using the CA, however, I interpreted some *performances* as part of a non interactive/authoritative environment, in that the performers were reproducing a ‘text’ that they had already constructed, for an audience that did not have an opportunity to change the science narratives presented to them (2007, p.118). By contrast, the preparation phases, which were longer in duration (with a typical contrasting ratio of one minute of performance to twenty minutes of preparation), appeared to be dialogic. Accepting that there was a potential for some improvisation within the performances, the conclusion was that the role-play itself did not support dialogic discourse, whereas the preparation, out of role, did engender dialogic discourse (p.118).

In Drama, the need to be in-role has been seen traditionally as a pre-requisite for dialogic-style learning (§2.5b). However, interpretive studies into physical simulations seem to suggest that the central feature for learning is not role but students' active negotiation of personal models within a group (Aubusson et al., 1997; Aubusson & Fogwill, 2006). This appeared to be echoed as well by Somers, writing from within the discipline of Drama in Education (DIE). He described the devising process as a collective thinking event (1994, p.52) and illustrated the parallels with physical simulations by using terms that were more normally associated with a Science lesson; the resultant metaphor strikingly resembled a scientific modelling approach:

> Having created a number of hypotheses in the speculative stage, students create drama models to explore situations which will advance or illustrate their thinking. Through discussion and negotiation they modify the chosen models, rerunning them to take account of changing perceptions.
>
> (Somers, 1994, p.52)

The emphasis here was in the interplay between individual thought, group negotiation and the creation of analogies. These features suggested that the dialectic within the preparation was the stimulus for dialogic behaviour. If corroborated, such an assertion may challenge present theory upon the dominance of role in drama-based pedagogy. This issue foregrounded the question of the nature of social interaction within physical simulations, which inspired the inclusion in this study of a research question into the affordances of students' behaviour, in mediating the construction of meaning within the interventions (RQ1a).

3.5 Capturing evidence of useful conceptions that result from physical simulations

The studies described in this review have suggested that physical simulations promote learning in relation to students' conceptual development, and that the construction of these concepts may differ in comparison with traditional teaching methods in Science (Metcalfe, 1984; Tveita, 1999; Dorion, 2009). Nonetheless, there has been little focus as yet on the nature of students' resultant conceptions, and the possible affordances for further conceptual development. This gap in the literature prompted the inclusion in this study of research questions focussed on the nature of students' conceptions (RQ3c). This section situates this research focus in respect to present constructivist assumptions, and the implications for methodology and analysis.

Between 1978 and 1984 a series of seminal papers laid out the assumptions for the constructivist research programme (Taber, 2009). This programme aimed to acknowledge learners' ideas as a starting point from which the learner would (in Piagetian terms) assimilate or accommodate concepts through more appropriate models, and enable pedagogies that would challenge learners' alternative conceptions (Treagust & Duit, 2008, p.2; Taber, 2009). A key theme of the time was that patterns could be identified across different students' conceptions (diSessa & Sherin, 1998). Given this assumption, some studies aimed to classify conceptions as accurate and inaccurate (Driver & Erickson, 1983). This suggested that the progression from transmission to knowing could then be manipulated, so that misconceptions could be mitigated.

Pencil-and-paper, multiple choice tests were used often, but such methods alone were criticized by researchers who found that these tests did not achieve their aim of capturing conceptual understanding (Peterson & Treagust, 1986). In an effort to provide richer detail, some researchers explored approaches which aimed to contextualize students' understanding, using, for example, concept maps and pictorial diagrams (Stains & Talanquer, 2007; Novak & Canas, 2006). The idea that using a single instrument such as a written test may capture students' conceptions became more distant in light of theories such as 'multiple heuristics', which asserted a web of interlinked cognitive propositions taken from different concept frameworks of science knowledge (Taber, 2000, p.403). In response to increasing views of the complexity of conceptual development, Novak and Canas noted that concept maps now aim to describe not just conceptions but 'concept frameworks' (2006).

In an echo of analogical reasoning theories which suggested that there may be a holistic process within conceptual development, Pope and Denicolo (1986) have argued that research should eschew attempts to capture conceptual frameworks as discrete classification schemes and instead aim to describe *how* explanations are put together, looking for *patterns in process*. In support of this perspective, Taber (2009) has shown that although some students' heuristics may be seemingly flawed, they nonetheless appear to be useful to the learner, and possibly indicate an efficient way for the learner to develop highly abstract knowledge (p.365).

Some researchers argued for an even more complex structure than this, in that affective features may not only inform the learner's behaviour but also play an integral role in the meaning of conceptions themselves (Kress et al., 2001). Such research seemed relevant to physical simulations, as in my Masters research I recorded five incidents in which humour seemed to contribute to the meaning of *attraction* between subatomic or molecular objects (Dorion, 2007). Some have argued that metacognitive[3] features are the missing factors in our understanding of student conceptions (Wallace, 2002; Justi, Gilbert, & Ferreira, 2009), while others note that an even wider frame of reference is needed, one that includes social, cultural and affective features (Treagust & Duit, 2008; Lemke, 2001).

In light of such complexity, a single or even a dual testing approach seemed unwise in an exploratory study. Defining 'accurate' and 'inaccurate' student conceptions may be useful as immediate categorisations, but are ultimately limited in value. It seemed reasonable to assume that in this exploration of physical simulations, a definition of *utility* should be used instead. Utility here implies that a concept has an impact upon the progression of student knowledge, and that it can support further development of the concept. Interpretation of utility should include the consideration of affective, cognitive, and metacognitive features, and the ability for the conception to be applied as a core heuristic when approaching new problems. This review suggested that it

[3] Definitions of metacognition vary (Efklides, 2005). This study adopts Flavell's (1979) perspective by which students are perceived to be aware that they are engaged in a cognitive action, and that they are monitoring that action, and that they are using conscious and deliberate strategies to support their thinking. This perspective is exemplified in interpretations of some model-making episodes (§5.2d) and in some anthropomorphic utterances (§13.0) in which students' are interpreted to identify gaps in their knowledge and then adopt strategies to bridge the gaps in order to continue with the task or discussion.

should also allow for students' inconsistent reasoning while approaching new problems (Cameron, 2003; Taber, 2000).

An interpretation of utility, in this context, would be supported by several measurements, across time. A useful means of data collection came from Taber, who had argued that considerable time needed to be spent with individual learners in order to repeatedly, through different approaches, evaluate and challenge student thinking within different applications of the concept to different problems (Taber, 2000; Watts & Taber, 2000). In order to develop appropriate sensitivity in the capturing of developing conceptions, it seemed therefore that an effective approach was to investigate episodes of conceptual change across data collected through a variety of observation and interview-based measurements, and within a longitudinal context.

3.6 Summary of Chapter Three

Physical simulations employ imagination and action to allow students to express and experience unobservable systems and processes. These activities are the less reported of two dominant drama strategies that have tended to be used in secondary Science classes in the UK since the 1980s. A small group of quantitative and qualitative studies suggest that physical simulations promote meaningful learning of abstract concepts in secondary Science. These studies have occurred over the past thirty years, and have progressively focused upon the conveying of conceptual features through a wider series of sensations, and with an increased interest in discourse and social interaction.

Physical simulation strategies employ implicit (BAPs) and explicit (HAMs) anthropomorphic analogies, a representational form that has traditionally been perceived to hinder conceptual development. However, recent research within Science Education and Psychology have suggested theories of analogy which support the use of a wider range of representational forms than previously warranted. Furthermore, research into anthropomorphism in Science now suggests that it may promote conceptual development in secondary students. Findings together suggest that physical simulations may provide a range of signifiers with which to convey particular conceptual features, and that student behaviour within physical simulations supports science-oriented discourse. In order to explore whether these activities enable useful conceptual development, a contemporary constructivist perspective suggests that a research design should be sensitive to the situated nature of conceptions, and should use methods to capture data through flexible, research designs, focussed over the long term.

4.0 Study Design

4.1 Research Questions

This exploratory study aimed to inform the gap in theory and evidence regarding the relationship between students' interaction in physical simulation-based lessons and their subsequent conceptual development. The literature review highlighted three aspects of this process: the construction of meaning within the lessons, the nature of resultant conceptions after the lessons, and the affordances for longer term conceptual development. In relation to the first aspect, the literature informed a socio-constructivist perspective that assumed that learning is a social process, mediated by discourse (Mercer, 2000; Bell & Cowie, 2001; Lemke, 2001; Scott, 2004), but also that social interaction and expression, as an indication of the negotiation of developing mental models in physical simulations, should be explored across verbal and actional modes (Roth, 2000; Franks & Jewitt, 2001). Influenced by literature into visualisation (Reiner and Gilbert, 2000) and analogy (Goswami, 1992; Holyoak, Gentner, & Kokinov, 2001), and by multimodal theory (Kress & Leeuwen, 2001; Jewitt, 2008), the study assumed that students' expressions could be interpreted as signifiers of conceptual features, and that patterns of expression across students might suggest patterns of conceptual understanding. Finally, the literature into the assessment of conceptual development informed an assumption that the complexity and mutability of conceptions (Novak & Canas, 2006; Treagust & Duit, 2008; Taber, 2009) was best explored via multiple data sources over time.

The research questions are:

How can physical simulations promote conceptual development of particle theory topics in secondary Science?

RQ1: What are the features of physical simulations that may support conceptual development?

a) What are the affordances and hindrances of student behaviour? (§3.4b)
b) What are the affordances of students' expressions? (§3.3)

RQ2: What are the characteristics of students' resultant conceptions?

a) Does this pedagogy elicit particular conceptual features? (§3.3; §3.3c)
b) Can the pedagogy enable thought experiment type visualisation? (§3.2; §3.3)
c) Do the anthropomorphic analogies in the intervention promote alternative conceptions? (§3.1; §3.3)

RQ3: Does the pedagogy develop conceptions which promote or enable further development?

a) How might pedagogy promote retention of particle theory conceptions? (§3.5)
b) What are the affordances of the physical simulations for supporting students' long term conceptual development? (§3.3)
c) What are the affordances for teachers to support long term conceptual development? (§3.3c)

4.1a Rationale for a multiple case, ethnographic study

The core requirement of the research questions was the need to explore links between external actions and internal conceptions. The key themes previously discussed in the *Theoretical Foundations* sections suggested that in order to retain the situated nature of the meaning-making process, a study design would need to be highly flexible, drawing upon a range of data collection approaches. In addressing this problem, I was informed by Stake's ethnographic approach (1996) that he employs within a case study format that Simons has described as 'sophisticated beholding' (2009), and which foregrounds the collection of rich data, with attention to 'thick description', 'experiential understanding' and 'multiple realities' (1996, p.43). Stake focuses upon the analysis of patterns and differences within and across data sources, from which themes and findings emerge: confidence in particular findings is developed through triangulation of multiple perspectives, i.e. the recurrent juxtaposition of different data from within and without different data sources.

Stake's single case study methodology on its own was unsatisfactory in relation to a continual criticism of Science through drama research: that the predominance of single case studies and differing methodologies made it difficult to compare findings (§2.4a). This criticism was addressed by developing a cross-case method, again informed by Stake (2006) in which individual cases were treated as idiographic, but which shared a similar design protocol, so that comparisons, and wider generalisations, could also be made across cases (§4.8). For example, cross-case similarity in this study included the use of a consistently applied research model in lessons (§4.3), using the same teacher (§4.3), and the same protocols for data collection and analysis in each case (§§4.4 – 4.5). This provided a balance between a reduction of variables (teaching style, drama form, teacher, topic, subject, age), while retaining the flexibility to explore the application of the model across a variety of situations.

A further criticism of previous studies into physical simulations has been that researchers have tended to approach drama in Science as informal educational events, driven by their research aims, rather than as a 'classroom resource' (Neelands, 1994) driven by the teaching objectives of an 'everyday' teacher. This study aimed to improve ecological validity by addressing this issue through the use of interventions which were based upon the 'everyday' teachers teaching approaches in my Masters study (§4.3). To further support validity, bespoke lessons were designed according to the classroom teachers' objectives with respect to the curriculum and the abilities and personalities of their students (§4.3b). Also, a set of warm-up activities was devised which provided a proxy for regular classroom simulations, so that students had some understanding of, and comfort with, the drama-based skills and terms before the topic concepts were introduced in the lesson (§4.4). The balance between the limitations and benefits of this approach are discussed in section 4.11.

4.1b Rationale for a focus upon particle theory topics

This study could have explored Science through drama in Physics or Biology. However, I was inspired by the tendency for researchers (Metcalfe et al., 1984; Tveita, 1999; Aubusson & Fogwill, 2006), and the Chemistry teachers in my Masters study (§2.5), to use physical simulations to teach *particle theory* explanations. I assumed that the topic would also provide a challenge to the pedagogy, as it has been asserted to be both a difficult concept for students to learn (Bouwma-Gearhart, Stewart, & Brown, 2009), and a linchpin theory within Science (Calyk, Ayas, & Ebenezer, 2005; Garcia-Franco & Taber, 2009) that, furthermore, was taught through the Key Stage 3 and 4 curriculums (DCSF, 2008). There was also a large body of research into students' chemical conceptions upon which to draw in analysis (Duit, 2007). Particle theory in particular has been a source for extensive descriptive research (Brook, Briggs & Driver, 1984; Johnson, 1998; Garcia-Franco & Taber, 2008). Johnson (Table 4.1) suggested a range of key issues related to students' conceptions of particle theory at secondary level, which appeared to correspond to potential affordances of physical simulations approaches. In a review of the evidence, Johnson argued that students revealed weak understanding of the relative spacing of gas particles, and little appreciation of intrinsic motion or the idea of a surrounding vacuum. Students often attributed macroscopic properties of a substance to the particles, and failed to use ideas of attraction (Figure 4.1). By contrast, physical simulations had been perceived to emphasise students' attention and understanding of spacing, movement and multiple levels of visualisation (§2.5). Research into particle theory has provided an opportunity to compare traditional patterns of students' conceptions with the students' conceptions in this study.

- The relative spacing for the gas state is underestimated
- Pupils show very little appreciation of the intrinsic motion of the particles
- Very few pupils use ideas of forces/attractions/cohesion between particles, even for the solid state
- The idea of 'nothing' between the particles, especially for the gas state, appears to cause considerable difficulties for pupils
- Many pupils attribute the macroscopic properties of the material sample to the individual particles

Figure 4.1 Common student conceptions related to particle theory (Johnson, 1998, p.394)

4.2 Sampling

Eight classes were chosen on an opportunity sampling basis, with the intention to explore the pedagogy across a variety of learning environments and a diversity of abilities, genders and schools (Table 4.1). The number of *eight* cases was initially a predicted number by which data saturation was assumed to be approached, and was influenced by the length of the final thesis in relation to the detail required for each case.

In keeping with Stake's advice to include multiple perspectives, the study aimed for a breadth and variety of students. Classes were drawn from UK state and independent schools across three counties. Students' ages within the study ranged from 11-15[1]. The choice of sampling across Key Stage 3 and Key Stage 4 allowed for a range in the maturity and sophistication in student responses. All classes were mixed gender. Abilities differed within and across classes: One Year 9 group was taking early GCSE triple Science, another class was described by one staff manager as, ‘a group of very low ability…who can't remember anything with conventional teaching’[4]. In total, 163 students and eight teachers took part in the study.

Table 4.1
Sample sizes for cases and total number of students

Case	Year	School type; (size)	County	Age	Ability; special features	Number of students
1	9	State	Herts	13-14	high ability; early GCSE group	26
2	7	Independent	Kent	11[5]-12	mixed ability	18
3	10	State	Herts	14-15	mixed ability	18
4	7	State	Herts	11-12	low ability	20
5	9	State	Cambs	13-14	mixed ability	23
6	9	State	Cambs	13-14	mixed ability; multicultural	27
7	9	State	Cambs	13-14	mixed ability	24
8	10	independent	Cambs	14-15	high ability	18
				Total		**163**

4.2a Interview sample

In each case, three students were chosen for interview across three data collection stages. This number allowed for analysis through triangulation of responses, but also provided a reasonable trade-off between depth of data and the resources for its collection and analysis (§4.7). In each case, in an effort to collect a variety of participant responses, a purposive sample was employed: Teachers were asked to

4 Source: email correspondence
5 One student was nine years old.

indicate students who represented a range of ability and gender within the class, again following Stake's advice for variety, but also to provide opportunities for intensive study (2006, p.24). Preference was given for those whom the classroom teachers felt would be able to provide extended answers and thoughtful responses. I employed this purposive sampling approach in my Masters research and found that it afforded a variety of perspectives (Dorion, 2007, p.38).

4.3 Intervention: The Research Model

Each intervention was delivered over a double-lesson period consisting of 70 to 100 minutes, depending on the standard length of the schools' individual lessons. The intervention followed a research model based on the pedagogical model developed from my Masters study (§2.5b; Figure 2.5 and Table 2.3). This model provided an opportunity for an iterative, model-making format, in which the modelling resources were the students themselves. It began with what Mortimer and Scott (2003) had identified as interactive/authoritative teaching and progressed towards the construction of interactive/dialogic learning environments in which students were asked to engage in group thought experiments, the results of which they performed to the class, and then evaluated within a forum session. A key feature of the intervention was its flexible structure which allowed the teacher to extend or break the cycle according to formative assessments of students' progress. A sample lesson plan can be found in Appendix 1.

4.3a Key simulation forms used in the interventions

Initially, the intervention designs would be supported by three simulation forms that had been identified in the literature. These were:

- Bodies-as-particles simulations (BAPs): whereby participants enact the behaviour of particles by following simple objectives (For example, see §2.4, Figure 2.4)

- Human-analogy-models (HAMs): whereby participants enact the behaviour of humans in society, as analogies for chemical phenomena (For example, see §2.5a)

- Gestural Teaching Models (GTMs): Gestural metaphors were referred to in observations of teacher demonstrations. My understanding of these developed further in the pilot studies: In one interview, a student mimed a two-particle model of a solid changing to liquid and then a gas. I was inspired by this and initiated gestural metaphors with other interviewees. I perceived that they were comfortable with these models, and that they supported our discussions. I devised a more formal set of gestural metaphors in order to simulate particle interaction during the intervention. Together, these are termed the Gestural Teaching Model (GTM) (Table 4.2; Figures 4.2-4.4).

Table 4.2
The Gestural Teaching Model

Particle state and phase change	Gesture	Features	Observed 'alternative' student gestures
Solid	Hands clenched in fists held in front of the body. Hands touching thumbs/forefingers, with small rotations in opposite directions or wiggling back and forth out of sync.	Particles close together. Movement confined to vibrations Strong attraction between particles	Hands touching, and still.
Liquid	Hands clenched in fists held in front of the body. Hands close to two centimetres apart moving slowly in asymmetric orbits around each other.	Particle spacing is 'in-between' gas and liquid. Particles move relatively slower than in a gas. Movement is affected by attraction to other particles.	Hands open with fingers wiggling gently. Hands close to two centimetres apart moving slowly in asymmetric orbits around each other.
Gas	Hands clenched in fists held in front of the body. Random, quick movements of the hands outwards to random distances then return and move outwards again. Hands may or may not bump into each other, but when they do, they move away from each other.	Particle spacing is relatively large. Particle speed is faster than in a liquid. Particle movement is random. Movement is affected by collisions between particles.	Hands open, with slow, rising, 'floaty' movement

Figure 4.2 Solid: Hands vibrate.

Figure 4.3 Liquid: Hands move around each other.

Figure 4.1 Gas: Hands move quickly and randomly

4.3b Rationale for researcher-as-instructor

The lessons were taught by me. This had the potential to reduce ecological validity but provided consistency of teaching across the cases, and allowed for a greater number of classes to be used in an otherwise small study. In contrast to my Masters research, which specifically sought out teachers who used role-play, and whose students therefore had some familiarity with the form, the doctoral study teachers might not have been accustomed to role-play in Science. Given the possibility that this might be a novel pedagogy, a more experienced physical simulations practitioner might be more sensitive to the application of the activities. Having a single researcher/teacher therefore reduced the level of preparation and training required for each lesson. This provided scope to increase the number of cases. Furthermore, I had piloted the KS3 particle theory intervention pedagogy three times (§4.10) and found that the impulse to revert to 'providing the answers' during dialogic activities was strong, which suggested that the teachers within the study, possibly unaccustomed to using dialogic approaches, might have required more rehearsal in this aspect than was reasonable to ask, and require more support than resources would allow.

In order to maintain ecological validity in matching the research model to the classroom teachers' objectives in regards to the curriculum, I developed bespoke lesson plans for each class, based upon the pre-intervention interviews and discussions with the classroom teacher. From a practical standpoint, this also allowed me to tailor the instruction to the teaching spaces, and to work with the unique personality and ability mix in each classroom. This method also promoted my own sense of creativity, as many of the activities had not been developed previously; in this respect, the approach helped me to echo the teaching style and attitude of the teachers within the Masters study, who themselves appeared to be inspired and motivated by the creative aspect of their role-play activities (Dorion, 2007, p.112), thus including an affective element that would otherwise have been omitted. The range of topics, activities, representational levels, groupings, and modes across the interventions are described in Table 4.2a.

Table 4.2a
Topics and Activities Designed for the Interventions

Case (Chapter)	Topic	Activity	Macro/ sub-micro /symbolic representation	Grouping	Assumed key modes during design process
1 (5.0)					
	Atom	Demonstration BAPs	Sub-micro; Symbolic (charges)	Teacher	Sight; body; gesture; facial; expression; spatial positioning; imagination; voice
	Atom	Student-centred BAPs Devised	Sub-micro; Symbolic (charges)	Groups of 3	Sight; body; gesture; facial; expression; spatial positioning; imagination; voice
	Roomful of hydrogen atoms	Teacher-led BAPs	Sub-micro; Symbolic (charges)	Groups of 3;Whole class	Sight; body; gesture; facial; expression; spatial positioning; imagination;
	Make the largest atom	Student-centred BAPs Devised	Sub-micro; Symbolic (charges)	Whole class	Sight; body; gesture; facial; expression; spatial positioning; imagination;
	ionisation	Teacher led	Sub-micro	Whole class &	Sight; body;

		BAPs		Teacher	gesture; embodied; movement; space; imagination; voice; touch
	ionisation	Student-centred BAPs Devised	Sub-micro	Groups of 4	
2 (6.0)					
	States of Matter	GTM Demonstration	Sub-micro	Teacher	Gesture; voice embodied
	States of Matter	Student-centred GTM Improvised	Sub-micro	Whole class	Gesture; voice embodied
	States of Matter	BAPs: chocolate bar story Student-centred Devised	Sub-micro	Groups of 5	Sight; body; gesture; facial; expression; spatial positioning; imagination; voice
	Magnesium combustion	BAPs Student-centred	Sub-micro	Groups of 5	Sight; body; gesture; facial; expression; spatial positioning; imagination;
3 (7.0)					
	Atom	Demonstration BAPs	Sub-micro; Symbolic (charges)	Teacher	Sight; imagination; voice
	Atom	Student-centred BAPs Devised	Sub-micro; Symbolic (charges)	Groups of 3	Sight; body; gesture; facial; expression; spatial positioning; imagination; voice
	Roomful of hydrogen atoms	BAPs	Sub-micro; Symbolic (charges)	Groups of 3;Whole class	Sight; body; gesture; facial; expression;

					spatial positioning; imagination;
	Make the largest atom	Student-centred BAPs Devised	Sub-micro; Symbolic (charges)	Whole class	Sight; body; gesture; facial; expression; spatial positioning; imagination;
	ionisation	Teacher led BAPs	Sub-micro	Whole class	Sight; body; gesture; facial; expression; spatial positioning; imagination;
	Point of ionisation	Student-centred BAPs Improvised	Sub-micro	In pairs	Sight; body; gesture; facial; expression; spatial positioning; imagination;
	ionisation	Student-centred HAMs Devised	Sub-micro	Groups of 4	Sight; body; gesture; facial; expression; spatial positioning; imagination;
4 (8.0)					
	States of Matter	demonstration GTM	Sub-micro	Teacher	Gesture; voice
	States of Matter	Student-centred GTM Improvised	Sub-micro	Whole class	Gesture
	States of Matter	Chocolate Bar Student-centred Devised	Sub-micro	Groups of 5	Sight; body; gesture; facial; expression; spatial positioning; imagination;
	Diffusion	Spy’s Perfume Student-centred Devised	Sub-micro	Groups of 5	Sight; body; gesture; facial; expression; spatial

					positioning; imagination;
	Dissolving	Student-centred GTM Devised	Sub-micro	Groups of 5	Gesture
5 (9.0)					
	States of Matter	Demonstration GTM	Sub-micro	Teacher	Gesture; voice
	States of Matter	Student-centred GTM Improvised	Sub-micro	Whole class	Gesture; sight
	States of Matter	Student-centred demo BAPs	Sub-micro	group of 4	Sight; body; gesture; facial; expression; spatial positioning; imagination;
	States of Matter	Chocolate Bar Student-centred Devised	Sub-micro	Groups of 5	Sight; body; gesture; facial; expression; spatial positioning; imagination;
	Diffusion	Spy's Perfume Student-centred Devised	Sub-micro	Groups of 5	Sight; body; gesture; facial; expression; spatial positioning; imagination;
	Dissolving	Student-centred HAM Devised	Sub-micro	Groups of 5	Sight; body; gesture; facial; expression; spatial positioning; imagination;
6 (10.0)					
	States of Matter	demonstration GTM	Sub-micro	Teacher	Gesture; voice
	States of Matter	Student-centred GTM Improvised	Sub-micro	Whole class	Gesture; voice
	States of	Chocolate Bar	Sub-micro	Groups of 6	Sight; body;

	Matter	Student-centred Devised			gesture; facial; expression; spatial positioning; imagination
	Balloon	Teacher led	Sub-micro	Whole class	Sight; body; gesture; facial; expression; spatial positioning; imagination
	Diffusion	Spy's Perfume Student-centred devised	Sub-micro	Groups of 12	Sight; body; gesture; facial; expression; spatial positioning; imagination; voice
7 (11.0)					
	Atom	demonstration BAPs	Sub-micro; Symbolic (charges)	Teacher	Sight, gesture; voice
	Atom	Student-centred BAPs	Sub-micro; Symbolic (charges)	Groups of 3	Sight; body; gesture; facial; expression; spatial positioning; imagination; voice
	Roomful of H atoms	Teacher led BAPs demonstration	Sub-micro	Groups of 3	Sight; body; gesture; facial; expression; spatial positioning; imagination;
	H Molecule	Student-centred BAPs	Sub-micro	Groups of 3; Whole class	Sight; body; gesture; facial; expression; spatial positioning; imagination;

	Balancing Water Equation	Teacher led activity BAPs	Sub-micro; symbolic	Whole class	Sight; body; gesture; facial; expression; spatial positioning; imagination; voice
	Balancing Water Equation	Student-centred BAPs	Sub-micro; symbolic	Whole class	
8 (12.0)					
	Water Molecule	BAPs	Sub-micro Symbolic	Teacher	Sight, gesture; voice
	Water Molecule	BAPs	Sub-micro symbolic	Teacher	Sight, gesture; voice
	Dipole Charged molecule	BAPs	Sub-micro symbolic	Whole class	Gesture; voice
	Dipole arrangement	BAPs	Sub-micro symbolic	Whole class	Sight; body; gesture; facial; expression; spatial positioning; imagination
	Solvent; Solute configuration	BAPs	Sub-micro symbolic	Groups of 5	Sight; body; gesture; facial; expression; spatial positioning; imagination; voice
	Dissolving	BAPs	Sub-micro	Group of 5	Sight; body; gesture; facial; expression; spatial positioning; imagination; voice
	Dissolving Sugar in cold water	HAMs	Sub-micro	Groups of 6	Sight; body; gesture; facial; expression; spatial

					positioning; imagination; voice
	Dissolving Sugar in hot water	HAMs	Sub-micro	Groups of 6	Sight; body; gesture; facial; expression; spatial positioning; imagination; voice
	Dissolving gas in cold water	BAPs	Sub-micro	Whole class	Sight; body; gesture; facial; expression; spatial positioning; imagination; voice
	Dissolving gas in hot water	BAPs	Sub-micro	Whole class	Sight; body; gesture; facial; expression; spatial positioning; imagination; voice

4.4 Rationale for the Warm-ups

In my experience in teaching physical simulations, and in teaching Drama, if the intervention tasks are introduced too boldly, then students can feel vulnerable. Also, it has been my experience as a teacher that students who have used drama-based activities show an increase in the subtlety and confidence with which they work together. In order to provide a proxy for regular classroom engagement in physical simulations, the interventions included ‘warm-ups’ in order for students to gain initial confidence and comfort with these activities.

4.4a Description of warm-up tasks

All cases received the same warm-up tasks, lasting approximately fifteen minutes in total (Table 4.2b). In each case the classes were divided into two half-class groups.

Students stayed in these groups for four activities. They received minimal instruction in order to maintain a sense of pace and to engender students' reliance on their own interpretations.

Students were initially asked to stand in their groups, in a circle. The first warm-up (create a square) required students to make no noise during the task, and to 'Create a square in any way you wish'. This first task aimed to provide a low cognitive challenge, working on the assumption that many students had already stood in a square previously at some point in their school careers. Butler (1989) has argued that there is a social risk involved in drama in Science, that confidence should be built with initial tasks that should 'require hardly any role taking skills' (p.572). In this context, the task focus was upon students' ability to negotiate the model and gain comfort with the group and the method, it was not focused on individual role-taking. I asked them to consider who was leading and who was supporting, and advise them to do both. As with all the tasks, students were asked to raise their hands when they believed that they were finished.

The second warm-up (create a star), followed similar instructions. This task was assumed to increase the cognitive challenge, and aimed to support motivation by introducing a sense of creativity, in that the concept of a star tended to inspire several different group expressions in the pilot studies. In these first two activities, my role was to support students with positive language and promote a sense of community, and also to describe out loud the mental and negotiation processes involved.

In the third warm-up (create a sofa), the students were asked to make explicit the ways in which gesture, levels etc. produced meaning. Whereas I alone described the groups' models previously, now I invited one group to evaluate the other, which stayed in tableau, then vice versa. The final warm-up also used this forum evaluation process. The task was to produce a previously unimagined concept (it was assumed). The aim was to have students engage in a similar process to a group thought experiment, albeit without the cognitive challenge of requiring curriculum science knowledge.

Table 4.2b
A description of the warm-up tasks including the concurrent evaluation sessions

	Instructions	Duration	Evaluation	Objectives
Create a square	Begin, standing in a circle. No noise 'Create a square in any way you wish'	One minute	Teacher evaluation of one group while the other looks on	Initiate group negotiation skills; Introduce non verbal communication; Initiate familiarity with the method
Create a star	Begin standing in a circle. No noise 'Create a star in any way you wish'	One minute	Teacher evaluation of one group in tableau while the other group looks on	As above and: Initiate creativity; Introduce metacognitive talk
Create a sofa	No noise 'Create a sofa'	One minute	Teacher and student evaluation of one group in tableau and then the next group	As above and: Apply terms of space, levels, gesture, and body language to describe construction of meaning
Create the world's most uncomfortable sofa	No noise 'Create the world's most uncomfortable sofa'	One minute	Teacher and student evaluation of one group in tableau and then the next group	As above and: Develop group expression of an abstract concept, similar to a TE-type visualisation

4.5 Data Collection

Data was collected at four stages over a four month period (Table 4.3). Three of these stages focused upon interview data, with a sample of three students from each case (and a post interview with their teacher). Interviews were semi-structured and included a range of devices to elicit student expressions of the topic concepts. Data from the intervention included participant observation, teacher observation (explored through stimulated recall in the post interviews with the teachers), and video of the lessons.

Table 4.3
Case Data Collection

	Pre interview	Intervention	Post interview	Delayed post interview (at 4 months)
Intervention		(approx)1hr 15min lesson; Either KS3 or KS4 particle theory - curriculum topic		
Data Collection Method	Semi-structured interviews for students and teacher (30min each)	Participant observation (researcher); two video recordings of the lesson observation of lesson by the class teacher	Semi-structured interviews for teacher and students (40min each)	Semi-structured interviews for students (30min)
Rationale for data collection methods	Provided a baseline context for student understanding	Data collection provided multiple perspectives through which to explore descriptions of interaction.	Highlighted key behaviour and student expressions during the intervention; compared students post concepts with baseline data	Explored features of students' delayed conceptions; enabled comparison of base and post interviews
Principal research questions covered	RQ2, RQ3	RQ1	RQ1, RQ2	RQ3
Specific resources	Concept maps; drawings	Three video recorders per class	Concept maps; drawings; stimulated recall	Concept maps; drawings

4.5a Pre-intervention data collection

Pre-intervention data collection aimed to provide a baseline for students' conceptions of the topic for comparison with data from later collection stages, in order to provide evidence for RQ2 and RQ3, related to short and longer-term conceptual development.

The data also informed the design of the lessons, providing an indication of the students' cognitive levels, their previous experience of the topic, their personalities, their perceptions of classroom management and their normal group work configurations. Along with school documentation, and informal discussions and emails with the teacher, the data collection consisted primarily of:

- A teacher discussion
- Three student interviews

4.5a.i Teacher discussions

The cases began with a series of informal discussions with the classroom teachers, who described their curriculum topic objectives, their assessment of student ability and suggested students for the interview sample. The teachers described the context of the everyday classroom environment, including the social dynamic within the class, and noted whether, as a class, they had used drama in Science previously.

4.5a.ii Student interviews

The students were interviewed separately. Each student interview lasted approximately thirty minutes. When time allowed, this was extended up to forty-five minutes. Students were invited to generate concept maps and drawings in order to stimulate discussion and focus the interviews (§4.6). Each interview was semi-structured, consisting of a set of open questions, which allowed me to move away from the text at any time to probe for more detail. While flexible, semi-structured interviews have been argued to provide a systematic framework which makes pattern-matching in analysis easier than with a more unstructured interview design (Cohen, Manion et al., 2000). Exemplar interviews from each stage can be found in Appendices 3-7 (see Appendices 9-11 for interview schedules).

4.5b Intervention

The data collection during the intervention consisted of:

- Participant observation
- Video recording
- Expert naturalistic observation

4.5b.i Participant observation

As the instructor within the interventions, my perspective provided a unique view of the students' interaction (RQ1) and of their developing conceptions (RQ2), through continuous formative assessment as a teacher. I provided a second 'expert' perspective with which to juxtapose the classroom teachers' observations, and also to provide a contrast between my *active* and their *privileged* observational viewpoints (Wolcott, 1997, p.160). I aimed to capture my perspective through naturalistic, participant observations which I wrote after each lesson. These observations were also useful in highlighting interesting episodes which would inform my questions in post interviews, specifically in guiding my choice of video episodes for viewing during stimulated recall episodes in the post interviews.

4.5b.ii Video data

Informed by multimodal methodology, the study design employed video in order to aid analysis of students' behaviour during the intervention (RQ1), and suggest ways in which they were beginning to perceive the topic concepts during the intervention (RQ2). Video data was employed in order to provide a detailed script of verbal and non verbal events (Franks and Jewitt, 2001, p.206). Three cameras were positioned within the classrooms in order to provide three different perspectives. This number was also intended to provide redundancy, if cameras failed.

4.5c Post intervention

The post intervention data collection aimed to elicit participant perspectives which would support analysis of student behaviour (RQ1) during the intervention. The data also aimed to elicit evidence of some students' resultant conceptions (RQ2), by comparing their responses to baseline, pre-interview data, and to provide a comparison with the delayed intervention data (RQ3). In this stage, data collection began within a few days of each intervention, although this differed across cases due to student availability (see Limitations, §4.11). The data included:

- Three student interviews
- One teacher interview

The initial sample of three students were again interviewed individually, and similar to pre-interview protocol, asked to create concepts map and drawings of the topic concepts (§4.6b). This post intervention interview also included a focused interview approach, which elicited 'subjective responses to a known situation' (Cohen et al., 2000, p.273). The focused interview was used previously (Dorion, 2007, p.36), when it had proved to be useful in guiding the analysis in new directions. For example, during the Masters study, both a teacher and her students argued that they *controlled* the learning within one activity; a contrast that led me to be sensitive within interviews to other examples of ‘control over learning’, which subsequently shaped the findings (Dorion, 2007, pp.73-75).

4.5c.i Teacher post intervention interviews

The classroom teachers observed the interventions in order to provide their unique expert points of view of the students’ behaviour, which they contextualised in respect to the students’ personalities and abilities (RQ1). Each teacher participated in a focused interview of thirty to forty-five minutes. Protocol included stimulated recall episodes (§4.6d) in which teachers watched videos of the lessons and informed their responses with their own ‘experiential understanding’ (Stake, 1996). An example of a teacher interview is provided in Appendix 8 (see Appendix 12 for the teacher interview schedule).

4.5d Delayed data collection

The delayed data collection aimed to provide evidence for RQ3, which sought to identify affordances for longer-term conceptual development. It did so by returning to the three student interviewees, to elicit their recall of the topic concepts and the scope for application of these concepts to new problems. This final set of interviews was conducted at four months. Each used a semi-structured design that was similar to the post intervention interviews, but with no stimulated recall (see Appendix 11). This provided further longitudinal data for an interpretation of the utility and durability of students’ emergent conceptions over the medium term.

4.5e Interview recordings

All interviews were taped. This approach aimed to provide, 'an accurate chronicle of the verbal component of the interview' (Goldman-Segal, 1998, p.67), which was required for creating valid transcriptions for CAQDAS (Atlas.ti) coding, and increase the ease of reviewing the interviews during subsequent analysis.

4.6 Interview Resources

4.6a Magic goggles

In the Key Stage 3 interviews, in an effort to begin without biasing the students' responses, such as increasing their tendency to focus on the particulate nature of matter, I avoided the use of particle terms by introducing a heuristic employed by Novick and Nussbaum (1982) to explore students' conceptions of sub-micro level phenomena. Students were asked to pretend that they were wearing 'Magic Goggles', which would allow them to view the world at a higher magnification than any microscope. I then pointed to a table (solid), then to water in a glass (liquid), and then raised my hands above my head and mimed a sphere (gas), and each time asked what students saw with their goggles in those spaces. These questions preceded the show cards (see below), in order to elicit students' understanding before the possible biasing effect of the show card terms. An example of the Magic Goggles section of an interview can be found at the start of Appendix 3.

4.6b Show cards and concept maps

While investigating students' conceptual understanding for RQ2 and RQ3, I began the interviews with open questions, and then provided some focus on the topic concept through the introduction of nine terms related to that topic (Figure 4.5). The format was adapted from Wellington and Osborne (2001), whose students were initially given a set of words ‘written on small boxes of paper’ (p.85). Students were expected to link the terms into the *semantic net* of a concept map. As in traditional concept mapping, the students were to accompany the lines with prepositional phrases that were written down on or near the lines (2001; Coffey et al., 2003).

Atom	Solubility	Saturated
Water Molecule	Insoluble	Solvent
Solute	Solution	Particle Theory

Figure 4.5 Dissolving (KS4) concept map terms (source: case 8)

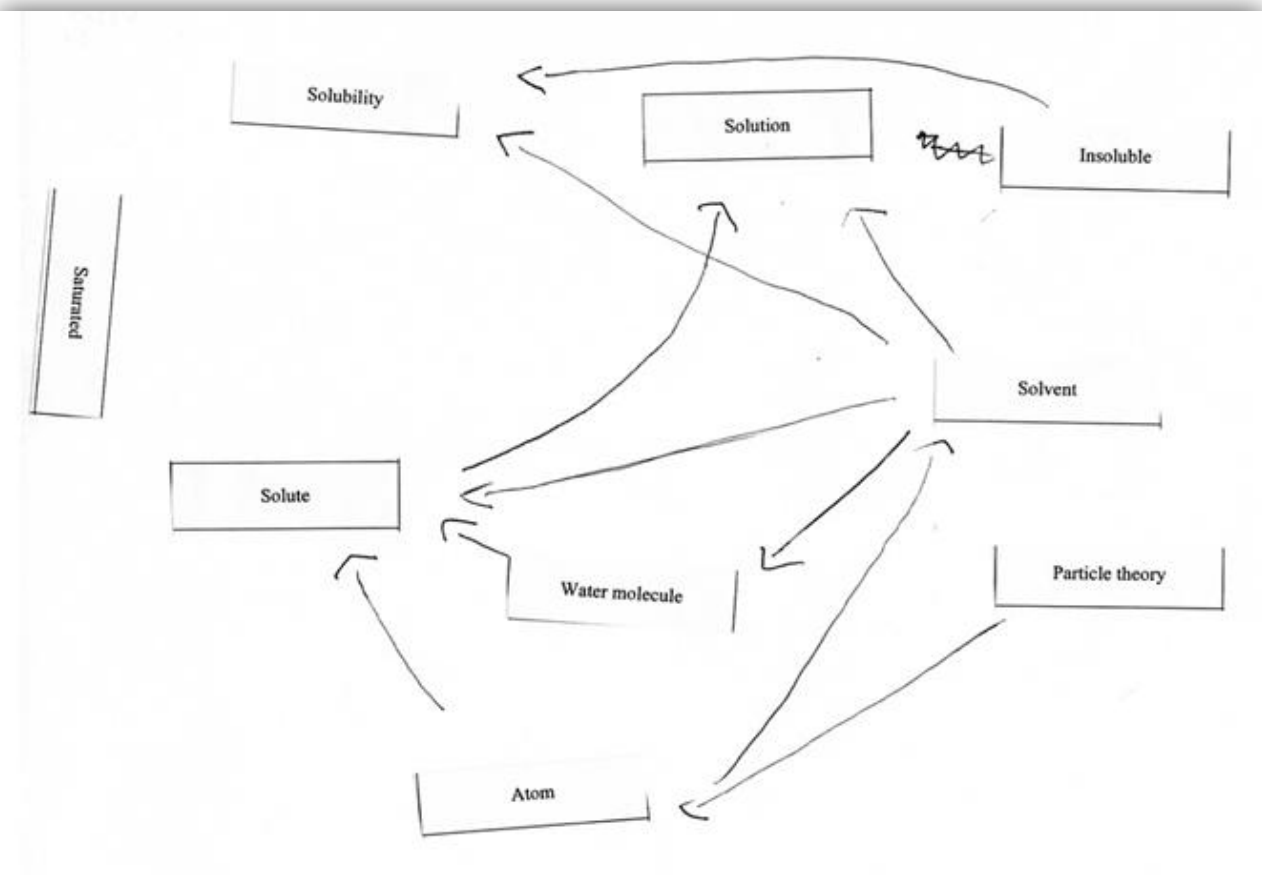

Figure 4.6 Dissolving (KS4) pre-interview concept map (source: Kay in case 8, pre-interview). N.B. the student has left the 'saturated' term to the side, which provided a suggestion that at that time she could not incorporate the term into the conceptual framework for dissolving.

Based on the pilot study, I added an extra level of inquiry. After giving the students the terms, I asked them to quickly define those words that they knew, and to push aside those that they did not feel that they understood (Figure 4.6). This provided an early indication of students' understanding of the terms, and hopefully reduced any feelings of stress. Next, the students placed the terms on a piece of paper and drew lines to connect the terms (I subsequently glued the terms down on the paper). I asked them to justify the links to themselves as they created their maps.

In an effort to save time, and to use the maps as an aid to discussion, I did not ask students to write prepositional phrases on the concept maps, but to describe the links out loud during our subsequent conversation (An example of a concept map and the corresponding interview section can be found in Appendix 2). At the end of the mapping session I asked students if they could define the terms that they initially excluded, based on the assumption that the concept mapping may have reminded them of more tentatively held knowledge in relation to the topic concept.

4.6c Drawing

Student drawings (Figure 4.7) have been used extensively to elicit ideas of the sub-microscopic world (Stains & Talanquer, 2007, p.649). Informed by multimodal theory, a central aim was to use the drawings to stimulate discourse and provide student expressions across different modes in order to elicit students' developing understanding of the topic concepts over the interview stages, and therefore support analysis for RQ2 and RQ3. Pilot study interviews revealed that verbal and drawn descriptions could complement or conflict with one another, and therefore highlight issues of interest.

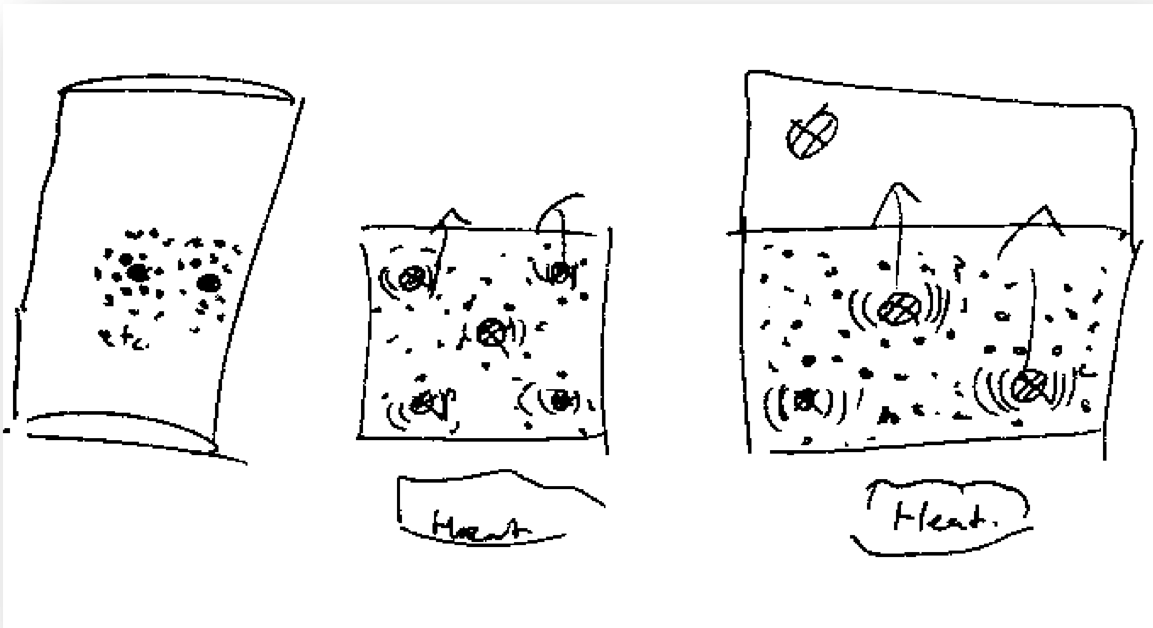

Figure 4.7 Example of a drawing. The page should be read as three separate frames signifying a before, middle, and after image of carbon dioxide and water (in a can of cola) that is being

progressively heated. The student has not been given instruction as to how to portray the system. The discussion related to this drawing can be found in Appendix 2.

4.6d Stimulated recall

Stimulated recall was employed to answer RQ1. It was used with both teachers and the student interviewees in post intervention interviews in order to help contextualise student interaction during the intervention. It aimed to elicit their recall of their cognitive and affective thought, and promote discussion of how the relationships between participants affected the learning environment. In this aim, it added a social and emotional aspect to a technique that Lyle described in which, 'videotaped passages of behaviour are replayed to individuals to stimulate recall of their concurrent cognitive activity [during the videotaped episode]' (2003). Each stimulated recall episode focused upon an incident which initial analysis (informed by participant observation notes (§4.5b.i)) suggested had potential value to the study.

4.7 Interview Collection Duration

In total, twenty-four students were interviewed three times each (Table 4.4). Eight teachers provided data through informal conversations and email, with one formal, post intervention interview each. The following table describes the approximate duration of the interviews, the intervention lessons, and their combined totals, both for individual cases and the whole study.

Table 4.4
Interview Durations

Stage	Teacher (minutes)	Each student (minutes)	Total per Case (minutes)	Total for the study (minutes)
Pre test		30	90	**720**
Post test	40	40	160	**1280**
Delayed post test		30	90	**720**
Total time	40 (and informal conversations)	100	340 (7hrs) **10 interviews per case**	**2720 (45.3 hrs)** 80 interviews in total

4.8 Analysis

Analysis occurred at case and cross-case levels. Eight individual case analyses were done before the multiple case analysis. Each case was treated as an idiographic, bounded study, as advised by Stake (2006). The analysis began with a series of initial themes identified within the literature review (Figure 4.8). These themes provided an initial focus which helped to draw out data that resonated with the themes. New connections generated new themes. Stake noted that during this analysis process, the researcher becomes attuned to themes which are either subtle or submerged in the data (2006). These new themes emphasized different features in the data, which were then triangulated with previous data. The strongest patterns or differences then became the case findings. These were presented in Case Reports (§4.8c).

Following Stake, the individual case analyses allowed one to spend time with, and continually return to, 'rich data' by reciprocally informing themes through newly discovered factors and vice versa. In this context, the research questions and design reflected what Stebbins has termed *investigative exploration*, by which an inductive approach is predominant within a flexible methodology and open-minded theoretical standpoint (2001, p.2).

Initial Themes (section)	Emergent themes (section)
Anthropomorphism (3.1)	Anchor metaphors (7.3b)
Visualisation (3.2)	GTM (10.3b)
Multimodal expression (3.3b)	Socio-affective features (8.2g)
Discourse (3.4)	Self-regulation (10.2g)
Concept utility (3.5)	Attraction (12.2.f)
	Metacognition (11.2b)
	Pretend Objects (7.3a)

Figure 4.8 Initial and Emergent Case Analysis Themes (and Example Sections)

4.8a Coding for specific research questions

Analysis for my first research question (RQ1) focused on video, participant observations and the transcripts of the post and delayed interviews. Analysis started immediately after the first intervention, when scenes were identified for stimulated recall episodes. Primary sources for coding for question RQ1 included video-based multimodal analysis observations (4.8b), transcripts of the post intervention interviews, and participant observation notes (see Appendix 14 for a coding example).

Analysis for research questions RQ2 and RQ3 included the data sources above and also the delayed interviews. The codes were cross-referenced during analysis in two ways: First, as cross-sectional data, with triangulation across a single stage; for example, comparing participant responses within the post interviews. Second, data was analysed within a time series, comparing data across all four interview stages.

4.8b Video analysis

Video of the intervention lessons provided a key data source for the analysis of action, as an indication of students' thought-processes during the interventions, following the assumption that, 'There is a direct, reciprocal and developmental relation between activity in the realm of physical social interaction and the realm of the inner mental activity of individuals' (Franks & Jewitt, 2001, p.202). Close observation of specific incidences of multimodal interaction, Jewitt has argued (2008), can provide insight into students' understanding of a topic. Video analysis therefore consisted of interpreting and describing the modalities through which meaning was expressed by the student. My use of video was informed by Jewitt's 2008 methodology (§3.3b), and also by Franks and Jewitt's systematic process of videotape viewing, 'with image only, with sound only, and with both image and sound' and across action, speech and visual modes (2001, p.206). During this process, I identified key episodes of interest based upon my experience as a teacher and researcher. I then wrote observational descriptions of the episodes (for example, see Appendix 13). I subsequently categorised the discourse (§4.8c), speculated (§3.3b) upon the potential analogical/conceptual meanings that students' actions suggested, and interpreted the key modalities of communication using Kress and Leeuwen's taxonomy of internal and external sensations (§3.3a). The resultant video analyses were then used in triangulation with teacher and student interviews in order to explore how patterns in behaviour may have impacted upon students' developing conceptions.

4.8c Analysing discourse

Attempts were made in the pilot and initial cases to record individual students, and to set camcorders near groups in order to record dialogue. However, while teacher-directed activities were clearly audible on tape, the nature of dynamic group work, and the noise and movement of students throughout the room, meant that one often could not clearly follow individual voices within multiple student discussions. Observations, multimodal video analysis, and interviews subsequently became key sources for exploring discourse during group work.

In some situations I was able to explore discourse within the interventions through an approach adopted from Mortimer and Scott (2003) called *The Communicative Approach* (CA) which I had used previously, and found to provide a useful delineation of dialogic and non-dialogic activity in lessons. This analysis tool assumes that that classroom discourse may promote one dominant viewpoint (authoritative), or it may be that there is a range of ideas, with no dominant voice (dialogic). These two extremes are paired with categories in which either only the teacher speaks as in a lecture (non-interactive) or in which there is a high degree of participation (interactive)[6]. The result is a matrix of potential discursive formats (Table 4.5). According to Scott, Mortimer and Aguiar (2006), the CA has been replicated and been found to be useful according to Gee's criteria for effective discourse analysis (1999, p.629).

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[6] Discourse is described by Scott more specifically through Bahktin's concept of 'interanimation' (Bahktin, 1981, cited in Scott & Mortimer, 2005, p.397), which implies a multi-voice exploration of ideas in which no single voice is authoritative.

Table 4.5
The communicative approach (Source Scott, Mortimer & Aguiar, 2006)

	Interactive	Non Interactive
Dialogic	Interactive/ Dialogic	Non-interactive/ Dialogic
Authoritative	Interactive/ Authoritative	Non-interactive/ Authoritative

In Chapter 9.0, due to the whole class nature of the balancing equation tasks, the clarity of discourse on the video was such that it could be clearly transcribed in detail (see Appendix 8). These two tasks aimed to solve similar problems with the same drama-based approach, but in which one was teacher-led and the other was student-centred. This provided the opportunity to explore dialogic and non-dialogic discourse (identified through initial analysis with the CA) at a finer grain level. The activities were further analysed with respect to Mercer's features of traditional classroom talk (2000) and Alexander's criteria for dialogic discourse (2006). These lenses afforded the opportunity to juxtapose different classifications of discourse with an aim to allow new theory to emerge from the data. The classifications and criteria are described in greater detail within the case report itself (§§11.2e.i-11.2e.ii).

4.8d Case reports

The process of case report writing provided a stage for reflection on themes, patterns and disparities which were emerging in the overall study. Since there was only one researcher who analysed all of the cases, the early case analyses inevitably informed later case analyses. This was assumed to aid sensitivity to the data and analysis: whereby the themes remained under consideration and reconsideration for over two years. The case reports are presented in chronological order. Cases have been semi-structured to make inter-case referencing easier. All included a brief comparison of pre and post (incl. delayed) analysis findings, and a concluding section which aimed to summarise case findings with respect to the wider literature.

4.8e Cross-case analysis

The multiple case analysis employed triangulation of findings across cases in order to identify patterns and differences: key findings were highlighted in respect to their frequency, exception, or illustration of the themes, with the intent of making some generalisations beyond the cases (Stake, 2006, pp.39-41). As in Stake's multiple case approach, this study cross-referenced findings with themes.[7] The most robust, or exceptional findings from this process were cross-referenced with the research questions RQ1, RQ2 and RQ3.

4.8e.i Cross-case analysis of anthropomorphic discourse

In an effort to explore the relationship between the anthropomorphic analogies employed within the interventions and the interviewees' resultant conceptions, the multiple-case findings included an analysis of anthropomorphic utterances across all interview stages. Anthropomorphic utterances were identified and categorized according to a classification theorised by Taber and Watts (1996). They presented a dichotomy of *strong* and *weak* anthropomorphisms. In this classification, strong anthropomorphisms were those which provided teleological explanations for processes, and tended to promote tenacious alternative conceptions. Weak versions tended to be descriptive, and promoted more labile conceptions. The results of the analysis are presented at the start of the multiple case findings chapter (§11.0).

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[7] Stake also advised the use of Factors (universal themes) and Assertions (findings, 1996, p.42 or emphasised findings 2006, p.50). However, these operate as extra support for large, multi-researcher ethnographic studies reflecting societal issues and large data collections, which must ultimately be filtered into single reports.

4.9 Ethical Issues

The study followed the British Education Research Association guidelines (BERA, 2004). Permission to enter schools was given by the Head Teachers, and permission to film was either gained through letters to parents via the school, or given in respect to whole school policies on filming. Students were asked to take part in the activities. All students agreed to participate. Participants' rights of anonymity and confidentiality have been maintained, with data kept in a locked facility in the Faculty of Education when not actively used by the researcher. Photos have been modified to obscure participants' identities.

The nature of the study did not draw major ethical dilemmas for the researcher, although in some situations, teachers' comments taken out of context may have been hurtful to students, and one student was observed on video to engage in behaviour that may have proved mildly embarrassing. I have followed BERA advice to omit such comments and observations from published material out of an 'ethic of respect for the person' (BERA, 2004, p.5).

4.10 Pilot Study

Preparation included two pilot studies. The first occurred in a double lesson in Science with a class of twenty-four, 10-11 year olds in an independent school in Cambridgeshire. A second intervention was used with a second class of twenty-three students aged 10-11 in the same school. All students were taking the Common Entrance Exam. In discussions with the teacher of both classes, it was apparent that the students were working within a Key Stage 3 level of understanding within the curriculum, and this was indicated in students' ability within interventions themselves. The intervention topics were similar to that in sections 3, 4, 6, and 7. It focused on the topics of states of matter, diffusion and dissolving. The pilot study groups were mixed gender and mixed ability.

I had the opportunity to run a third pilot in a Canadian ‘state’ school for twenty-six students aged 12-13, running an intervention upon the same topic as previously. The group was mixed gender and mixed ability. The topic was the same as the previous pilot studies. It was during the interviews for this study that I first considered the utility of students’ gestural metaphors, and of employing a gestural teaching metaphor (GTM) in the intervention.

4.11 Research issues and limitations

In a perfect world, I would have preferred the students in the interventions to be more familiar with cross-curricular drama, since an aim of the research programme was to investigate these activities as a regular classroom resource. However, I deemed it impractical, with my resources, to sample for Chemistry teachers who regularly used drama-based activities, and who used these to teach particle theory at KS3/KS4, and then train them to employ the pedagogical model. Methods for overcoming this issue were discussed in sections 4.3b and 4.4.

The timing of post intervention interviews was variable, due to students’ schedules. Interviews tended to occur the following day, but also up to a week later for two students, due to a snowstorm on the day of one interview, and illness in the day of the other. This variation may have affected differences in students’ recall of concepts. It is hoped that triangulation would mitigate this issue.

It was not until the fourth case study that I began to provide evidence of students' gestures in the interviews by describing their gestures out loud. This may have changed the nature of the interviews to a degree, and with one student (Amelia, §9.0) she stopped using her gestures at one point during a post interview.

These lessons were developed in a bespoke manner, informed by the teachers' descriptions of their schemes of work, and their teaching objectives. In the two cases in which ionisation was taught, I employed the teachers' models, which tended to focus upon an electron transfer approach. While the language of electron transfer can be found in exams as recently as two years ago (Edexcel, 2009), it is not now the present UK curriculum guidance. While this may not be an issue over the four months duration of the studies, during which students were not exposed to further curriculum models, it may be of consideration with findings of any potential follow-up studies with these students.

4.12 Notes on referencing of transcripts and observations

When interviews and observations are referenced within the case reports, they will be followed by a reference code. The case reports incorporate a referencing system which reduces the repetition of the terms, *teacher interview, student pre-interview, student post-interview, student delayed-interview, video, and participant observation notes*. The following codes reference the relevant case study transcript from that section and identify the participant speaking:

Table 4.6 Case codes

Reference	Code
If the interview stage (pre, post, delayed) has been made clear in the preceding text then the referencing code will identify the speaker	
Teacher interview	**T**
First Student interview	**S1**
Second Student interview	**S2**
Third Student interview	**S3**
If the interview stage is ambiguous then the code above will be followed by a phase description	
Pre-interview	**Pre**
Post-interview	**Post**
Delayed-interview	**Del**
Observations, camcorder identifiers and time of video are identified with the codes below	
Observation	**Obs**
Video	**V# (time)**
Reference to sections outside a case report will use case and section codes	
See the research questions in the methodology section	**§4.1a**

Some transcription lines have been numbered to aid referencing from the surrounding analysis

5.0

Case 1: Anthropomorphic Bridges, and Exuberance

> 'Because of that little technique there, with the deuterium atom with only one electron, proton and neutron; I think that would have, I believe that would have helped. It is so graphic, it's so clear, you know, you have got the spacing all sorted out, and the people, you know, going, little people going around the outside kind of thing.' (T)

5.1 Case Description

This case took place at a state comprehensive boarding school in Hertfordshire, with a Year 9 mixed gender group of twenty-six students. Assessed to be highly academic (T), the students were working within the Key Stage 4 curriculum. The teacher had used role-play during the previous school year, in particular during a demonstration of a Geiger-Marsden experiment. The classroom was a modern lab with moveable worktables which had been placed at the front of the classroom (Figure 5.1, §5.6). This left the back half of the classroom clear except for two pillars and two immoveable square tables. The 1hour, 15 minute interventions took place one morning during the Lent term.

5.1a Teaching objectives

- Review atomic structure
- Introduce the terms *ions*, *ionic bonding*, and *displacement reactions*
- Develop sub-micro level visualisations of ionisation and displacement reactions

5.1b Lesson description

The lesson began with an interactive/authoritative (§4.8c) discussion on the use of models to describe atomic and molecular systems. Students then engaged in the four warm-up tasks (§4.4a.i). The topic-related tasks began with a teacher-demonstrated dynamic model of an ideal atom. Following this, students in groups of three created their own ideal atom models (Figure 5.1; 5.2). After a teacher evaluation of the models, students were told to remain with their individual roles but to silently, as a whole class, create the largest atom they could (Fluorine). I directed the electron-actors into 'shells', and then introduced a 'pretend object', an imagined potassium atom of the same size as their model. In-role as the electron on the outer shell, I illustrated the attraction by moving towards the nucleus of the halogen. As I did so, I directed the students to call out in unison, 'halogen, halogen…halide' as I moved towards the outer shell of the fluorine atom. Next followed a brief ad hoc demonstration of a drama technique to show how proximity and movement may be used to convey force over a distance. The final task aimed to promote a TE-type group visualisation of a displacement reaction between a halogen and alkali metal. Four groups produced human analogy model simulations (HAMs) related to the question: What happens when chlorine is added to a solution of potassium bromide? Fifteen minutes were allowed to the students to prepare their simulations for performance to the class. Afterwards, one group performed their model while the class engaged in a forum evaluation, followed by a review of the lesson.

5.2 Analysis

5.2a Pre-interviews

Pre-interview responses suggested a wide range of conceptions of the atom. One student, Genny, described it as, 'like the solar system, like that but like kind of twisted-ish' (S3). A second student, Kelvin, described a Bohr-like shell structure:

> Well, there would be the nucleus, with protons and neutrons... And you would see the shells with the electrons around it. (S2)

A third student, Ani, seemed to be aware that atoms must be translated into a visual representation:

> Well, you can't actually see atoms but you ... you can use, like light or, how they, I can't really explain it, like the way they behave, and what they look like and stuff we can see. (S1)

These comments suggested that the students could describe sub-micro level representations, and that Ani might be able to apply a metavisual context when thinking about atoms. All three students could describe atoms as having charged particles, and asserted that these particles were involved in attraction. For example, Genny and Kelvin described ‘magnet’ analogies in which, as Genny noted, the ‘the positive [particles] attract the negative ones’ (S3). Ani used the term ‘bond’ (S1), which she described as two elements ‘stick[ing]’ together in a compound. Although they were therefore aware of attraction, and the role of charged particles in this interaction, none of the students could provide a clear description of how that related to reactivity. Kelvin asserted vaguely that, ‘reactivity; that is when something is more or less reactive with something else, [and that] it might be, if X is a chemical in this reaction it might react with something’ (S2). Ani’s response focussed upon describing the conditions for reactivity as relating to the outer shell configuration,

> … the amount of the electrons in the outer shells affect the reactivity. So like

> the noble gases in the outer shell is full. (S1)

None of the students defined *ion*; Genny and Ani left the term out of the concept maps that they had drawn during the interviews. Ani was the one student to describe the term *displacement reaction*,

> And displacement reaction is a reaction where, for example, you have got a compound and then when you react it with another element, then if that element is more reactive then it will gain, the, they kind of like battle with the other elements, and will displace that element out and make a compound. (S1pre)

Ani described the displacement reaction as the pushing out of one element in a partnership in order to make a new partnership. Although she employed the terms ‘element’ and ‘compound’, the mechanism for the reaction was unstated, but seemed to rely upon the chemist, ‘you’, or an intention on the part of the elements to do ‘battle’. This vagueness suggested lack of a clear visualisation of the interaction of constituent units. This was echoed in Genny’s efforts at drawing a displacement reaction, when she noted of her drawing that when chlorine was added to a solution of potassium bromide,

> I was going to, sort of like, trying to draw the chlorine atoms like reacting to the potassium bromide. Um, I think maybe, I'm not too sure how but, like maybe show them, I don`t know. (S3pre)

5.2b Post interviews

Post interviews revealed an increased tendency for the interviewees to use the terms ‘ion’, ‘halide’ and ‘displacement reaction’, and more consistently explain ‘ionisation’. For example, although she could not define ions previously, Genny now viewed these as charged *atoms*: ‘An ion is like a group of atoms with an overall charge’. Kelvin similarly described ‘ion’ as an ‘atom with the charge, positive or negative’ (S2). He also initiated the use of ‘halide’, a term not previously used in the pre interviews,

> *So why is this bromide called bromide, and not bromine?*
>
> Because it's a halide, because it's become an ion. (S2)

One of the characteristics of the post interviews was the students’ explanations were longer in relation to the pre-interview explanations of the ionisation and displacement processes. This was illustrated by Genny, who, in contrast to the pre-interview in which she could not conceive of how to draw ionisation at the sub-micro level, could now engage in a more extended discussion of ionisation and displacement: Over the course of one-hundred lines we discussed her conception of displacement. The passage below supported an interpretation that throughout the discourse she appeared capable of holding in mind various particles within the reaction (lines 7, 13, and 15), and included charge and its relation to attraction (line 15).

1. Um, you have the potassium solution.
2. *Yeah.*
3. And the bromide, bromine, and if you add them all together --
4. *Okay.*

5. I think, with some water.
6. *So, they have reacted, is what you are saying?*
7. Yes. And then, ahm, and then they`ve got some atoms (sic) in the potassium, and there is an ion there because there is a negative charge.
8. *Okay. Is there a positive charge?*
9. I don't think so, I am not sure. I think the bromine has a positive charge.
10. *You think the bromine has a positive charge.*
11. Yeah, when they are together. I'm not sure.
12. *Okay. We will come back to that.*
13. Oh no, separately I think the potassium and the bromine have, I think the potassium has a negative and the bromine has a positive [charge], but together they are neutral.
14. *Okay. Right, right.*
15. And then, the chlorine comes along. And it has, I think it's something to do with their shells and electrons that lead to a bigger attraction with potassium,
16. …
17. Because there are less shells. And they are attracted to the nucleus.
18. *Okay.*
19. So they would want to go to the element with the less shells, so they could be closer. (S3post)

In this passage, although Genny mis-labelled electrons as ‘atoms’ (line 7), and bromide as a positively charged ion, she seemed to reveal a visual awareness with, ‘the chlorine comes along’, and also suggested a mechanism for reactivity as the distance from an ion’s nucleus to the outer electron shells (lines 17 and 19).

5.2c Anthropomorphic imagery

An analysis of anthropomorphic utterances suggested that these occurred across all interview stages with Ani and Genny, but not with Kelvin (§11.2). Ani and Genny stopped using anthropomorphic descriptions for some conceptions, whereas they began using new anthropomorphic descriptions in later interviews (§11.1) in answer to new prompts not asked in the pre-interviews. The following examples supported an interpretation that Ani's anthropomorphic language in the pre-interview was replaced by more technical language in the post and delayed interviews. For example, in the pre-interview, Ani had used an octet heuristic (Taber, 1995), a teleological explanation for the reactivity of fluorine in relation to the other halogens.

1. [Halogens] have seven electrons in their outer layer.
2. *Okay.*
3. Outer shell, I mean.
4. *Why is that important? If it is important at all? Is it important that there are seven electrons in the outer shell?*
5. Yes, because, like, it makes it more reactive like that, it tends to, it tends to, *it wants to* react with other atoms to gain an electron and like that becomes stable, like the noble gases, which is when it has a full outer shell. (S1pre)

Here, Ani vacillated over her terminology, first in 'outer layer'/'outer shell' (lines 1 and 3) but then after trying out the term, 'tends to' she instead favoured, 'it wants to'; (line 5) in doing so, Ani seemed to have provided an anthropomorphic response, with 'wants to react' within her description of ionic bonding between a halogen and an alkali metal. Within the context of the passage, the anthropomorphism appeared to stand for the mechanism of interaction.

In the post interview, Ani seemed to eschew her previous, anthropomorphic language in favour of more scientific language.

> Because it has an, okay it's, it's, I think it is because it has one, it is *one electron off having a full shell*. So it is easy for an electron (sic) to become stable. And also because it is from the halogens, so it is one that *has less electrons*, so this means that *it has less shells*. So, this means that *it is smaller*, and so there is a bigger *attraction to the outer shell* [for a free electron]. So, there will be a *bigger attraction to the other atom* to react. (S1post)

Ani here presented a series of propositions which illustrated an increased use of consensus terminology, with *full shell*, *less [fewer] electrons*, *less [fewer] shells*, *smaller [shell]*, and *outer shell*, and ‘there is a bigger attraction’. Ani was now focused on the mechanism for interaction: highlighting distance to the nucleus as an indicator of reactivity in halogens, as ‘attraction’ now replaced ‘wants to’. This was more pithily stated later in her post interview:

> *Fabulous, which is the most reactive halogen?*
>
> Fluorine… it is smaller [than the other halogens], and so there is a bigger attraction to the outer shell. So, there will be a bigger attraction then, to the other atom, to react. (S1)

Four months later, and Ani continued to use the scientific terminology described in the post intervention, although some anthropomorphisms had returned. Examples are highlighted in italics (within Ani's responses) below.

1. I had to go down the group of the halogens, as you go down you get less reactive, and because fluorine at the top and it's more reactive than chlorine.
2. *Okay. Any thoughts of why that might be?*
3. Because, because as you go down the atomic number increases. That means that fluorine's has less shells than the chlorine. So when you have to attract negative charge, like an electron to the nuclei, the attraction, from the positive (sic) attraction from the nuclei is less away [to the fluorine electron than it is for the chlorine electron] from the electron that it is *trying to attract*. Distance-wise.
4. *…Okay, and a final question. I am interested here – we have the potassium and the chlorine beside each other and then fluorine is a distance away –*
5. I think it should be nearer to the fluorine, *so that it can steal the electron away.* (S1del)

Ani did not completely eschew anthropomorphic images, in that she said the nucleus was 'trying' to attract, and later, 'steal' an electron (line 3 and line 5). However, earlier within this interview, Ani had clarified that she had said, 'trying to attract' as a synonym for 'opposite charges' (S1del). Within this context, the anthropomorphic language appeared to provide a metavisual short-hand, whereas in her pre-interview explanations, it seemed to provide a place-holder or bridge between the process that she knew and the mechanism for reaction that she did not understand.

5.2d Human Analogy Models: How they highlighted a gap in some students' knowledge of polar water molecules, which was then bridged with the teaching analogy of a barn-dance

In an echo of the anthropomorphic terms in Ani's descriptions, the physical simulations were interpreted to support students' abilities to bridge narrative gaps in their group expressions of displacement reactions. For example, initially the students had been instructed to provide a physical simulation of their response to the question of what happens if chlorine is introduced into a solution of potassium bromide. This would be described through the analogy of a couple at a party who are confronted by a new suitor for one partner. Students were asked to express their responses to the following sub-questions:

- Is there a chemical reaction?
- If so, what is the new compound?
- What happens at a sub-microscopic level?

It was my assumption that the groups would progress through a before, middle and after image, in which an electron transfer model might be illustrated between competing ions, resulting in a new student pairing. Observation notes indicated that all of the groups concluded that there was a chemical reaction, and that the chlorine would displace the bromide to form a new compound with potassium. All groups described the transfer of a negative charge between the halide and the introduced halogen. However, during the preparations, representatives from three groups came to me with a problem. They could not continue to construct their simulations because they could not figure out how to separate the initial ionic compound. These three groups attempted to account for the mechanism by which a potassium ion was, as Genny noted, '*freed* to combine with the bromine' (S2). Ani later recalled that she could not at the time understand how bromide was transformed from its ionic state back into bromine,

> … How did, it, chlorine get rid of the bromine, because if [the ions] were positive and negatively charged, how did they go back to like their normal state, and, for the potassium to be able to react with the chlorine? (S1)

Her problem appeared to stem from a lack of knowledge that the halide and alkali metal ions will interact with solvent particles in solution. This information, relating to polar molecules and Hydrogen-bonds, had come as a surprise to me and the teacher, who noted that the behaviour of polar molecules were not yet a feature of the curriculum work that they were to engage with. (T)

Three of the six groups, as was expected, did not seem to be confronted by this question. Rather, their performances included a compound that separated into ions without solvent interaction, as the electron was transferred from one halide to another. For the three groups with the mental obstacle, this presented an opportunity to support conceptions of a multi-particle environment. I assessed that the students could proceed if they were given a simple model that would enable them to visualise the separation of ions in a solution. For them, I described the dipole nature of water molecules. I compared their interaction to that of partners in a barn dance, grabbing and letting go rapidly in a crowd of other dancers. The students adopted the 'barn dance' analogy, and completed the task (Obs; V2:39:27).

5.2e Affordances for student autonomy

Observations of the bodies-as-particle simulations (BAPs) and the Human analogy models (HAMs) suggested a difference in the affordance of autonomy over the simulation-making process: For example, the initial ideal atom BAPs signifiers had been described by me. The HAMs however, provided scope for students to develop a wider range of signifiers, drawn from their own social experience. In the ideal atom BAPs, students were afforded creative freedom within a functional range: for example, the electron actors were seen to make expressions that I interpreted as expressing sadness and anger, in keeping with the objective to provide a personification of a 'negative' charge. Within the HAMs, however, the potential for creative input was extended beyond signifiers to social situations and roles as well. This appeared to support a greater breadth of creative discourse. This was exemplified in Genny's description of her groups' ideas:

> So, um, some people were, someone was chlorine, and we called him Chlorine Boy. And one was Mrs Potassium, and then someone was Mr Bromide, bromine… Um, I think we kind of like had it in our minds kind of like, a bit like ah, you know, like soaps and things…You have, like those tragic stories like … Like, romantic couple get split up, you know. (S2)

Here, Genny's group developed the base analogy for a displacement reaction by drawing upon previous knowledge of a dramatic genre, i.e. 'soaps and things…those tragic stories'. The description suggested a degree of self-reflexive language, implying a metacognitive awareness as a co-modeller or co-director. The HAM was furthermore suggested to be developed through group complicity: in that she referred to '[having] it in *our* minds'. These features, along with the observations of students' motivation, (Obs; T), suggested that the HAM context supported autonomy and scope for creativity.

5.2f Formative assessment: multimodal features for highlighting students' conceptions during the lesson

Two episodes suggested the potential for formative assessment of multimodal features. During the physical simulation of an ideal atom, eight groups simultaneously performed a dynamic model of a deuterium atom. Students' repetition of movement and spatial features provided a sameness of action throughout the room, which provided a context from which contrasting actions stood out. For example, one girl, Sarah, in role as a neutron, held onto her friends with outstretched arms (Figure 5.1). This image of her arms on the shoulders of her other proton and electron actors contrasted with the actions of the five other 'neutrons' in the classroom, who did not raise their arms. The electron actor, while crouched over and holding her hand in a 'negative' sign similar to other electron actors, was much closer to her neutron actor than were electron actors to their neutrons in other groups (Figure 5.1). The room was cacophonous with students' voices as they personified their particles, saying loudly 'no' (as a negatively charged electron) and 'yes' (as a positively charged proton). Nonetheless, the visual mode was not obscured by the noise.

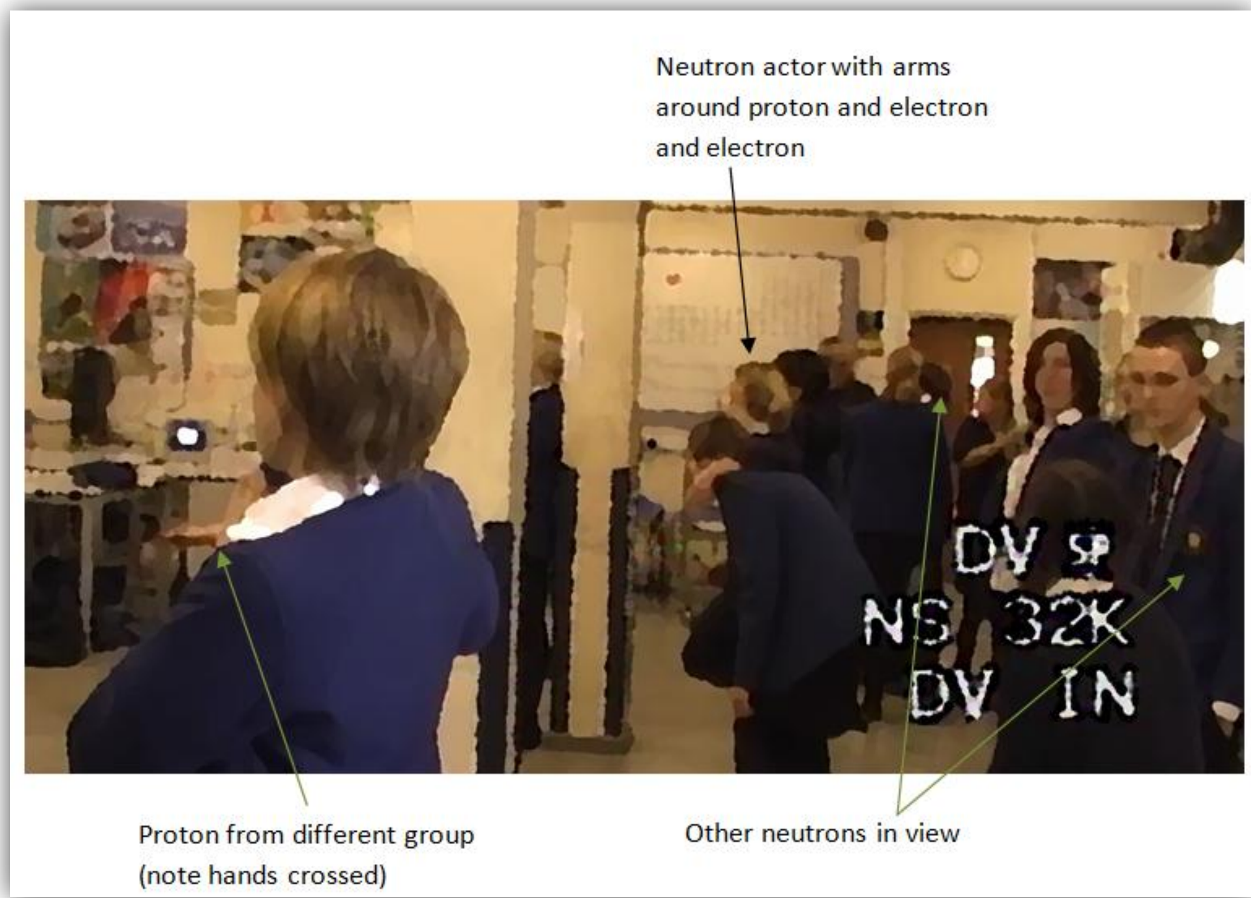

Figure 5.1 Incongruous actions. The centre group contrasts with the other groups' actions (V1:18:53)

After asking students to 'freeze', I began to describe what I saw in Sarah's group. I first began by praising them,

> You're the neutron, and I see that you [proton] are taller and your gestures are the plus sign, that's excellent.

I praised the clarity of their representation of the proton, of the relative position to the neutron, and their personifying of a 'positive attitude' with shoulders back, standing tall, and using gesture to signify a positive charge. I next asked them to justify their proximity. Sarah said that they had aimed to show that the neutron was an aid to the attraction between the electron and the proton. Her perception, now elucidated, helped me to identify a feature of my original instructions in the teacher demonstration when I suggested that the neutron might be seen as a rather relaxed 'peacemaker'. It was an impulsive anthropomorphic comment that I thought might help the students remember the neutron's neutral charge, but which broke with a design protocol by which I would aim to avoid teleological comments such as that implied in the role of 'making peace'. With an aim to maintain congruity across the groups I instructed the Sarah's group to show the distance 'in five seconds'. Students quickly moved into place (Figure 5.2).

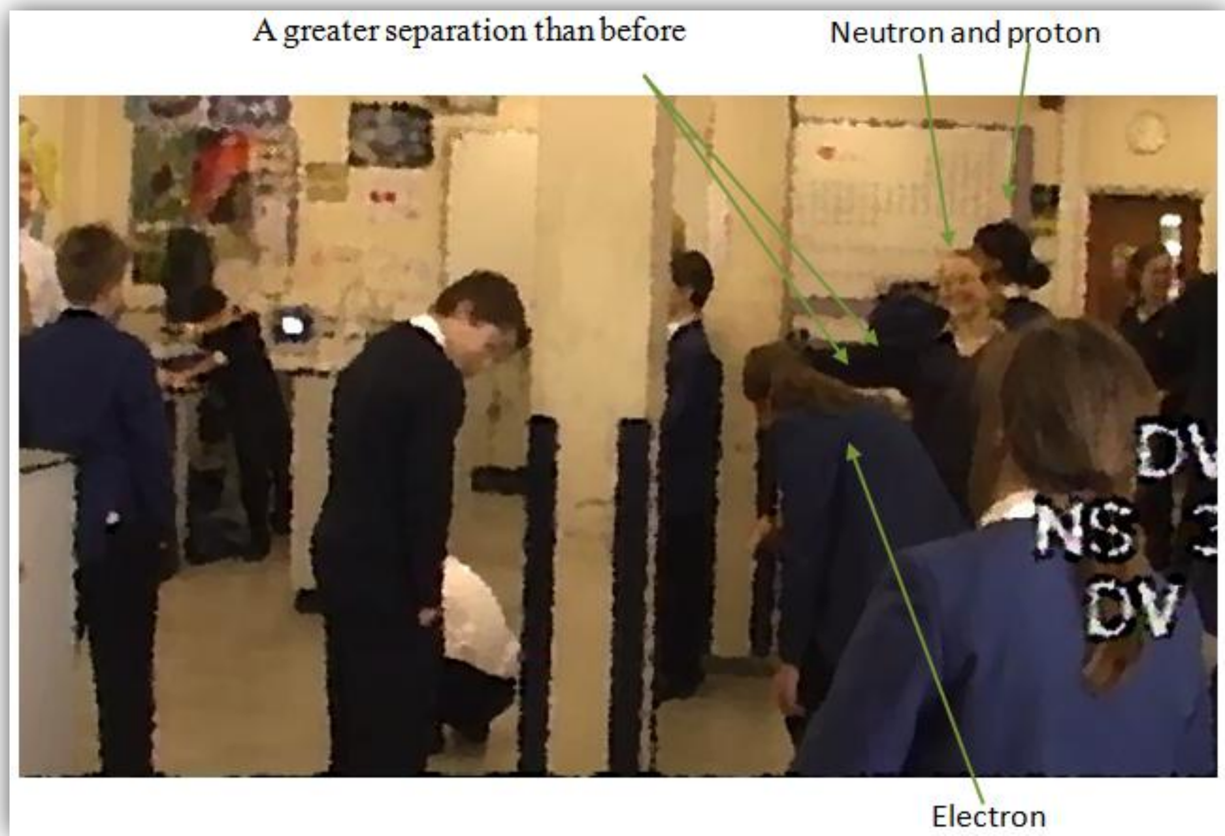

Figure 5.2 Ideal atom. Previous centre group reconfigured to include space between electron and nucleus. Relative spacing and lower level of electrons are evident around the classroom. (V1: 19:10)

A second affordance of the simulations was that students could support a decision-making process non-verbally. This was suggested in the expression of (what appeared to be similar to the drama concept) a *ripple effect* in which an action was replicated rapidly across a group of participants. A first example of the ripple effect occurred during a whole class activity in which students were assigned the task to create the largest atom that the class population would allow for. When they finished, having created fluorine, I asked of those in the nucleus, ‘How can we more clearly show who the protons are?’(V2: 21:51). Seven students, over the course of three seconds, raised their hands above their heads and created plus-sign gestures with two open-palmed hands perpendicular to each other (Figures 5.3; 5.4; 5.5). I interpreted these gestures as signifying a positive charge, which contrasted with the lowered hands of the non-protons in the group. The speed suggested rapid agreement amongst those students who made the gestures.

Figure 5.3 Ripple effect - two students (V2 21:52:23)

Figure 5.4 Ripple effect - four students (V2 21:53:15)

Figure 5.5 Ripple Effect – 7 students (V2 21:55:00)

For the teacher, this response, similar to the 'incongruous ideal atom' (Figure, 5.1), provided a means by which several individual responses were observable, not lost in a cacophony of verbal answers. It also afforded a rapid response from the students which allowed the activity to continue quickly at this stage.

In a similar example of a ripple effect, in the 'world's most uncomfortable sofa' task, students were to complete their tasks silently in less than a minute. Beginning from an initial disorganised group of individuals, tentative movements were either ignored, or repeated by other students as they formed the 'back' and 'cushions' of the sofa. Out of a slow continual 'shaping' of the sofa, one student made a claw shape with her hand. Immediately four other students repeated the gesture, so that it appeared as if they had the same idea concurrently (V1:11:52:16).

5.2g Group-regulation and 'exuberance'

Observation of the video corroborated participant observation notes that suggested that the pedagogy drew full participation during the performances. Also, students appeared, as a class, to be attentive and engaged throughout the lesson, as corroborated by the teacher, who observed of the students:

> They were superbly behaved, I thought, in general. And extremely focused, listening very, very carefully to what was going on. (T)

Students' 'focused' and 'careful' listening suggested a sense of motivation and self-regulation amongst class-members. Focus was also interpreted through observations of group regulation during periods of intense activity, which I interpreted to be examples of what I called *exuberance*, defined in accordance with the Oxford English Dictionary as 'overflowing fullness (of joy)' (Sykes, 1984). It was manifest here with a *temporary* contrast between the intensity and behaviour of a group member in relation to the group. During preparation for the student-centred BAPs and HAMs some students appeared to become so excited that they revealed a potential to disrupt their groups. A first example from the 'world's most uncomfortable sofa' task saw one group beginning to form the shape of a sofa with their bodies, as one boy (V1:11:52:20) pumped the air with his fists rapidly. From my experience within the pilot study, I interpreted the boy's action as signifying an 'uncomfortable sofa' feature: perhaps a club or bat with which to hit the imagined sitter. The rapidity of his gesture was incongruous with those of the other group members, who were arranging themselves without sharp, violent movements. These other students did not respond but continued to move and shape their body language and gestures at a consistent pace which contrasted with his. The boy stopped the behaviour within seconds after starting, moved around to the other side from where he was, and changed his response to a slower punching action and then, finally, held his fist in a raised position, a decision which aligned his action to the static image created around him. Within the context of the group behaviour, this was interpreted to reveal a positive, group-regulation effect that supported the learning environment.

A second example of exuberance occurred during the displacement HAMs when two boys from different groups walked to the centre of the classroom, and one mimed shooting another, who fell, clutching his chest (V1; Obs). No one else paid attention. Once the faller stood, the two students immediately returned back to their different groups. This was a spontaneous improvisation that appeared to be inspired by the demonstration that I gave minutes beforehand in which I aimed to show how an actor could reveal 'invisible' forces and objects via a dialogue of action and reaction with another actor. The students' exuberance appeared to result from, and added to what I interpreted as a sense of play and creativity in the room. That the students could express themselves in this manner, and then return without incident to their groups, indicated a sense of personal freedom and comfort, as well as regulation.

5.3 Discussion

The post interviews suggested that the simulations supported the interviewees' 'metavisual' skills (Gilbert, 2005), in particular, in the increased tendency for extended discussions of ionisation, a concept that Genny and Kelvin had not previously been able to define (§5.2a). Ani and Genny also employed more scientific terms, visually descriptive language, and a reduction in anthropomorphism after the intervention (§5.2b) (Kelvin was not observed to use anthropomorphic terms). The utility of the physical simulations in aiding visualisation was suggested in three groups' inability to continue with their group thought experiments for displacement activities due to their lack of understanding of how ions separate in solution. The concrete nature of the physical simulation appeared to provide such a clear visual narrative that the inability to visualise the compound separation proved an obstacle to further visualisation of the reaction. The teacher noted that his students would not encounter this mechanism as a curriculum topic for another year; it is plausible that such an issue, if not dealt with in the interview, might have hindered further conceptual understanding. In this respect, the simulations afforded a bridging analogy, the 'barn dance', with which the students appeared comfortable as they completed the task.

The example of Ani's reduction in anthropomorphisms in her descriptions of ionic bonding, in the post interview, suggested that she substituted a more scientific explanation for her previous anthropomorphic terms. This supported the idea of anthropomorphic explanation as a placeholder or bridging analogy (Taber & Watts, 1996). This was also interpreted in the 'barn dance' analogy, by which students were helped to bridge the mechanism of solvent interaction with a vague visual analogy. The barn dance analogy operated like Kelemen and Rosset's (2009) students' initial anthropomorphic explanations, as an initial heuristic with which to understand an unknown concept (§3.1).

In this context, these findings suggested the utility of physical simulations, and suggested scope for further research into viewing anthropomorphic analogies as student learning tactics when key topic knowledge of concepts are inaccessible. This supports the hypothesis of Taber and Watts, that:

> If *strong* anthropomorphism is just a stage in developing understanding, then one might expect anthropomorphic language to diminish as other levels of explanation become available (1996, p.565).

The evidence from Ani's substitution of scientific terms, (combined with multiple case findings of anthropomorphic utterances across all interview stages (§13.2)) suggested that Taber and Watts' hypothesis might reveal that the edges or boundaries of students' conceptual understanding can be found during episodes of discourse where new scientific expressions and new anthropomorphic expressions are juxtaposed.

5.3a Scope for formative assessment

When groups simultaneously performed the ideal atom BAPs, they were found to express similar patterns of action, in which incongruous student actions were foregrounded in juxtaposition with other groups. This supported formative assessment by the teacher (§5.2f). That these patterns occurred across the visual mode allowed for assessment within a noisy environment. Also, by pausing the simulations like individual tableaux, I could focus the class on those particular physical signifiers, in a particular group, which were incongruous. The ripple effect provided a second feature for teacher assessment of student conceptions, and also suggested that students themselves may have also been engaged in multimodal assessment as they chose to agree, or disagree with their peers (§5.2f).

5.3b Group-work

The lesson appeared to support self-regulation within groups, as evidenced in responses to student exuberance, student participation and the teacher's observation, such as, 'Your style of classroom management worked perfectly. They, they were perfect' (T). Examples of the *ripple effect* and *exuberance* suggested the complex multimodal nature of communication between students during physical simulations. These are concepts that I have not encountered within the Science Education literature. As a feature for assessment, exuberance may provide a marker of *useful intensity*, whereby these episodes reflect a tension between creativity, intensity, and group cohesion.

5.4 Summary of Case 1

This case focussed upon the teaching of ionic bonding and displacement reactions. The lesson progressed from the warm-ups to group BAPs of ideal atoms, a whole class TE BAPs which resulted in a model of a Fluorine atom, a BAPs demonstration of ionisation with a 'pretend' potassium atom, and finally to group HAMs of a system in which fluorine is introduced into a solution of potassium chloride. Physical simulations were observed to promote scope for formative assessment during the lesson and in subsequent interviews. Extended group work negotiation was observed in the TE preparation for the final task. An investigation of verbal and action-based anthropomorphic analogies suggested that these were employed to bridge gaps in the students' understanding, which supported further conceptual development. Students were interpreted to visualise interaction at the sub micro level, and to express this in coherent narratives of chemical processes.

6.0

Case 2: Intense Particles

> '…and it occurred to me that it might, those kinds of activities, because you're using your imagination, may act as a better memory aid at some point in the future in terms of understanding the difference between the way particles behave in solids liquids and gases, yeah.' (T)

6.1 Case Description

This case took place in an independent school in Kent with a Year 7 Key Stage 3 class of eighteen mixed ability students[8]. The intervention was delivered in the last two lessons of the day. The classroom's four large rectangular hardwood tables were fixed to the floor, leaving space only between tables and at the back of the classroom (Figure 6.1). The students ordinarily worked in pairs, or individually at their tables (T). Students had previously engaged in demonstrations of magnesium in acid (and the 'pop' test for hydrogen) and the heating of magnesium in a crucible. Students had recently been introduced to the curriculum topic of 'combustion' (T; S1pre; S2pre).

6.1a Learning objectives

- Review particle theory as it related to the states of matter
- Develop sub-micro level visualisations of states of matter
- Develop sub-micro level visualisations of a reaction of magnesium and oxygen

6.1b Lesson description

The lesson began with an interactive/authoritative discussion on the utility of particle models to describe atoms. The class was split into two groups and the students

[8] The class included one nine year old (who was on a special arrangement to shadow his brother; both had recently arrived from abroad (T)).

engaged in the four warm-ups. The topic tasks began with a brief review of particle theory and a teacher demonstration of the Gestural Teaching Model (GTM) for states of matter. This led to a whole class activity in which students applied the GTM at varying temperatures, which I called out. Then four groups were formed in which students prepared and then acted out bodies-as-particle simulations (BAPs) for states of matter as I narrated, 'The Chocolate Bar' Story (see Appendix 1).

Four new groups were formed and prepared brief scenes of reactants within a magnesium oxide reaction. Performances were shown simultaneously. Students were next asked to prepare a *before*, *during*, and *after* image of a particle perspective of the combustion of magnesium and oxygen. The activity was interrupted for further interactive/authoritative discussion of the reaction of magnesium and oxygen. Students were next asked to prepare and perform a dynamic, bodies-as-particles simulation of the heating of magnesium (BAPs). Performances were evaluated, then a review of the key features of particles within states of matter completed the lesson.

6.2 Analysis

6.2a Pre-Interviews

Previous to the show card terms task, students tended to describe solids, liquids and gases at a macro and micro levels, rather than sub-micro level. In the magic goggles task, a common response was to include biological descriptions, such as, 'cells' (S1pre; S3pre), germs (S3pre), grains of wood and tiny seeds (S3pre), microbes (S2pre) and micro-organisms:

> Is it, like, particles are microorganisms put together -- I don't know -- and

> they are just like in the air (S1pre).

The show card task reminded one of the interviewees, Peter, of particle theory models that they had been introduced six months previously, at the beginning of the year,

> I think he [the teacher] gave us a sheet.
>
> *Yes.*
>
> And then I think we watched a video of it… It was like a cartoony, cartoony thing. And it like, it said liquid and then like floating around and stuff.
>
> (S3pre)

He recalled liquid particles to be 'floating around', suggesting that he imbued the particles with macro properties. Peter had also noted that particles move with heat, 'Because sometimes when particles are hot they bounce around' (S3pre). The term 'bounce', like 'floating around' appeared to be drawn from personal domain knowledge of macro phenomena. While he had a visual awareness of particle movement, it was unclear to what degree he perceived of this process as occurring at the atomic, sub-micro scale.

Pre-interview visualisations of particles suggested a focus on shape and relative proximity, with Peter and another student, Robert, describing particles as, 'balls' (S2pre; S3pre). A third, Abigail, described them as 'circles' (S1pre). When asked to explain solid particles, Robert, suggested that they were packed into a finite space,

> They go tight together.

So, they go tight together. Do you know why they might go tight together?

Because of the space, because of all the space being full. (S3pre)

Robert also used the term ‘linking’, which I interpreted as a description of attraction. However, this speculation conflicted with his reference above: That particles ‘go tight together’ seemed to suggest a teleology, within the context of the interview, implying that particles somehow link *because* they are tight together, because the space is full, rather than due to attractive forces.

6.2a.i Difficulties with delineating macro and sub-micro levels of representation

The interviewees used a range of scientific terms in the pre-interviews, such as ‘oxygen’ (S1; S2; S3), ‘carbon dioxide’ (S1), and combustion (S2; S3). They described magnesium as a ‘metal’ (S1; S2) and ‘sort of metal’ (S2). Their proficiency with terms contrasted with their inability to describe products of the magnesium investigations that they had participated in during previous lessons. This was strikingly evident in Robert’s drawings and explanations in which he appeared to conflate the two investigations, with magnesium placed in acid *and also* heated (Figure 6.1).

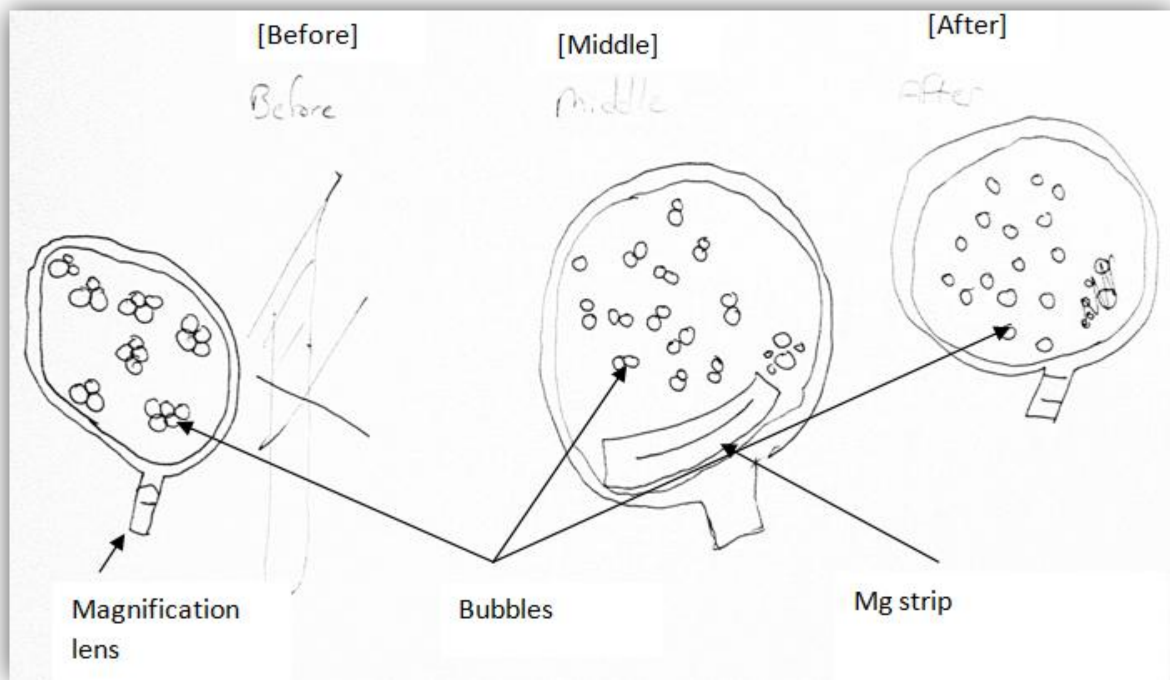

Figure 6.1 Robert pre-interview drawing of the heating of magnesium, which he draws as magnesium in acid (Source, S1pre)

Robert’s drawing, although it employed magnifying lenses, nonetheless signified circles as ‘bubbles’ at the same scale as the magnesium strip, suggesting an entirely macro-level perception of the reaction. By contrast, Peter’s drawing did not include acid, but did (Figure 6.2) include a sub-micro perspective of the magnesium reactant as particulate, which he supported with a magnifying window as a sort of zoom lens. Interestingly, he still provided a macro image of the magnesium oxide, suggested by the cloud of marks. Peter noted that this was ‘magnesium ash’ and that, ‘you could see it’. When asked where the particles were, Peter gave what I interpreted as an anthropomorphic response with, ‘I think that particles might have left because there was nothing there to go into’ (S3pre).

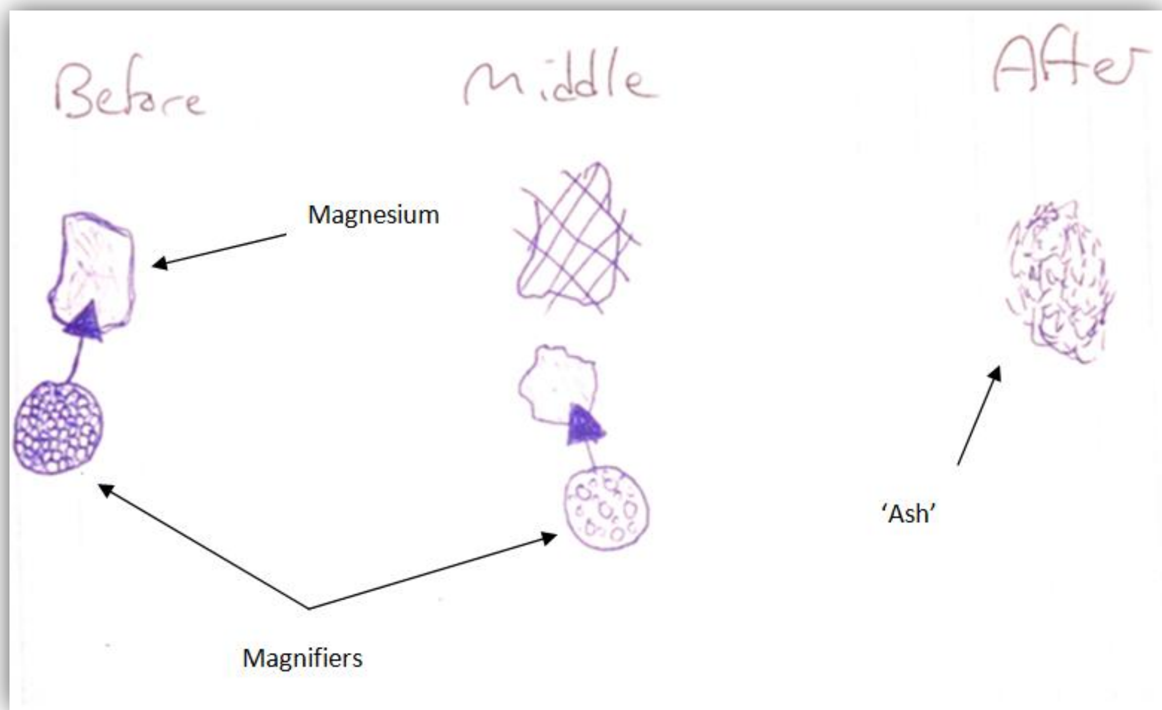

Figure 6.2 Peter pre-interview MgO drawing (Source, S3)

No interviewees drew reactions in which gas reactants featured. For example, neither Peter nor Robert, in the drawings above, signified surrounding air or oxygen.

The interviews suggested that the interviewees held a weak understanding of the sub-micro nature of particles, with little to no understanding of the relation between heat energy and particle movement.

6.2b Post interviews

Rather than focus on micro objects such as 'germs', post and delayed interview responses revealed an increased tendency for students to describe substances as consisting of particles. This section argues that all interviewees more clearly delineated macro and sub-micro levels of representation, and provided particle-based responses which included a focus on proximity and distance, and on attraction and the effect of heat upon particle energy. For example, Robert combined sub-micro level and multi-particle descriptions when he described a solid containing, ‘Millions of particles locked together’ (S2). Abigail now noted that gas particles, ‘are like bouncing everywhere like a billion miles per hour’ (S1). Peter said, ‘It's [gas particles are moving] like a thousand metres a second.’ The plurality and high-speed in Abigail and Robert’s comments respectively suggested an aim to express the extreme nature of particle movement in relation to the human dimension. Consistent descriptions of movement had not featured in the pre-interviews (e.g., suggested in the static nature of particles in the drawings). Now, expressions of movement tended to be more consistent across voice, gesture and drawings: Their focus on movement was noted in their use of gestural teaching metaphors (GTMs). For example, Peter initiated a gestural simulation, in which he illustrated particles in solids and liquids,

1. Yeah.
2. *You've got your hands in fists and they are [moving]. What would you describe the movement as?*
3. Just as, they wobble
4. *Wobbling, okay good.*
5. Yeah, and then it was a liquid so they were moving around each other. (S3)

Signifiers for movement were also evident now in Peter's drawing of the magnesium reaction (Figure 6.3).

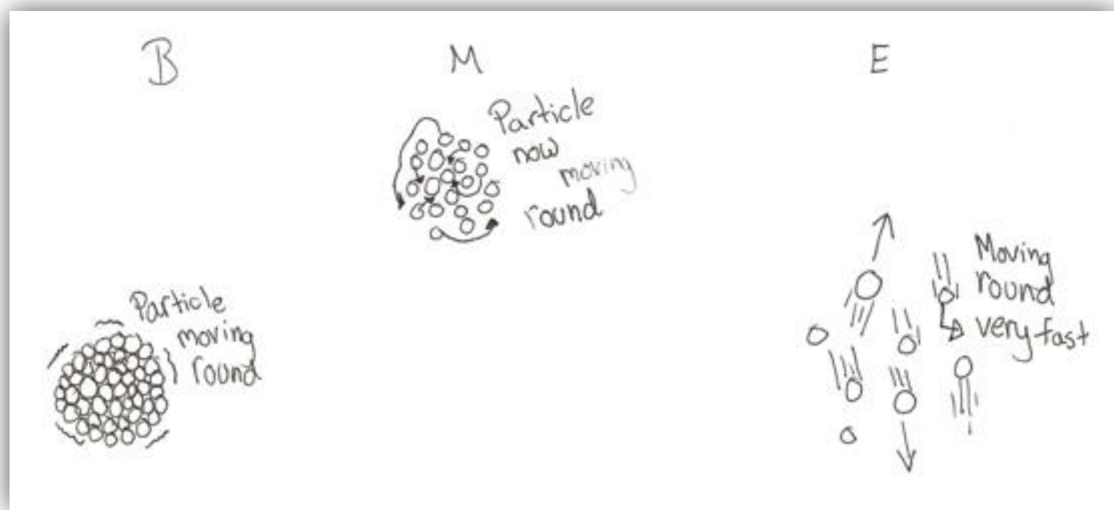

Figure 6.3 Peter post-interview MgO reaction drawing

In the above post interview descriptions, Peter began to relate heat and energy ('…heat gives energy to particles.'(S3post)), which he had not done previously. In the delayed interview he subsequently provided a clearer link between heat and interaction, responding, 'When it is hot they [particles] have more energy to move around' (S3del). Abigail also illustrated an awareness of energy and movement in the delayed interview, noting vaguely at first that energy is, 'some way that [particles] can move fast', and then describing a link between energy and movement through a discussion of states of matter:

1. *Okay, do solid particles have energy?*
2. No, liquid [particles] have a little; gas have a lot.
3. *Okay and how do you know that liquid has a little and gas has a lot of energy?*
4. Because, ah, solid particles are like, together, and they can't move, but a liquid

kind of. (S2del)

Here Abigail noted that more energy equates to more movement in liquid and gas particles, although in line 1 she says that solid particles have ‘no’ energy. Section 6.2c suggests that this comment was informed by an incompletely recalled GTM.

6.2b.i Increased focus upon multiple representations

Post intervention drawings reflected an increased tendency for students to focus upon sub-micro features: Although he continued to believe that he had observed a reaction in which magnesium was placed in heated acid, Robert’s drawing of the magnesium reaction, although confused, showed evidence of more complex visualisation than in his pre-interview: He now attempted to present macro and sub-micro perspectives, for example, within the superimposition of circles and the Mg strip in the ‘before’ drawing, and in the arrows that implied movement in the separation of particles of gas (Figure 6.4).

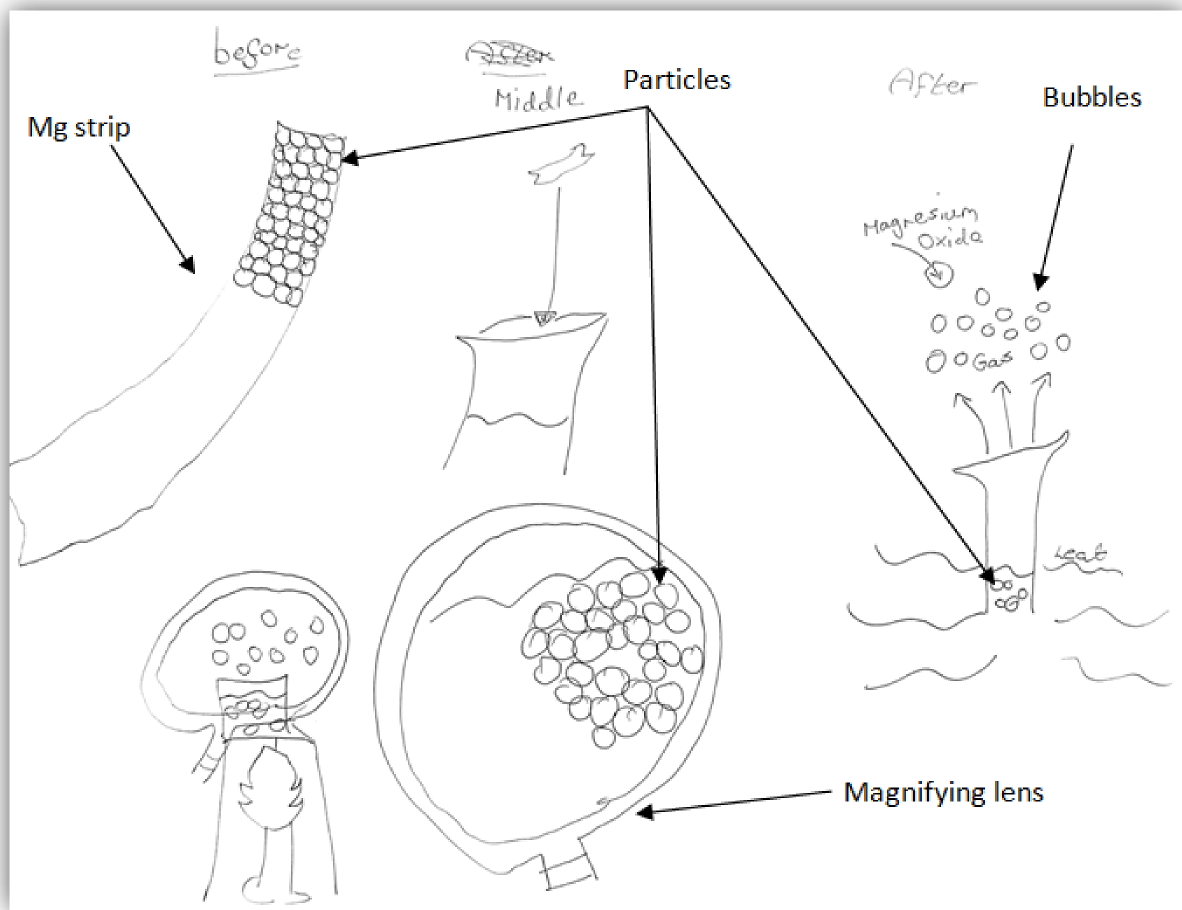

Figure 6.4 Robert post-interview MgO reaction drawing

Robert's comprehensiveness within his drawing emphasised both an interest in detail, and a lack of understanding of convention, the latter was evident in the use of circles to denote particles and bubbles (line 3, below), which obscured the different representational levels,

1. And then after, they [the reactants] are all gases, when the magnesium has reacted with the chemical [acid].
2. *Okay so we moved from liquid, separate from the magnesium strip... and then gas particles. They, this is interesting, I noticed -- these are gas particles- are they, or are they bubbles?*

3. They are bubbles.
4. *They are bubbles in the gas?*
5. Yes.

The use of circles to describe ‘bubbles’ as well as ‘particles’ suggested that Robert continued to lack clear visualisation of the *products* of the magnesium reaction, but that sub-micro perceptions were emerging.

6.2bia Diffusion.

Within the context of diffusion, the interviewees’ post and delayed interview responses and drawings suggested a greater clarity of expression, more clearly delineating macro and sub-micro levels of representation. For example, in Peter’s drawing (Figure 6.5) the groupings of particles for solid and liquid remained similar to his post drawing (Figure 6.3), and the gas particle spacing was retained, but more particles were added than in both pre and post drawings (Figures 6.2 and 6.3). The macro details of the bottles, the magnifying lens in the first and second frames, and the association of ‘visible gas’ to gas particles that were closer together in the middle than in the final frame suggested a sensitivity to particle size that the preceding drawings were not interpreted to convey.

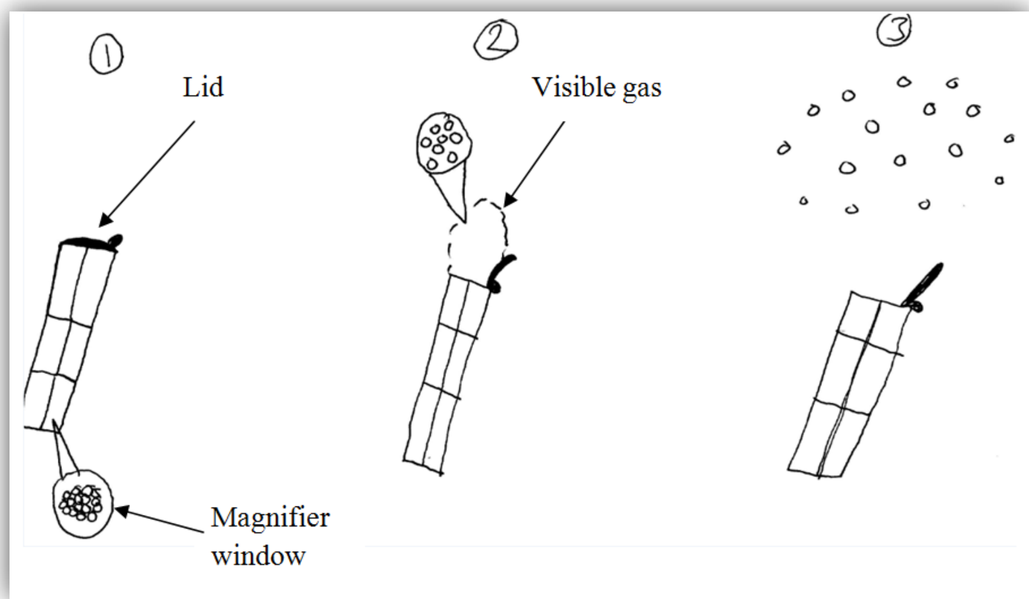

Figure 6.5 Peter delayed-interview diffusion drawing

6.2b.ii An animistic analogy as a discrete 'diffusion domain' conception

During the delayed interview, one episode suggested the influence of a non-science conception on a student's developing visualisation of particle interaction during diffusion. In his show card discussion during the delayed interview, Robert described air particles in seemingly perpetual, fast, motion:

> *Definition of air.*
>
> Particles in the gas, like but we have got around us is air, and it's just there, speeding about everywhere. (S1)

This description appeared to suggest an understanding in, 'It's just there, speeding…' of the perpetual nature of particle movement. However, later in the interview, Robert introduced an anthropomorphic conception of particles that he had not previously used; during a TE question about the diffusion of gas particles from a just-opened bottle, he noted that 'when it opens, all their energy starts' but that, 'After, in a couple of hours they'll start to just die' (S1). Robert's diffusion drawing (Figure 6.6) at first appeared to reveal a more scientifically literate description of particles than previous drawings: he filled the unopened container with particles evenly spread, and used arrows to signify movement in the middle diagram. While there was still a lack of air particles and gas movement indicators in the closed bottle, a striking feature was noticeable in the third part, on the right hand side: particles appeared to drop to the ground.

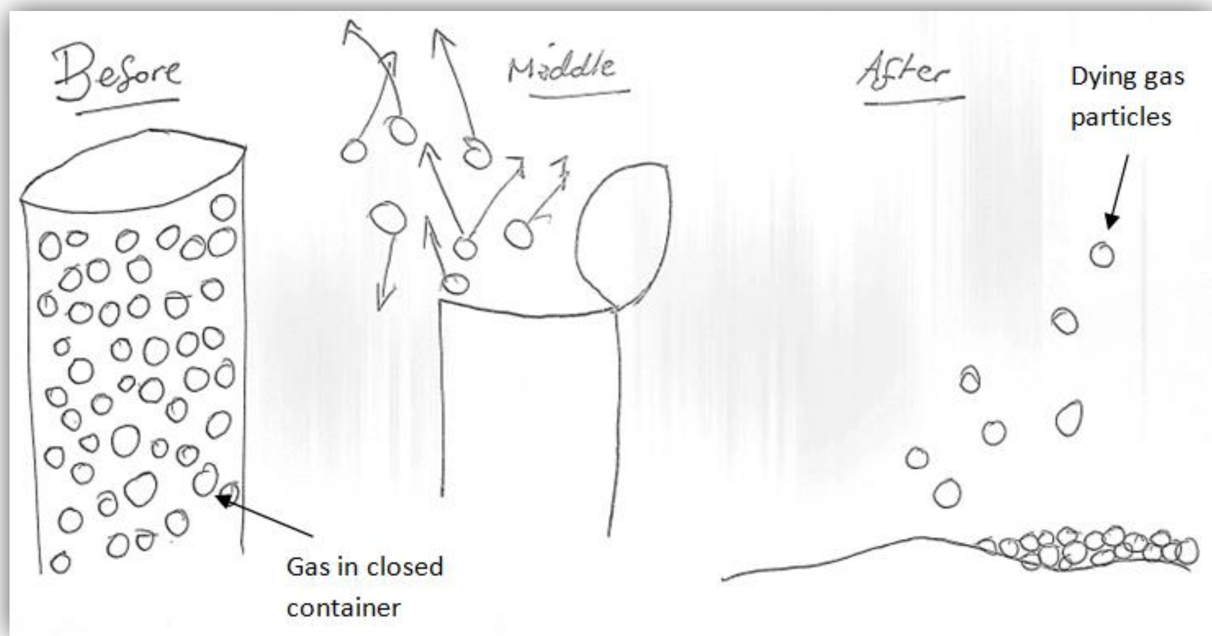

Figure 6.6 Robert delayed interview diffusion drawing

Roberts's comments, above, about dying particles, and the third image within Figure 6.6 strikingly suggested the influence of an animistic perspective. This was not in evidence during the second interview, nor was it in evidence in relation to the show cards, which focused upon states of matter. This suggested that as a conception, the animistic perspective coexisted with his otherwise scientific 'perpetual movement' understanding.

6.2c Re-reading GTMs: An episode when the gestural metaphor is suggested to be a preferred heuristic in the longer term

A recurring affordance of the GTMs was that they provided a real-time illustration for discussing curriculum topics in interview: the GTMs appeared to be readily recalled by Abigail and Peter across all post interview stages. They either initiated, as with Peter discussing solids and liquids (§6.2b), or could respond to a request to use GTMs in the post and delayed interviews. However, in the delayed interview Abigail's behaviour suggested that although she could remember the GTM, she did not appear to immediately understand the particular signifiers that she gestured. This section describes an instance which appeared to suggest that rather than illustrate a discussion with recourse to the GTM, Abigail appeared to re-read or re-conceptualise her gestures.

Abigail had presented a consistent GTM across the post interview, and with corresponding verbal explication. For example, during the show card tasks in the post interview she declared that solid particles vibrate: 'They would be close but still moving' (S1post). However, she was noted in the delayed interview show card task to omit moving her hands (§6.2b). Later in that interview, she initiated the GTM again, and once again omitted the 'vibration' of solid particles (line 5, below).

1. *... And if I look at, with my magic goggles that [I tap on the table] or that [I tap on a book] or that [I knock on scissors] what might I see?*
2. Solid particles.
3. *Solid particles.*
4. [Holds up fists in front, thumbs touching] Particles that are like stacked

together, not completely but with gaps in between them.

5. *These, so you put your hands together there.*
6. Yup.
7. *And, stacked them together.*
8. Yes.   (S2del)

I observed that in this exchange Abigail appeared to pause and look at her hands before speaking in line 4 (Int. notes). Unlike her clear recall of the GTM and of the vibration of particles in the post intervention four months previously, she now appeared to have a moment of conceptual conflict: whether to believe her gesture or not. That she agreed and gave authority to her remembered GTM suggested that she did not recall a strong mental visualisation of states of matter which could compete with the GTM. Although the GTM was inconsistently remembered, in that she omitted to vibrate her fists, it nonetheless held a degree of heuristic authority. While this observation is speculative, it is retained in order to echo a similar interpretation of deferral to the gesture in section 10.2d.

6.2d Informing conceptions of gas particle movement through intense expressions

During the GTM tasks and 'The Chocolate Bar Story', students' high intensity in their actions appeared to inform a corresponding embodied sense of intensity in their conceptions of gas particle speed. This was evident in part in juxtaposition with expressions of 'slow-motion' as an abstract signifier for high-speed, which seemed to hinder Peter's understanding of relative particle speed. This section first describes an interpretation of how students' intense actions informed their visualisations of particle movement. It then describes interview responses that suggested that if an interviewee had a high metacognitive understanding of the simulations, then the intensity of the expressions was less prone to inform their visualisations.

First, the GTMs appeared to promote increasing emotional intensity as the relative speed of particles was expressed with respect to an increase in heat energy. The students began arranged in a line across the room. Figures 6.7-6.9 below illustrate the students' responses to my commands of different levels of heat. This task followed my teacher demonstration of the GTM. Student gaze in the figures illustrate what I interpreted to be a high degree of attention across all three phases, and an interpretation that some students watched others' behaviour, as the three girls can be seen to do on the right side of Figure 6.7.

In this figure, students' held their fists together and wiggled or shook them slightly. In Figure 6.8, in response to my calling out that I 'turned the heat up', the students adopted a faster movement for liquid, as they rotated their fists at greater and lesser distances from one another. As I called out that the heat was increasing further, the students increased the speed of their gestures and the distance between their fists (Figure 6.10). Similarly, the students seemed to become more *intense* in their enthusiasm. Examples of this intensity included the observation of *exuberant* behaviour, such as in Figure 6.9, where the blonde and dark pony-tailed girls turned to each other with their arms outstretched as if dancing, but then return to their demonstration of particles in Figure 6.10.

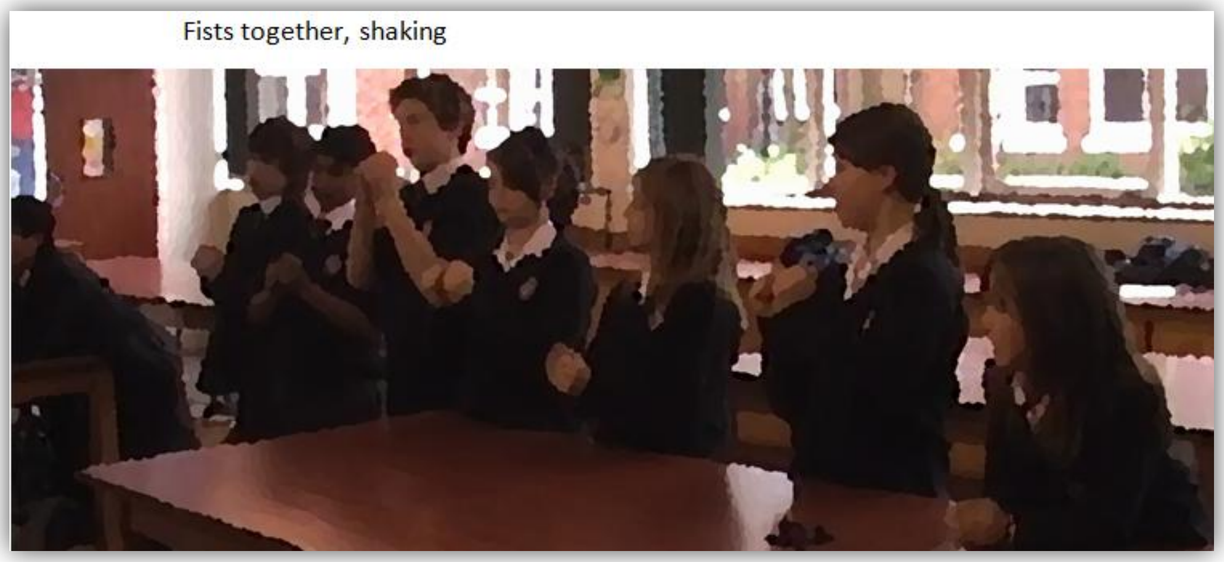

Figure 6.7 Solid GTM. Students hold their fists together, vibrating their hands. The class extends out in a line from the left side of the group. Note that the three girls to the right are watching the gestures of the students to their left.

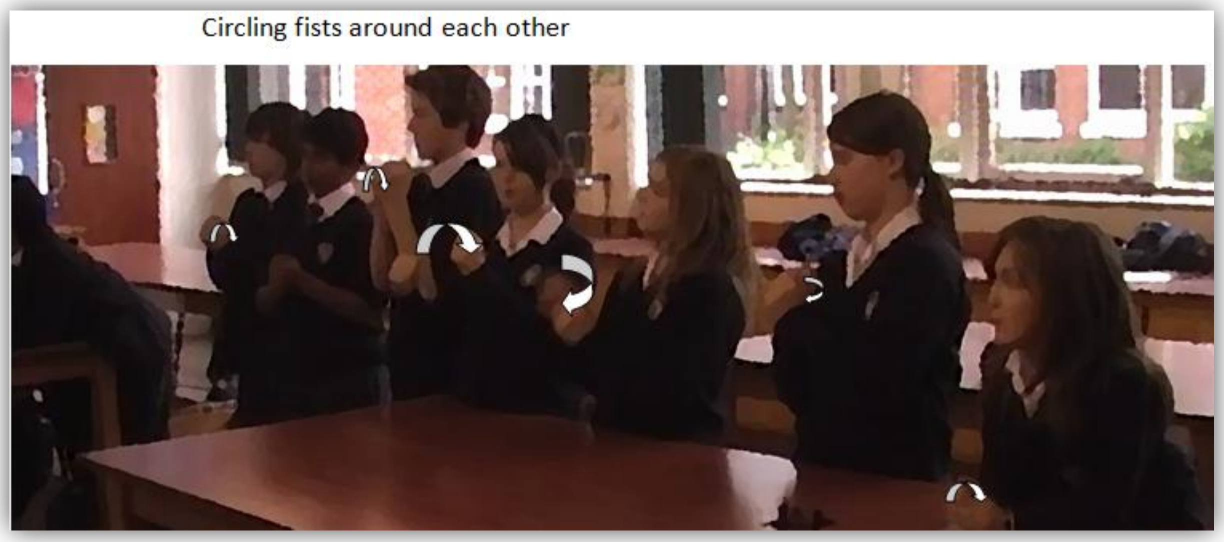

Figure 6.8 Liquid GTM. The arrows denote movement as the students simulate liquid particles.(V2: 19:51)

Figure 6.9 An exuberant moment during the gas GTM. These two girls briefly swayed and swung their arms out (as if dancing) during the beginning of the gas simulations (V2 20:38)

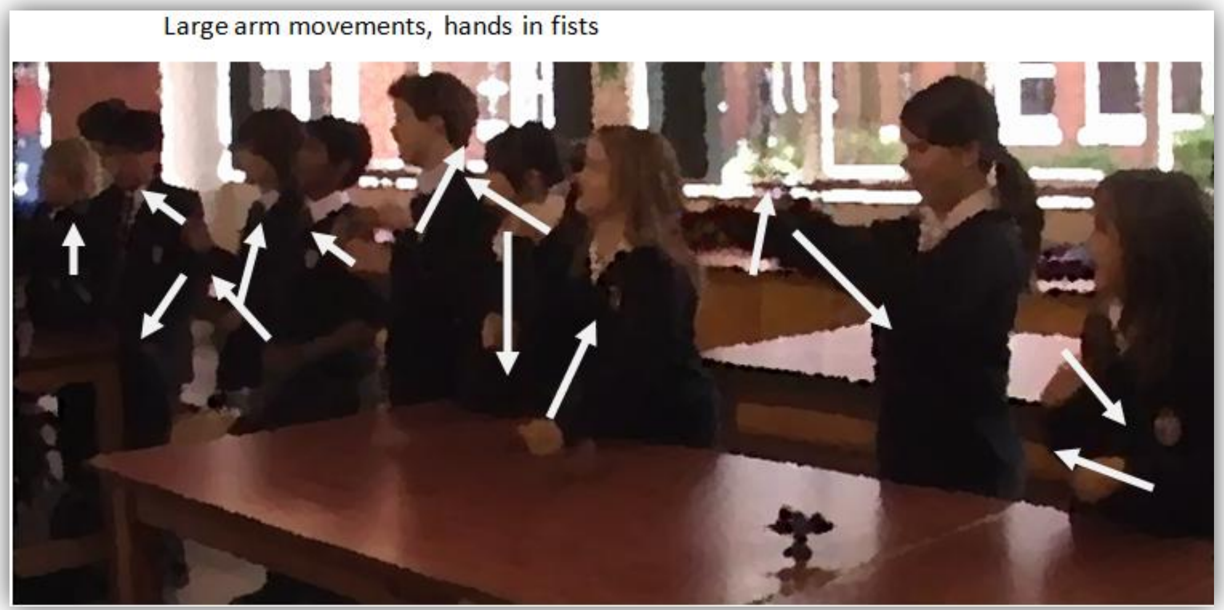

Figure 6.10 Gas GTMs. The arrows denote movement of students' fists while portraying gas particle movement. Note the full participation of the group. (V2: 20:44)

A high level of intensity was also observed later, during 'The Chocolate Bar Story'. Here, two of the three groups ran 'randomly' around the room at the point in the story at which the chocolate bar was 'vaporised' by the heat of an alien's laser. Figure 6.11 illustrates the students' vigorous movements; the raised elbow of the white-shirted boy suggested his energetic behaviour. This episode and the GTM task provided two experiences of intense expression of gas particle behaviour for two groups in which bodies and emotions were engaged in a heightened experience. In this context, both the BAPs and the GTM suggested a potential for students' expressions of speed to support an embodied feeling of relatively intense, i.e. energetic, gas particles.

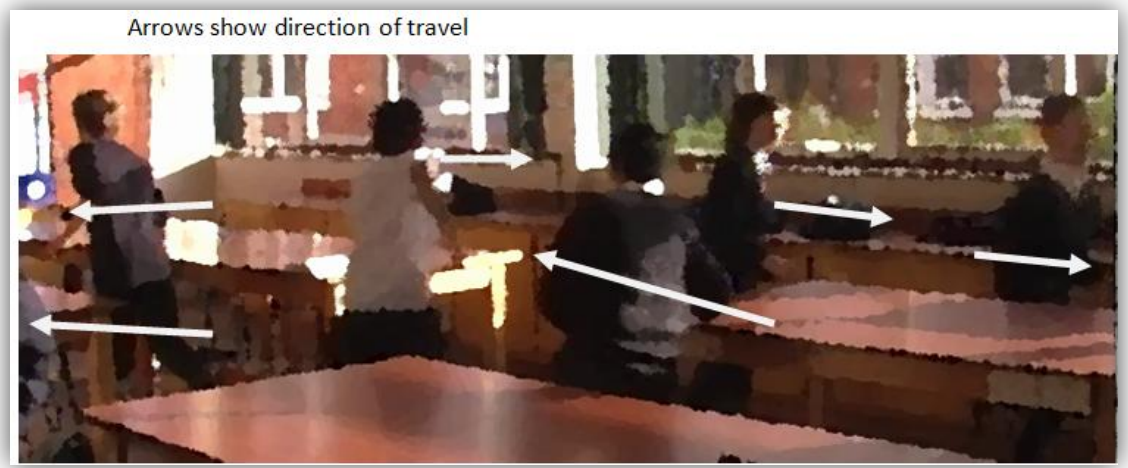

Figure 6.11 Gas BAPs in 'The Chocolate Bar Story'. The arrows denote the direction of students who were members of groups that did not use slow-motion, and instead ran randomly around the room. (V2:29:47)

6.2d.i Slow-motion action in the chocolate bar story

The scope for this embodied, affective quality to inform gas particle conceptions was suggested in part through contrasting it with a BAPs in which slow-motion was used by some students as an analogy for high-speed particles. During the preparations for 'The Chocolate Bar Story', I chose one group with which to discuss how they might use drama to better convey the high speeds of gas particles. I offered the students the idea that to express extreme speed, they might consider 'slow-motion'. I spoke with the assumption that they had seen this technique in film, TV or theatre previously. These students then prepared and performed the slow-motion movements.

This seemed to impact upon Peter. In the first magnesium reaction BAPs that followed 'The Chocolate Bar Story', in which Peter was to represent a BAPs model of oxygen gas, he and another group member extended their arms and contorted their bodies in a slow rhythm. This expression stood out as incongruous in relation to the other actions. Their movements were not only slow and dance-like but now used extended waving arms, as if they were swimming in a viscous substance. In describing this expression, Peter noted that he and other actors of oxygen particles, 'like started to move slowly'. Peter seemed to reflect upon this image, noting, 'and then we should have moved faster because [it was] the gas' (S3post). This statement suggested that Peter had not previously held the metacognitive perspective that slow-motion movement could signify hyper-fast gas particles.

As Peter's reflection that he *should have* been fast indicated, he nonetheless had an understanding of the relative speed of gas. He had previously described the speed of gas particles as fast (i.e. '1000 kilometres per second' (S3post)). He seemed to recall this too in the delayed interview four months later, when he initiated a GTM and moved his hands rapidly, spread out and random,

> They move like that. [He gestures]
>
> *Oh okay, so they [your fists] are all over the shop.*
>
> (S3del)

However, later in the interview, in an explanation of the diffusion of a gas, he noted, 'A few hours later, they [the gas particles] are just floating around'. Here Peter appeared to repeat a slow particle conception. This description occurred during an explanation of diffusion. That it was not a feature of his states of matter explanations suggested that Peter appeared to hold onto this alternative conception outside the domain of describing states of matter.

Robert had been in Peter's 'chocolate bar' group, but did not appear to hold a slow gas perspective. A possible difference between the two appeared to be that he had retained the metacognitive context of 'slow-motion' when recalling 'The Chocolate Bar Story' in the post interview,

1. And then in the liquids we were just slowly going about. And then the gas, we did in slow-motion.
2. *And what did that show?*
3. That we were going really fast
4. *Okay*.
5. But it had been put in slow-motion. (S1del)

Robert repeated that he used slow-motion actions, as if to indicate that he understood the significance of the action. Unlike Peter, Robert continued to display a consistent expression of speed within different contexts, throughout the post and delayed interviews, such as in his show card definition of air as, 'speeding about everywhere' (S2post), and in describing gas particles, 'flying around freely' (S2del).

As a suggestion of what conceptions resulted when only high-speed expressions of gas were employed in the intervention, Abigail, who did not use slow-motion within her group, but who instead ran quickly to signify gas particle movement, continued to describe gas as relatively fast, such as ‘whizzing around past each other’ (S1del) and in a TE response on diffusion she noted they would go ‘anywhere because they would, if it is a gas, they would shoot anywhere’ (S1). The contrast between Abigail, Robert and Peter supported an interpretation that intensities of gestural or bodily action, mediated by metacognitive awareness, appeared to inform the interviewee’s conceptions of gas movement.

6.2e A distancing effect of humans-as-particles?

After the intervention, when asked how they visualised particles, the interviewees seemed to share a common mental model. The imagery that they preferred was similar to diagrammatic representations, for example, ‘circles’ (S3post), ‘little balls’ (S1post), and, ‘Like, balls, blue coloured balls going all around’ (S2del). In what appeared to be a pre-metavisual perspective, Robert rationalised why he perceived particles, ‘As little balls.’

1. *Why do you think you think of them like that?*
2. Well, because it just makes sense them knocking altogether as balls.
3. *Okay.*
4. Because as people, because they need, like, leg-space and that.
5. *Exactly.*
6. Their legs just can't link together.
7. *Yes.*
8. Because their arms would have to too. (S1post)

Robert suggested the impracticality in the shape of the human model, as opposed to ‘balls’. He argued that a human model required the linking of legs (line 6) and arms (line 7). Robert’s description of, ‘it just makes sense’ in regard to ball imagery suggested that the ball-image was more realistic than the human analogy.

6.3 Discussion

The post interview descriptions and explanations increasingly emphasised a focus on movement, proximity and distance of particles, and a tendency to relate movement to the concept of energy. Drawings across post and delayed interviews revealed increasing delineation of sub-micro and macro features. However, the potential robustness of students’ developing conceptions of diffusion was drawn into question with Robert’s delayed drawing and description of particles as ‘dying’ during diffusion. The inclusion of this animistic feature was not evident in the post interview, suggesting the influence of non-Chemistry domains of experience upon the concept of diffusion promoted in the intervention.

6.3a Juxtapositions of new and old images of particles

The intervention did not appear to develop new visualisations of the shape or texture of particles. Despite the introduction of the imagery of interacting students-as particles, the interviewees retained a conception of particles as ‘balls’ and ‘circles’ throughout the interviews. Although it seemed that the students had not been taught particle theory for at least several months, they held strong images of particle shape, and for Abigail, colour.

That Robert’s animistic explanation was not evident in his post and delayed interview descriptions of states of matter suggested that he held at least two competing conceptions of gas particle movement in mind. Peter's use of both *fast* and *slow* gas particles during the intervention and in interviews also suggested that he held two conceptions. Peter's *slow* conception appeared to be informed by slow-motion actions during 'The Chocolate Bar Story' in which he recalled the embodied image, but not the modelling significance of the image, later in the intervention. Robert, who also took part in Peter's group which used slow-motion in 'The Chocolate Bar Story', was interpreted to hold a metacognitive understanding that the use of slow-motion could convey hyper-fast motion. His comments supported the perspective that a metacognitive awareness may help to contextualise limitations in some models (Penner, Giles, Lehrer, & Schauble, 1997), and that students who hold strong metavisual skills might be able to learn through increasingly abstract physical simulations.

6.3b Questions of shared visual perspectives

As the teacher, with a line of nineteen students before me, I was struck by the size of the resultant system of particles expressed through these thirty-eight fists moving interacting simultaneously. This suggested the potential to present such activities as large multiple particle representations. This perspective may not have been shared by the students, as they did not have the same perspective, facing their lone instructor, which drew into question the degree to which they perceived themselves as within or separate from the system. The potential for several points of view foregrounded the potential individualistic nature of their perspectives, and the question of what features can be said to be 'shared' in such an activity, with respect to the visual modality.

6.3c Intensity of movement informed the concept of relative speed of gas particles

The level of *intensity* as expressed in the GTMs and BAPs of gas particle movement seemed to have the potential to influence students' later expressions and conceptions of gas movement. This appeared to emphasise the impact of embodied sensation as an affordance for highlighting particular conceptual features.

6.3d Intense GTMs or slow-motion action?

One of the objectives that inspired me to promote the technique of slow-motion was in order to explore how a teacher might reduce the need to move around the classroom quickly as gas particles. Some teachers perceive that drama provides a safety or control issue in Science (Heathcote, 1971; Brown, 1995) and therefore analogies that promote less action may be desired. For those teachers, this case suggested that with students with low metacognitive of representational forms, it may be preferable to use intense gestural metaphors such as the GTM, rather than slow-motion BAPs.

6.4 Summary of Case 2

This case focussed upon the teaching of states of matter and the combustion of magnesium in oxygen. The lesson progressed from the warm-ups to a whole class GTM task, group BAPs of states of matter, and finally group BAPs of the Magnesium Oxide reaction. The intensity of students' movements appeared to support their visualisation of relative particle speeds. The use of slow motion to signify high speed promoted conceptions of slow gas particles, for students who exhibited a weak understanding of the representational nature of the models. Students tended to develop a greater delineation of macro and sub-micro features, and in delayed interviews provided richer descriptions of particle interaction. The GTM was interpreted to provide a memorable, shared metaphor for discussing particle interaction in the post and delayed interviews.

7.0

Case 3: Pretend Objects and Anchor Metaphors

> ‘And when you visualise this sort of thing, these reactions, what do you see in your mind's eye? Do you see anything? Do you feel something? Do you just come up with the answer?
>
> I can't really describe it. I would, when I think about it, I most likely think back to your lesson, because that gave me a better understanding because I see things in a physical way.’
>
> (S2del)

7.1 Case Description

This case took place in a comprehensive state school in Hertfordshire, with a class of twenty Year 10 students. They were described by the teacher and Head of Department as a mixed ability group. The classroom had a white board at the front, windows at the back, several long tables pushed to the sides, and a teacher’s table that was fixed to the floor (Figure 7.3). This gave about two thirds of the floor-space cleared of obstacles.

7.1a Teaching objectives

- Review atomic structure
- Introduce ionisation with halogens and alkali metals in solution
- Introduce displacement reactions in solution

7.1b Lesson description

The lesson began with a teacher-led discussion of our inability to directly observe atoms, and on the scientists’ use of models in order to aid visualisation. For the subsequent twenty-two minutes students engaged in the four warm-up tasks (§4.4). The topic tasks began with a teacher-led demonstration of an ideal atom. Students in groups of three then performed simulations of an ideal atom. This was followed by a question and answer session on related features of charge, movement, relative distance, and attraction between particles.

Next, students performed a whole class improvisation using their previous roles as protons, neutrons and electrons to create the largest atom that they could. The students identified their resultant atom as fluorine. I then asked the students to pretend that there was a potassium atom opposite their own atom. In-role as the outermost electron of this imagined potassium atom, I described an attraction between myself and the nucleus of the students' fluorine atom as I moved towards the group model (described further in 7.2d). During the subsequent question and answer session, students stood in pairs and were asked to act-out what happens at the point the two new potassium and fluoride ions are created by an imbalance of charge. Next, students in groups of four devised and performed a Human Analogy Model (HAM) of ionisation of fluorine and potassium. After seven minutes of preparation, the students were handed a slip of paper on which they were asked to solve a new problem, to describe verbally and through action, what happens with the introduction of chlorine into the solution. Although this was a non-reaction, students were required to express what might happen in order to assess the clarity of their visualisations of the event. The lesson ended with a short debriefing session.

7.2 Analysis

7.2a Pre-interview: fractured explanations and multiple heuristics

An overriding feature of the pre-interview responses was the breadth of malapropisms, vague terms, and confusions of terms with which they described atomic structure and ionisation. For example, when asked to describe the compound sodium chloride at the sub-microscopic level, one of the interviewees, Sophie, appeared to place an ion inside an ion, noting, 'An ion is inside along with the electrons' and then conferred an anthropomorphic attribute to the nucleus with, 'and the nucleus sends out the electrons which will go into a shell formation' (S3pre). Another student, Simon, seemed to substitute neutrons and ions as terms for electrons, when he said,

> And then the neutrons, and the *ions*, are around the outside [shell] and then if you take away one neutron it becomes a positive, it becomes a positive something. (S1pre)

Simon's, 'something' illustrated a tendency for vagueness exhibited by all interviewees. For example, in describing drawings of NaCl, which he chose to draw using a shell diagram, the third interviewee, named Morely, continuously used the term 'X' to describe his drawing of the structure of NaCl (Figure 7.1). When asked to define 'X' he said that it was, 'protons and electrons' (S2pre) (Simon also described the 'X's' in his shell diagrams as 'ions' as well as 'electrons' (S1pre)).

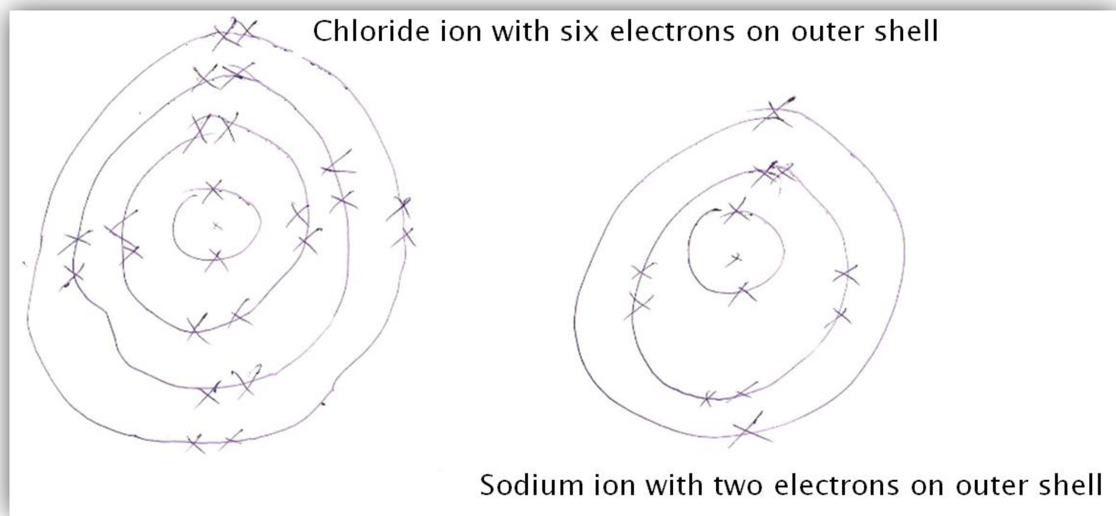

Figure 7.2 Pre-interview drawing for ionisation (Source, S3pre)

Morley's drawing suggested an awareness of shell theory and ionisation, but his conception was inconsistent. He appeared to have 'transferred' an electron from the chloride ion to the sodium ion, suggesting a confusion of an electron transfer model. As with his drawing, all drawings focussed upon an idealised two particle, rather than upon a multi-particle, environment.

7.2a.i A myriad of alternative metaphors

A characteristic of these interviews was the range of heuristics, images and alternative analogies that the students drew from, in what I interpreted as their attempts to inform gaps in their understanding during the interview. The interviewees provided rather mechanistic responses in relation to their descriptions of the drawings, with Morley and Sophie focussed upon the *number* of 'X's (S2pre; S3pre), and Sophie's use of a weight-gain analogy: '[The chlorine is] getting one [electron]… As a result of gaining one, its electron charge is minus one because … if you gained weight you wouldn't be too happy about it [i.e., you would be negative]' (S3). Sophie noted that this heuristic was taught in a previous Chemistry lesson. The interviewees also drew explanations from a range of science and social domains. Morley and Sophie held that the nucleus was the ‘brain’ of an atom (S2pre; S3pre). Simon compared attraction between charged particles to plastic grey ‘sticks’ in molymods (chemical modelling sets) (S1pre) and Morely compared attraction to magnets (S2pre). He and Sophie also, for example, described atom reactivity and structure in relation to radioactivity (S2pre; S3pre). Sophie said that electron shell structure, ‘helps keep [the atom] in balance so that it’s not like a nuclear weapon or something... and it can become quite dangerous’ (S3pre).

The interviewees could not explain the bonding process in relation to the distance between outer electrons and atomic nuclei. For example, when the students were asked to describe the bonding process of sodium and chlorine, Morely indicated that bonding may not occur when he noted that,

> They [the ions] are staying together while the things [electrons] are changing around and then, then they float off. I'm sure I remember, because I mean they don't bond do they?

All three interviewees left ‘displacement reaction’ off their concept maps in the pre-interview (S1; S2; S3). When asked to define the term, Simon appeared to draw from personal experience when he asked, ‘Is that where a reaction occurs, because um something like moves, as in when you displace water…? (S1). Morley’s response vaguely suggested a scientific connection in the use of ‘element’ when he said, ‘I don't know how to describe it, so you've got one element that goes into another one that goes from that into another one’ (S2).

7.2b Post interviews

The post-interviews suggested that the students continued to hold more consistent, but still fragmentary, conceptions, and with a lesser tendency to refer to the range of alternative explanations and analogies in the pre-interviews. However, there were instances in which students made terminological errors that suggested the influence of non-topic metaphors, such as ‘reaction diffusion’ (S3), and a ‘thing in the nucleus…I think it might have been protein’ (S2). The choices involved in these responses were indicative of a tendency to continue to piece together images and ideas from other domains of knowledge. Nonetheless, within this context, the interviewees exhibited a stronger visual understanding of the key features in ionisation, and could engage at length in detailed conversations related to the topic concepts (S1; S3). Morley was interpreted to express a more dynamic visualisation, and a greater sense of critical thought, than in his more mechanistic pre-interview responses. For example, below, he described his confusion about his recent learning of the attraction between ions. Whereas in the pre-interviews Morley had not used the term ‘forces’ nor initiated the idea of attraction, he now used ‘forces’ and revealed an awareness that these relate to subatomic and ionic interaction,

> But I’m confused as to whether the forces involved are with attracting the electron to the object [the halide] or attracting the two objects together. Which one, which way is it going? Or it could be going both ways. (S2)

A second example suggested that he engaged in a richer visualisation of sub-micro objects, when he was unsatisfied by a two-particle electron structure diagram (similar to Figure 7.1) that he had drawn for NaCl; he wanted to show a three-dimensional relationship between the ions. Morely subsequently drew a lattice-like structure that he recalled from a previous class (Figure 7.2). He could not recall what the image represented, but the significance of this was to suggest that he was now considering

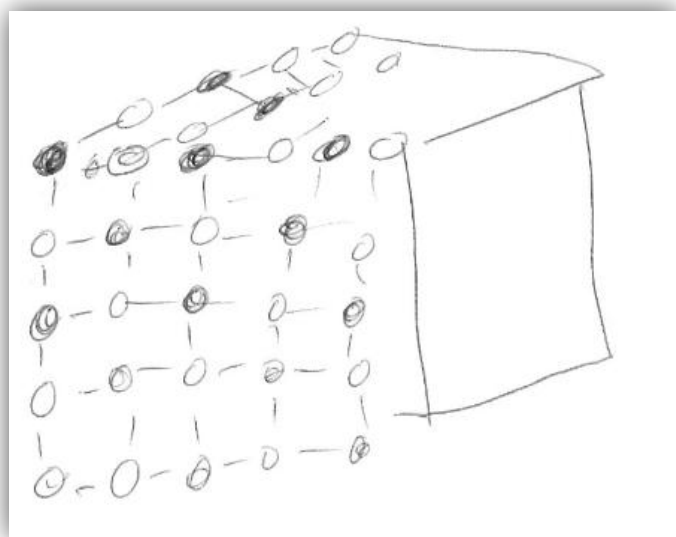

Figure 7.2 Morley's post intervention interview lattice drawing (Source, S2post)

a multi-particle visualisation. He then questioned this drawing as to why the lines between the circles appeared to hold the ions apart, noting, 'that something is in the middle [between each ion] there causing a boundary between the two and they can't touch each other'. I interpreted this as a lack of awareness of modelling convention, but also that Morley was attempting to apply his visualisation skills towards the concept of *attraction* in sodium chloride.

Improvement was noted in respect to the interviewee's understanding of the mechanisms of ionisation, in that they now described the importance of distance between the nucleus and outer electrons as a feature of reactivity (§7.2d). However, they continued to rely upon anthropomorphic and heuristic metaphors, such as in Simon's use of the octet heuristic, 'It needs to have, to have a full outer ring (S1), and anthropomorphisms such as Sophie's a, 'displacement reaction is bringing one electron to another' (S3) and Morley's, 'the Nucleus … releases a proton' (S2). Such explanations suggested that their resultant conceptions of particular conceptual features remained tentative.

7.2c Students recall attraction as conveyed through staring particle-actors

Particular images from the lesson were strongly remembered in the post and delayed interviews, and the concept meanings associated with those images tended to be retained clearly too. One striking example was the clarity with which Sophie and Simon illustrated their understanding of proton-electron attraction with reference to their interactions within the ideal atom simulations. They, in-role as electron and protons, held their gaze with co-actors in order to model the attraction between the particles. Amidst sometimes inconsistent explanations, both described the image and its significance,

> Yeah, and then, then I had to try to keep eye contact with them because positive and negative attract. (S1)

> You had the electrons, or the electrons, protons like, looking at each other to show that they were attracted with one another. And then you have the neutrons in like, in between them. (S2)

In consideration of both students' strong recall of staring as a sign for attraction, I speculated that this feature may have included an affective aspect in regards to the intensity and explicit complicity required in this shared action, with each student staring at another student, who stared back, as the electron actors circled around the neutron actor(s).

7.2c.i. The possible degradation of a conception between the intervention and post interviews

During the intervention itself, students' responses during the HAMs task suggested that a key learning objective appeared to be met, in that students tended to describe reactivity as related to the distance from the nucleus to the attracted electron: During the intervention, three of the groups included in their TE responses the conclusion that fluorine was more reactive than chlorine, and related this to the idea that fluorine's outer electrons were closer to the nucleus (Obs).

However, in the post and delayed interviews, the responses suggested an awareness, rather than an understanding of this concept. Initially they did suggest that the shorter the distance to the nucleus of the halogen, the greater the attraction. Sophie noted, 'The closer [the alkali metal electron] is to the centre of the nucleus, the more reactive it's going to be' (S3). Morley provided a similar description when he said that, 'depending on the reactivity, the closer it [the outer shell] is to the centre of the nucleus, the more reactive it's going to be (S2). However, Sophie followed up her response by erroneously indicating that larger atoms are found higher up the halogens column:

> The further they move out [the electron shells from the nucleus], ah, the further it's [the element is to be found] up the periodic table… (S3)

Morely also appeared tentative in respect to the relationship between halogens and alkali metals, as suggested in his confusion over whether chlorine or fluorine were more reactive:

> Sorry, I went wrong. It's one of them, it's just that they both end in 'ine'. That's where I get it wrong. I think it was the chlorine that was most reactive, it was closest to the centre.

Simon, below, also related reactivity to distance from the nucleus (line 2). However, he seemed to contradict himself in line 6, and then supposed that fluorine *would not* displace chlorine in a displacement reaction (line 8) (the alkali metal ion was potassium).

1. *Which is more reactive fluorine or chlorine?*
2. Chlorine because it's, the shells are further away so it hasn't got a stronger pull on the outer shell.
3. *So chlorine is more reactive because there's a greater distance to the outer shell of the nucleus.*
4. Yes.
5. *So it is has got more attraction.*
6. No, it has got less.
7. *Okay, so if fluorine is introduced to this reaction what do you think happens?*
8. I'm not too sure… Nothing. (S1)

These latter examples supported my interpretation that over the course of the post and delayed interviews, the students seemed to be blocked from visualising a clear narrative of ionisation and of displacement reactions. The post interviews occurred almost a week later, the latest of all cases, in part due to a snowstorm, school schedules, and Morley being ill for an extra day. The duration may have exacerbated an issue related to their visual recall. However, it was my interpretation that these interviewees' understanding of the relationship between halogen and alkali ions was due in part to their inability to visualise the alkali metal ion in their post interviews. The potential for this omission was suggested during analysis, in the degree to which students based their TE simulations upon my teacher demonstration of ionisation in which I used a *pretend object*, an imagined potassium atom. The following sections describe the progression of imagery and conceptual features that suggested that students could work with this proposition to imagine a potassium atom in class, but that the proposition was not recalled in the post and delayed interviews, hindering students' overall understanding of ionisation and displacement.

7.2d The whole class atom and the pretend object

I initiated a whole class simulation after the ideal atom task similar to that in section 5.2. Students were told to create a model of an atom using everyone in the class, and then classify that atom. The students were a few short for the fluorine that I intended that they would make, so I assigned neutrons to play the roles of electrons and protons. The following section sets the context for subsequent sections in that it illustrates the process of creating the whole class atom, from which the expressions in later tasks were drawn. In an example of the progressive nature of the imagery within the intervention, the figures below suggested that students relied upon key features from their previous atomic models for expressing the whole class model.

Figure 7.3 Whole Class comes together to discuss simulation (V:1:27:13)

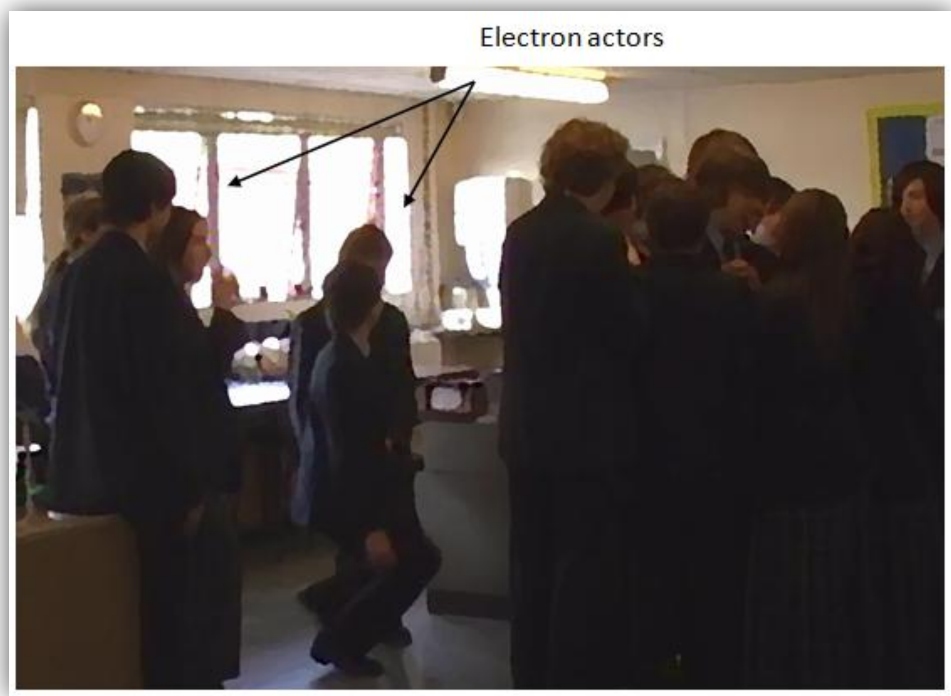

Figure 7.4 The electron group decides to separate from the main group. Two students' move and crouch to lower levels in an echo of the electrons in the atomic simulations trios. (V2:1:27:41)

Figure 7.5 The electron actors move initially as a group, following a 'leader around the nucleus.' (V2:1:27:49)

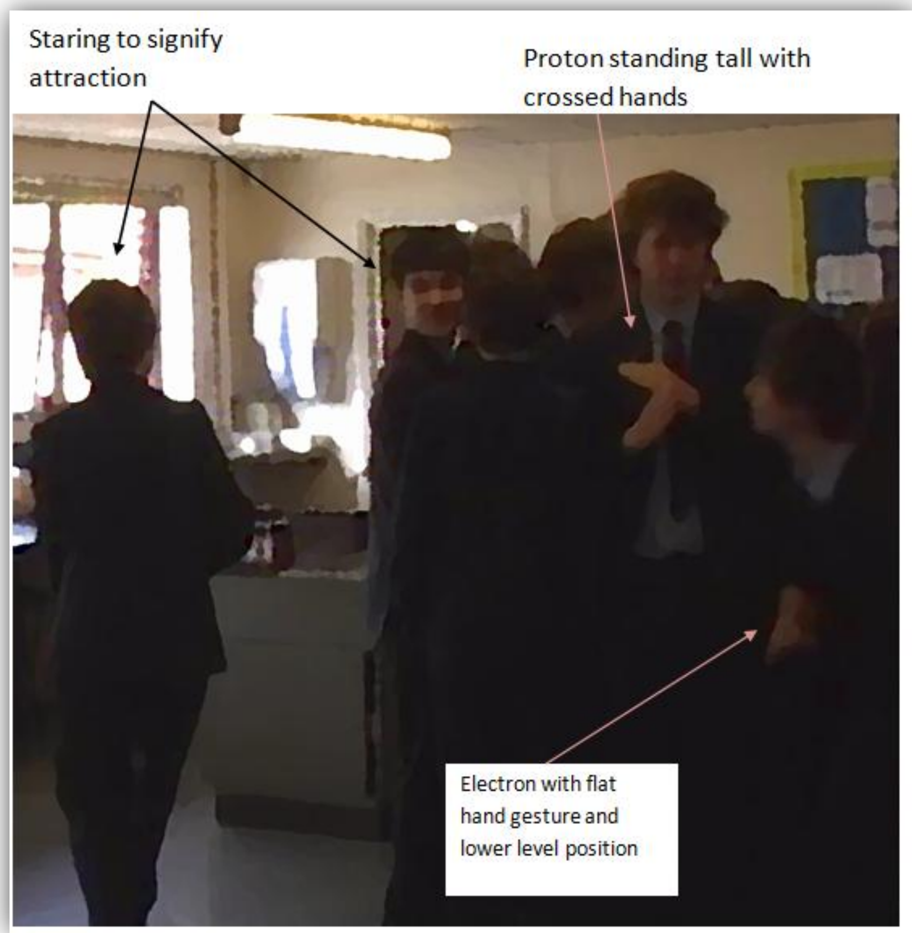

Figure 7.6 Within seconds the electrons have spread out from one another, and each gestures to signify negative charge, as they did in the ideal atom trios earlier. The centre group now separates into those with cross-hand gestures and those without. (V2:1:27:57)

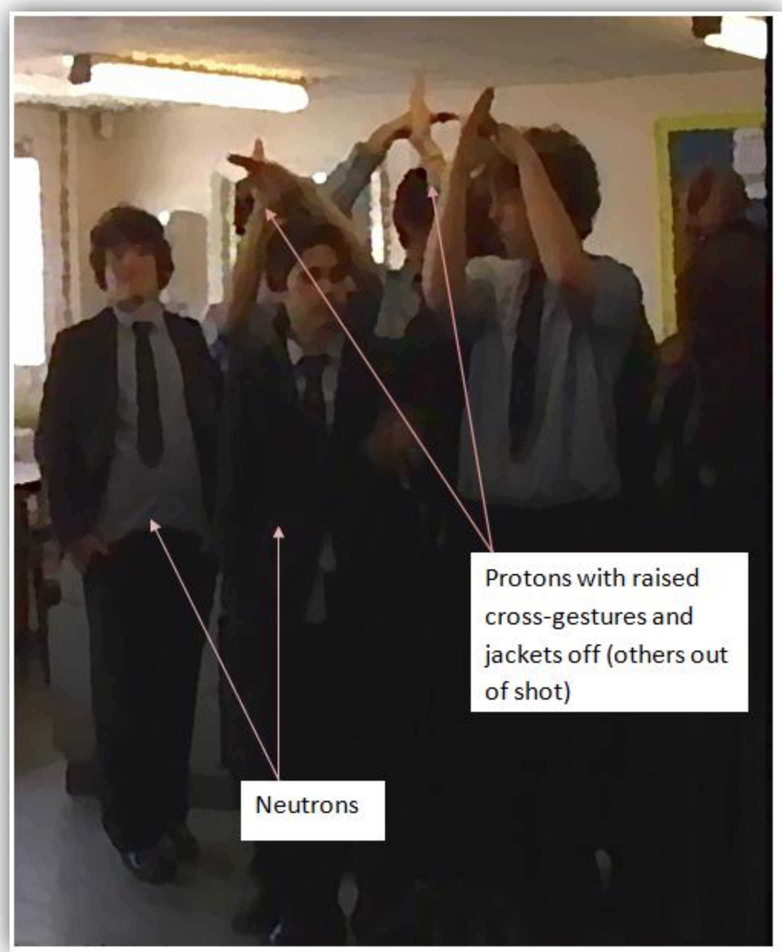

Figure 7.7 During a forum evaluation, proton- actors emphasise gesture and remove jackets (V2: 1:29:11)

Once the whole class simulation of the fluorine atom was completed, I asked the students in the nucleus to sit down within the halogen (fluorine) configuration, in order to foreground the electron configuration (Figure 7.8). Then I adopted the role of a potassium electron.

Figure 7.8 Whole class fluorine atom after nucleus actors sit down (electron actors stand) (V1: 1:30:52)

I asked the students to imagine a potassium atom at a distance which corresponded to somewhere just beyond the wall of the classroom. This atom was further inferred through the fact that I, as its electron, emanated from its direction. As I moved from towards their outer shell, I invoked a mnemonic technique as I asked students to call out ‘Halogen, halogen, halide!’ and to smile, to indicate that a chemical change had occurred.

7.2e The HAMs TE task: incorporating the pretend object

The subsequent task was a HAMs task. The task included a thought simulation – a translation of the teacher demonstration of electron transfer – and a TE task whereby students were given a question towards the end of their HAMs preparation in which they needed to visualise the addition of another halogen.

Rather than provide students with the human situation and roles, as I did in Chapter 5.0, this task allowed students to create their own signifiers and relations between base and target analogies. The choices were eclectic, with groups choosing situations involving children running to an ice cream van, a scenario employing the Stockholm syndrome, drug dealers and slave traders. These were drawn from a range of domains: the Stockholm syndrome, for example was inspired by a previous History lesson, according one of the group members (V1:37:21). For the teacher, personal choice was a key benefit of the activity,

> I think one of the strengths of it was because the way they did the role-play was based upon their own choice, they have a choice, therefore they had to [choose]. Whatever they were coming up with was rooted in, rooted in something they were interested in. (T)

The analogies drew together features of their chosen social domain analogy features from the previous demonstration of the whole class fluorine atom (Figure 7.7). The interweaving of these features appeared to motivate students to visualise and express *dynamic* particle behaviour at the sub-micro level. However, the imagined object configured an asymmetrical feature within their expressions. This was illustrated in the post intervention with Morley’s extended description of his group’s analogy, along with Simon’s description of the same group, and corroborated with video evidence. Morley’s passage, below, suggested the impact of the demonstration upon the subsequent group work models, but also a lack of a metacognitive awareness when they modelled the imagined potassium atom.

An initial focus for Morley’s group appeared to be to convey the concept of attraction between the potassium electron and fluorine atom. In line 4, Morley described the attraction between potassium’s outer shell electron and fluorine, with a child’s desire for ice cream.

1. *Okay who came up with the idea of the ice cream?*
2. I did.
3. *That's lovely. Why, why do you say ice cream?*
4. It attracts kids when you're going past, and you have to run after what you want. And so that's what I was thinking, the potassium electron would be attracted by a [ice cream] truck.

This response suggested that Morley’s ‘kid’ corresponded with my potassium’s electron. There was no associate role or image with which to signify the potassium atom. By contrast, fluorine was signified by a student in-role as vendor, miming driving the imaginary van. On the video, the student mimed a steering wheel as he and Morley moved in a line forward. During a stimulated recall session with video, Morley described the situation,

1. Okay, and let's go through the recording again that you guys did, you've talked about seven electrons –

2. Electrons that’s it, yeah.

3. *What were they?*
4. Electrons
5. *What was the ice cream version of electrons? Were they actually seven electrons?*
6. No they were *seven*, well basically we acted as if they were ice cream. We said, 'Would you like seven electrons?' and they were like a make of ice cream.

In the video (V1: 1:52:30) the vendor mimed handing Morley to the student playing the 'kid'. The student who was handed over was the ice cream, the '7 electrons' flavour that signified the fluorine outer shell. The handover resulted in the 'uniting' of the eight electrons between potassium and fluoride ions. At the point of touching, Morley and the other student vibrated, as if charged.

5. *Okay brilliant, a make of ice cream.*
6. Then he gave them out and he [the electron] was so happy that a reaction had happened.

During the ideal atom modelling task, the signifier that I had demonstrated for a positive charge was to smile. During the whole class ionisation demonstration, students were to frown until the point of charge imbalance and then smile. Morley's potassium electron was also happy. This was ostensibly an example of metonymy, in which the electron-actor's smile signified the potassium's positive charge.

Morley finally described their modelling of the non-displacement reaction when a chlorine atom appeared:

7. *Good, was there any other coding; you said the attraction between ions?*
8. I am not sure; all I remember is that that happened then Simon came along and said, ‘Okay’ can I have some [ice cream/electrons], and something that we should have done is said that we've run out now go away.

On the video, Simon can be seen at the edge of the frame being pushed away by the vendor; suggesting potential competition between halogens.

The figure below (Figure 7.9) illustrates how concrete images were provided for the potassium electron, for the fluorine outer shell (the mimed ice cream cone), and the fluorine atom (the vendor driving his van) (the chlorine atom is not shown but was acted by Simon). The top image illustrates my interpretation that the potassium was solely a proposition (signified by the empty circle) rather than concretised image.

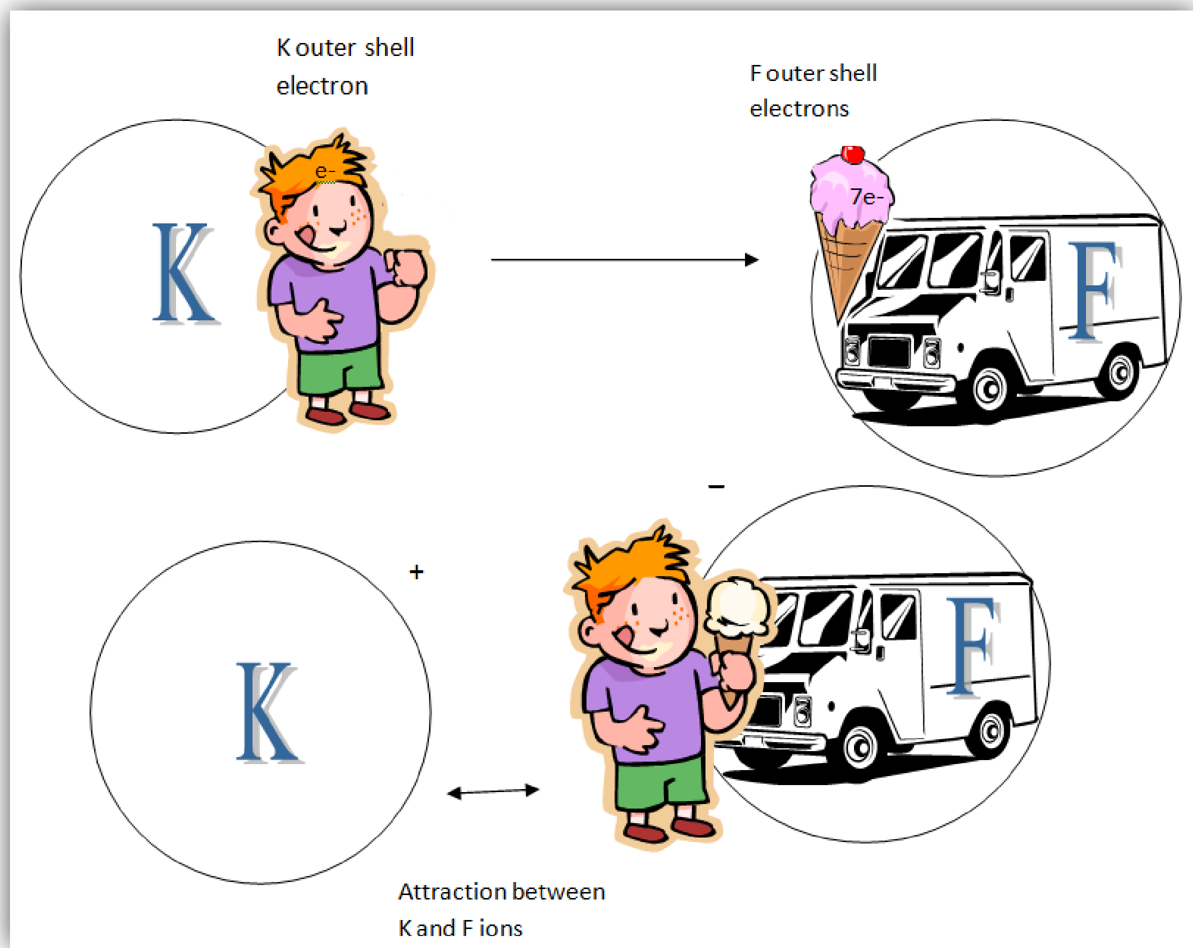

Figure 7.9 The ice cream analogy: K and F outer shell electrons interact

This scene suggested that the students re-enacted the key features in my BAPs demonstration through their HAMs. While the value of this new model appeared to support a greater metavisual sense of changes in charge due to the movement of electrons, the use of my BAPs signifiers potentially left a visualisation *gap* in place of the alkali metal atom.

7.2f A positive affective environment

Morley's loquacity in respect to his description of the TE task suggested a sense of confidence in the post interview. Sophie and Morley were reticent in pre-interviews; they appeared unsure and unwilling to express themselves freely. This reticence was echoed by the teacher, who indicated that many of the students tended to be reserved in lessons,

> [They] don't readily volunteer ideas. [They] sit and wait to be told what the answers are. There is normally, there is about two or three people who will always have their hands up and the rest just sit and let them get on with it.

By contrast, the intervention appeared to support a positive affective influence, for example, in that all interviewees described the intervention as ‘fun’ in the post and delayed interviews. In respect to their perceived utility of the lessons, near the end of the post-interviews I purposely asked a biased question in order to elicit criticism of the lesson: Were there any moments in the class when you felt like you weren't learning? For all three interviewees the response was similar, with, ‘No.’ (S1), ‘No, actually’ (S2), and, ‘No’ (S1). Their responses were corroborated by the teacher, who observed that the intervention held students’ focus to a high degree. He noted in particular that aspects of the lesson drove student focus through a ‘gradual build-up’ within the lesson structure, aligned with continuous formative assessment and a novel means of expression,

> Again I liked the way it was started, I liked the gradual build-up, and I liked the idea. But you start with the central concept, that, that's in their head; and through various methods you tease out how they actually perceive what you are trying to teach them instead of just assuming that they are involved [i.e.] ‘We did this last day therefore you’ve understood it’ - It's expressing their understanding through new ways other than just

trying to write it down. (T)

The teacher's observations appeared to support an interpretation of inclusiveness within the intervention, but also that I held a degree of control over the learning environment, in particular in how I 'tease[d] out' perceptions. In this context, both a teacher and the students may potentially feel empowered and comfortable with this teaching approach.

7.3 Discussion

7.3a Pretend objects

This intervention appeared to support interviewees' conceptions that the distance between outer electrons and the nucleus related to their reactivity. However, they appeared to have difficulty applying this concept to a visualisation of ionisation and displacement at the sub-microscopic level. In exploring the reason for this failure, I interpreted that the issue had its inception in the whole class teacher demonstration, when students were asked to *pretend* that there was a potassium atom, rather than being offered a concrete model. It appeared that the students maintained this pretend object as a proposition with no definite associated image. While students appeared to be able to express group simulations of ionisation, and could respond to a 'trick' question about how particles would interact with the addition of a less reactive halogen, they could not do so clearly in their post and delayed intervention interviews.

There has been no research that I know of into the use of 'pretend objects' in such a way, with respect to memory and visualisation in Science. However, the issue echoes the theories of analogical reasoning (Lakoff & Johnson, 1980; Lakoff & Nunez, 2000;

Sfard, 1994) which assert that metaphors are informed by visual and sensory-motor experience. Such theory would suggest that concrete images, which the students enact, might provide immediate sensory experience which makes a model more vivid in the mind than a model constructed from the teacher's call to pretend.

7.3b Anchor metaphors

However, this issue of selective memory, i.e., the selection of discrete images and corresponding explanations, resonated with evidence of interviewees' recall of striking images, analogies or events in the interviews. That these memories appeared to be accessed in a fractured manner, but then became aids to *anchor* their understanding led me to term them *anchor metaphors*. Interestingly, this fractured recall was not interpreted to occur in the context of the lesson tasks, in which students' expressions suggested that they focussed on the narrow range of topic concepts and models which they were taught. It seemed as if the students relied on two different schemas: in the lesson they relied on applying their immediate experience, whereas in the interviews they seemed to rely on an unpredictable range of images and events. Dagher (1995) and Jarman (1996) have asserted that students' idiosyncratic explanations are drawn from the world around them. This led to me to consider the metaphor of conceptual development as a competition of discrete images and explanations. These seemed to be analogies of scientific concepts which were recalled or retained *in preference* to other images and events that students had experienced. These appeared to be centred upon novel and vivid images and events, and therefore shared features of Loi and Dillon's eccentric objects and odd experiences (2006), principally the idea that novel or odd juxtapositions drew students' attention. However, some of the anchor metaphors in the intervention appeared to draw their importance also from the students' relationship to another person, or the group, or the class. For example, the interviewees' recall of their eye contact to represent attraction between protons and electrons, and the group chant of 'Halide…halogen!' indicated the influence of the community experience on the retention or comprehension of the memory. This suggested that relationships and a sense of community provided an *affective* quality which further enhanced the recall of an analogy.

7.4 Summary of Case 3

This case focussed upon the teaching of ionic bonding and displacement reactions. The lesson progressed from the warm-ups to group BAPs of ideal atoms, a whole class TE BAPs which resulted in a model of a Fluorine atom, a BAPs demonstration of ionisation with a 'pretend' potassium atom, and finally to group HAMs which model the a solution of potassium fluoride, and the behaviour of particles when aqueous chlorine is introduced. The HAMs were observed to promote extended group work and creativity. All interview stages suggested that conceptions competed with alternative conceptions for explanations of the topics. Pretend objects appeared to hinder post interview understanding, as they were not remembered by the students. Post and delayed interviews suggested that students developed an understanding of the influence of distance between the electrons and the nuclei of the atoms as a cause of ionisation.

8.0

Case 4: Diffusion Revelation in DT Class

> 'Because it is fun, we got, like, enjoyment out of it, instead of writing down, we got to like get up and make it more fun so we get to work with each other, team work and things like that. Making the shapes. We did that, we did, like, teamwork, you know like, it was more fun.'
>
> (S3)

8.1 Case Description

This case reports on twenty students in a Science class of 11-12 year olds in a state school in Hertfordshire. Students were described as kinaesthetic and unwilling to write (T). The class was a bottom set, who were perceived by the teacher and Head of Department as difficult to teach (§8.6). The classroom had a white board at the front, windows at the back, and several long tables that were pushed to the sides and towards the teacher's table, which was fixed to the floor.

8.1a Teaching objectives

- Review a particle theory description of solids, liquids and gases
- Provide a particle theory explanation of diffusion
- Provide a particle theory explanation of dissolving of sugar in water

8.1b Lesson description

After a brief interactive/authoritative discussion on the utility of particle models, the class was divided into two groups of ten, and the students engaged in the warm-up tasks (§4.4a). The topic tasks began with a review of the states of matter and the introduction of the Gestural Teaching Model (GTM). The class was asked to form a line and simultaneously apply their simulations as I called out an increase or decrease in temperature. Next, four students acted as particles in a teacher-directed bodies-as-particle simulation (BAPs) of states of matter. Then students were put into four groups, to prepare and then perform particle behaviour corresponding to my narration of 'The Chocolate Bar Story' (Appendix 1). The students next formed five new groups of four, and prepared and performed the BAPs task, 'The Spy's Perfume' (Appendix 1). Each group was evaluated by their peers. Four groups were then created and tasked with producing gestural metaphors of a sugar particle dissolving in water; these were not evaluated, due to time pressure. The lesson ended with a brief review of states of matter, dissolving and diffusion.

8.2 Analysis

In the pre-interview, two students, Aisha and Mark, declared that particles could not be found at any magnification in either liquid water or gas: Mark described air as, 'like something invisible, something we just breathe in all day' (S3). Aisha also said that particles existed in some but not all solids, such as 'chocolate' (S2). She described particles as, 'like bits in a table' (S2). Sarah was the only interviewer to reveal an awareness of particle attraction, or 'stickiness' (S1). Mark professed not to have previously heard of the terms 'atom', 'molecule', or 'particle' (S3). Aisha defined the term *atom* as, 'A part of a chemical, or it can be in water as well' (S2). None of the students could define the show card term *diffusion*.

Interviewees' drawings supported the interpretation that the students had a tendency to perceive dissolving and diffusion from a macro perspective. For example, drawings revealed representations of water and sugar as continuous substances. In Figure 1.0 Sarah appeared to describe a macro perspective: The water was signified by the water-line, which suggested a continuous substance, and labels of ‘bubbles’ and ‘greyey’ (sic) liquid suggested descriptions drawn from macro experience (Figure 8.1).

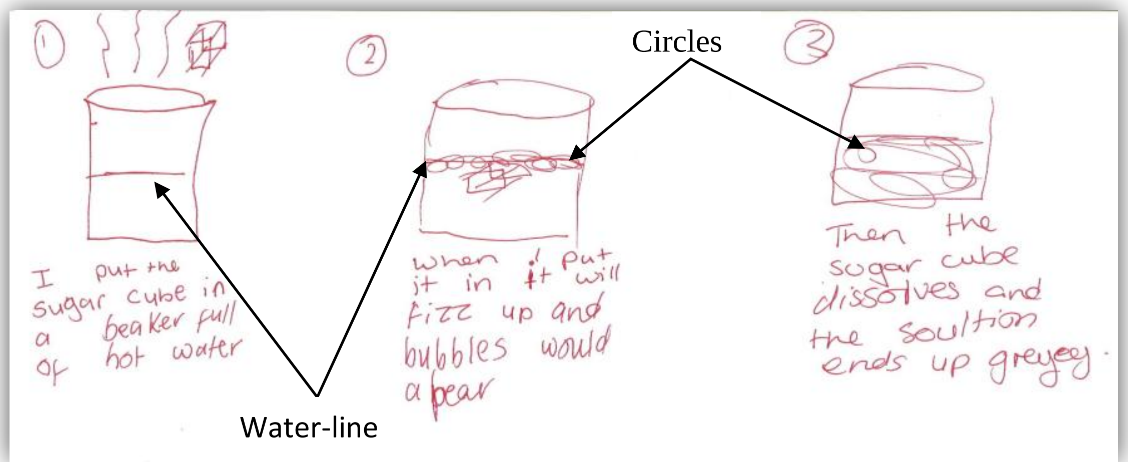

Figure 8.1 Pre-interview dissolving (Source, S1pre)

At the stage in the interviews in which the drawings occurred, Sarah had heard the term, ‘particles’, during ‘magic goggle’ questions related to a sub-micro perspective of physical phenomena. She seemed to attempt to include this concept in her subsequent drawings. Within the squiggles signifying sugar, there appeared to be circles, which I interpreted as particle-like features. This intention appeared to be in even greater evidence within the diffusion diagram as the interview progressed (Figure 8.2).

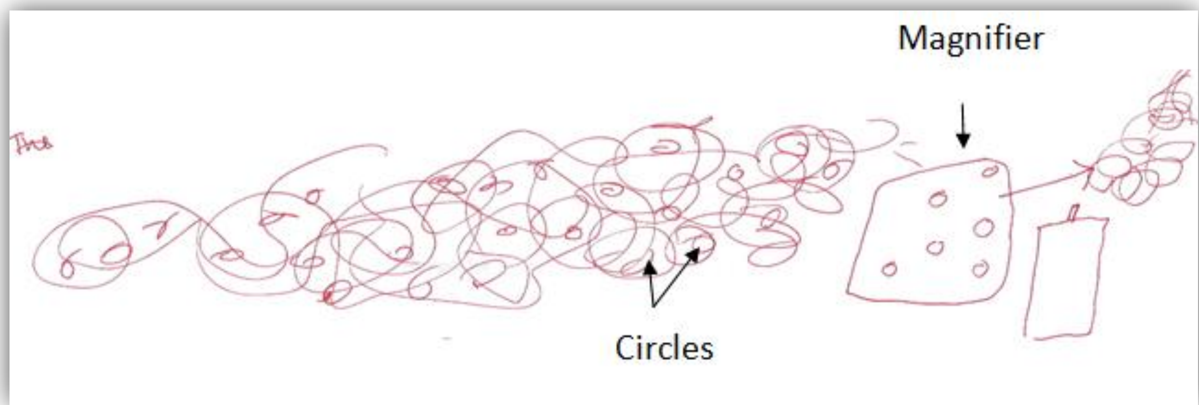

Figure 8.2 Pre-interview diffusion (Source, S1pre)

It is therefore plausible that she was trying to incorporate a naïve particle conception by this stage into her drawing. To this extent, her responses suggested her awareness that some substances are particulate, but as yet she had a vague understanding of how these might be visualised.

Sarah's description echoed Aisha's vague expression of particles in her sugar drawing, below (Figure 8.3). At first I interpreted Aisha's interstitial particles to be a representation of sugar particles, similar to a 'zoom lens', e.g., the circles in the final frame appeared to be superimposed over a macro description of undissolved sugar. However, she said that these were 'Teeny bits of sugar', suggesting that they were not molecules.

> The particles are in between the sugar. Teeny bits of sugar.
>
> *Okay. Teeny bits of sugar.*
>
> And so you won't actually see it from, like pretend this is the cup with sugar in, you can't really see it … (S2pre)

The use of 'really' suggested that the particles were almost visible (rather than of an atomic scale). The drawing (Figure 8.3) of sugar dissolving, with the circles at the bottom of the beaker on the right seemed to be a mixture of visible residue, large and smaller pieces, or 'bits' of sugar. There was no indication of water 'particles'.

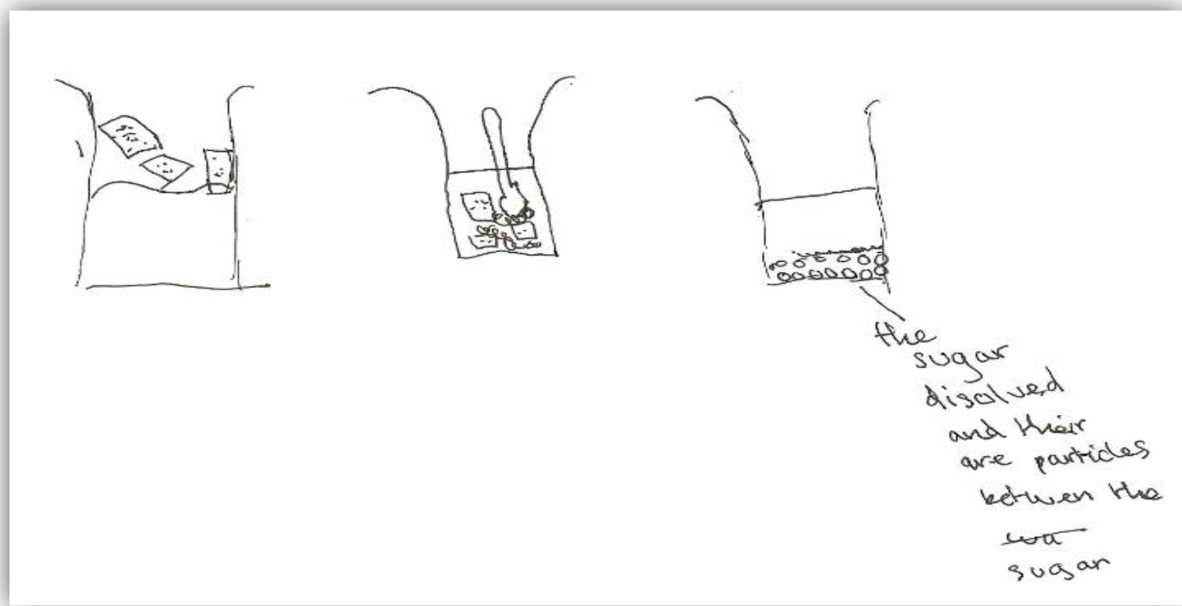

Figure 8.3 Pre-interview dissolving (Source, S2pre)

In the pre-interviews, these descriptions reinforced an interpretation that the interviewees expressed only a vague awareness of sub-micro level representations of particles.

8.2a Post interviews

Post interview descriptions indicated that after the intervention students were more inclined to portray phenomena at the sub-micro level, and describe particle movement, interaction, and the effect of heat energy. Whereas Mark and Aisha had not described particles in liquid and air, now, they did, with Aisha offering the example of melting chocolate, whose particles she noted,

> Well in the chocolate the particles are close and when melted.
>
> *You've got your fists together and –*
>
> Then they move apart. (S2post)

Aisha supported her comments with gesture, suggestive of the solid gesture from the GTM. Mark too employed the GTM, and noted that,

> I learnt lots about like the particles, do you remember the particles, like, together, [gestures (Int.obs.)] and then sort of liquid being like moving around like, the gas is far apart, and the solid is really close together. (S3)

Whereas Aisha and Mark did not previously describe attraction, now Aisha said that particles ‘are attracted in a solid. Not to a liquid’ (S2), whereas Mark perceived that attraction occurred, ‘even in a liquid, but just not as much as like a solid, but they are still attracted, still moving around, but they are still always connecting’ (S3). Mark’s comments were sensitive to the complexity of the multi-particle system, particle movement, and attraction between solid and liquid particles.

All interviewees increased the number of show card terms that they used in their concept maps, with Mark adding ‘energy’ and Aisha adding ‘dissolve’, although both continued to leave off the term ‘diffusion’, whereas Sarah now added this term. In the delayed interviews Mark would subsequently add ‘diffusion’ to his concept map.

The post interview drawings foregrounded sub-micro level perspectives with more consistency. For example, Sarah’s diffusion drawing (Figure 8.4) eschewed the squiggles of her pre-interview drawing, and now only showed circles, not squiggles. In conversation she noted that there were ‘air particles’ as well, although she did not indicate different types of particles in the drawing. The increasingly filled spaces with a random-like distribution of circles across the three sections (before/middle/end) suggested her perception of a gradual diffusion of particles in and around the opened container.

Figure 8.4 Sarah’s post interview drawing of diffusion (Source, S1)

8.2b A student-initiated thought experiment-type visualisation

The interviewees' explanations of diffusion in the post interview suggested an increased ability to delineate and telescope between macro and sub-micro levels of thought. In one episode, Mark was interpreted to have engaged in a thought experiment-type visualisation outside class. In the pre-interview, Mark had held a particularly tenacious view of particles as 'living' (§8.2g), which I had assumed may hinder his development of the concept of diffusion. Also, in his drawing and verbal description of diffusion, he described gas being released from a bottle as a continuous substance, with squiggles signifying its flowing up and out of the bottle (Figure 8.5). Mark, noted, they then 'spread everywhere' (S3), but in his drawing, the gas appeared to have completely left the bottle, and poured down the side, rather than developing a new equilibrium within the surrounding environment.

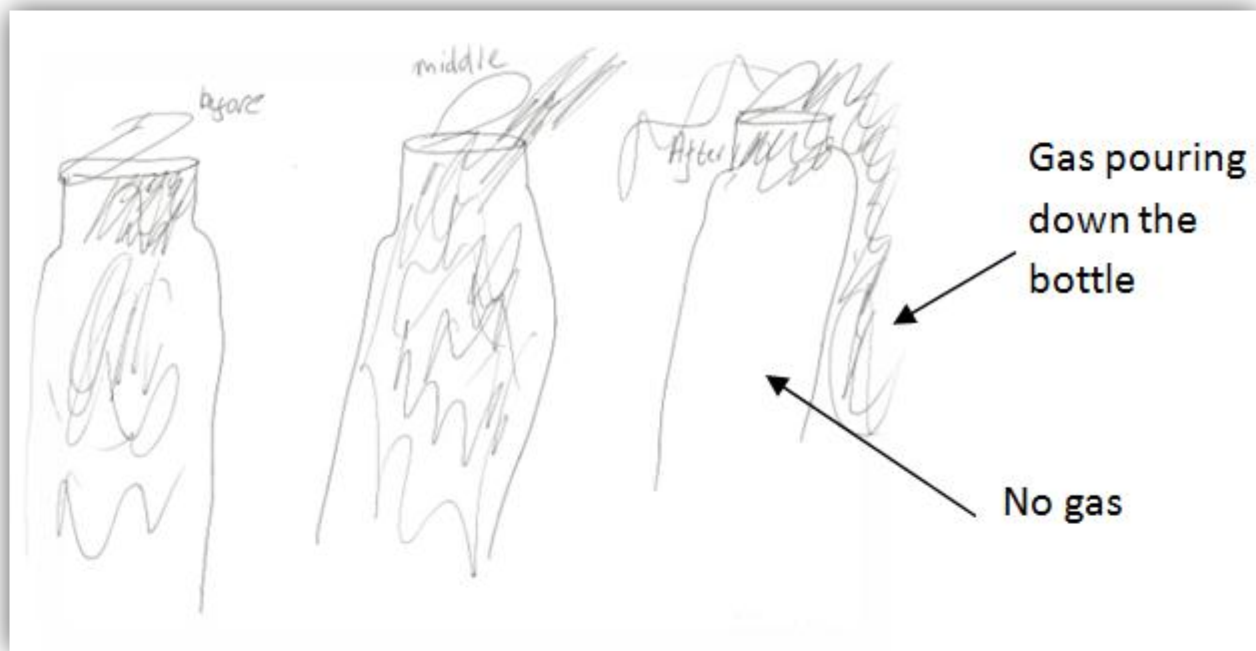

Figure 8.5 Mark's pre-interview drawing of diffusion (Source, S3pre)

The squiggles and lack of signifier for air seemed to reflect Mark's perception of a continuous gas substance in that, ‘Air is like something indivisible, something we just breathe in all day’ (S3pre). His subsequent explanation of diffusion initially appeared to reveal a macro-level perception, which, while it included concepts of mixing and spreading out, nonetheless avoided a sub-micro perspective.

> Is it something to do with the air? I think it, I think it is something to do with the air and like the gas because it's like mixed together, and it could spread out, because I had a kind of deodorant and I sprayed it and so if you are near you would be the one to smell it but after a while, like a couple of minutes for a couple of seconds it would like spread to every end in the room, and eventually someone there would have the chance to smell it. (S3pre)

By contrast, in the following passage, a post intervention response suggested a self-motivated visualisation of the process of diffusion at both the macro and sub-micro level. He began with a description similar to the pre-interview response above,

> I tried this the other day because I, cause I was bored and I was sitting in DT [Design and Technology] and I had a bottle, and I finished my bottle of drink and I was squeezing it, and I went and I caused the smell of the drink and it took a second or thirty seconds or a minute, and the smell was coming from a bit away from me. It just kind of went round and then I smelt it. (S3post)

This first passage paralleled the macro focus of the pre-interview passage above, focussing upon sensory observation. However, Mark then described his contemplation of the relationship between particle behaviour and observation (line 3).

1. *That's interesting.*
2. So I was like ooh. Because it don't come in [I did not smell it] straight away. They [the gas particles] go like really fast, but in the end, it [the gas] was quite slow, and it kind of takes time to [smell] it.

Mark compared the speed of particles to the observed gas movement. My subsequent prompt, however, lead to brief confusion. As Mark and I re-oriented our discussion, he noted that he considered that gas can ‘move’ without open windows or moving air. In line 7 he discounted the effect of these variables. This appeared to help him to illustrate that the gas particles themselves were the agents of movement.

3. The gas was, the gas was. Oh no, the gas wasn't because it spread out, because it was all going like that really quite fast.
4. *Okay so it's fast and yet you've made an empirical observation that for you at human size it is slow. Why do you think that might be?*
5. I have got two reasons; when I think, ah, in films when you let a gas out, it's quite slow and gets around, like, the room --
6. *I agree.*
7. Because, like there are no windows: no oxygen is coming in, air.
8. ...
9. Yeah.

10. *So, so why is it that –*

11. It depends on the particles.

12. *You said it depends on the particles, go on. But didn't you say they were going fast?* [see line 5]

13. Yeah, but gas.

In line 14, I aimed reiterate my questions about relative speed in order to support redundancy in the data. Mark clarified his view.

14. *So while they are moving fast how come we see it moving kind of slow?... the gas. Just something to keep in the back of your mind.*

15. Maybe to the particles it might be like, fast, because they are probably teeny, teeny things. Teeny, really small. To them, because like, we hardly can see them before using like a really good microscope thing. And I think to them, because they are so far away [then] we can't see them moving quite fast, to us, because they are like in a big bunch, then it would be really slow. (S3post)

This description was in marked difference to Mark's expression in the pre-interview passage when he explained diffusion through a series of visual and olfactory sensations. He appeared now to show a sense of empathy towards the gas particles similar to Metcalfe's perspective (1984) when he perceived that 'to them [the particles]' their speed would be 'quite fast'. A sense of visual-pictorial imagery was also indicated in reference to 'films', 'microscope' and of shifts in point of view.

Mark was perceived by staff as low achieving and unfocussed in previous lessons (T). Nonetheless, Mark's explanation of what occurred when he squeezed his pop bottle appeared to meet Gilbert's criteria for a thought experiment visualisation: Gilbert's *goal* was evidenced by Mark's self-motivated attempt in DT class to answer the question, 'why is [the odour moving] slow?' question. *Experiential knowledge* was indicated by the Mark's experience of the cola odour, and his understanding of gas particle movement. The *internal coherency* was indicated in the final passage, in the ability to describe both a human perspective and a particle's hypothetical perspective. Mark's delineation of macro and sub-micro worlds (employing reference to the DT class, to film, and to perspectives of particles) reflected the 'spontaneous operation of structured imagination' (Gilbert, 2005, p.65). Such evidence suggested too that Mark was operating with a degree of metacognitive thought in delineating our reality and that of the sub-micro world.

8.2c Gestural inconsistency with diffusion

In the pre-interviews, Sarah and Aisha had initiated gestural metaphors without prompting. These expressions were observed to change over the course of the interviews. Two key modes which appeared to impact upon these expressions were the GTMs that were introduced in the lesson, and the BAPs; in particular, the BAPs in which students had used slow motion as a signifier for fast gas particle movement. This section begins by exploring the breadth of Sarah's gestures, and a possible influence of a previous BAPs upon her gestural metaphor of solid particles. Sarah responded to a pre-interview show-card question on solids with,

> Particles. Squashed together.

So you have taken your hands and you have put your fingers together haven't you; and squashed them together. Okay; do they move?

They jiggle.

They jiggle. So they are squashed together and they are jiggling. Can you show me that? (S1)

The passage above indicated that for Sarah the solid particles appeared to have no defined shape, as her fingers were intertwined, and ‘squashed’. The term, ‘jiggle’ arose after the initial gestural metaphor. She did not *enact* ‘jiggle’ until the end of this dialogue, i.e. she did not imply movement in her gestural metaphor.

Sarah next showed gas movement with her finger raised in front of her, as if her fingertip were one particle.

Gases, well, gases which are moving around.

Okay. You had your finger moving very quickly, are you saying they are, they move that quick. Do they move that quick? Or actually slower or faster?

I don’t know but they are moving about, bouncing. (S1)

Rather than emphasising a collapsed sphere-shape, this appeared to convey not image but speed and random-like movement. In contrast with the GTM, Sarah’s choice of gestures appeared inconsistent, suggesting that the particles had changed form. Interested in why she did not retain a consistent model with the solid particle gestures (i.e., why not continue to use ‘open-hands for particles in a gas?) I then probed her to model liquid particles:

And they are squashed together.

And you are almost clapping your hands they are so squashed together; is that right?

Yeah. (S1)

The gesture of an open-handed limp clap for 'liquid' echoed her gesture for the solid. The question remained as to why Sarah had shifted from the squashed-hands model for solid and liquid particles, to a finger-pointing model for gas. Her confidence in using the term 'squashed' inspired me to assume that she may have encountered this term in a previous lesson. In the post interview, I asked about previous role-plays that she might have done. Corroboration seemed to appear in her recall of a past class demonstration:

Well, Mr Cowling told us when we were doing particles, we had to stand in this room and like jiggle about.

...

Did you do liquid?

No, we just did [solid]. (S1)

It seemed plausible that her 'squashed' particle model was informed by the role-play in the previous lesson, in which the students 'just did' one state of matter. It suggested that Sarah entered my intervention lesson with a conception of particles drawn from a dialectic of images of particles as objects (gas particles as 'tennis balls' (S1pre)), gestural representations, and BAPs of a solid, and that these had informed a potentially inconsistent visualisation of particles shape and movement.

8.2d Floating gas particles.

In the post interviews, it was within this multimodal context that previous discourse across a combination of talk, gesture and action may have contributed to Sarah's gestural choices such as portraying gas particle movement in diffusion as seemingly slow and 'floating' (S1; S2). Interestingly, the show-card stage of the post interview revealed that all three interviewees had described solid and liquid particles in a manner consistent with the Gestural Teaching Model (§8.2a for Mark and Aisha). Sarah, no longer used a finger to describe a single gas particle, but instead retained a two-fists based gesture similar to the GTM,

> The gas will be like that.
>
> *Good, your fists are moving all over the place.* (S1)

Sarah and Aisha did not remain consistent with their GTMs. Later in their interviews, they gestured gas particles at a much slower speed when discussing diffusion. Both interviewees, when asked to show gas behaviour with their gestures used open palms while moving hands slowly upwards (S1; S2). Aisha had provided a similar gesture in the pre-interview:

> *You are saying that they are spreading apart they are floating.*
>
> Yes, because like --
>
> *Do they float? Do gas particles float?*
>
> I'm not sure. I think so. It goes up in. [Gestures (Int.Obs.]
>
> …
>
> *With your fingers outstretched and your hands flat? Okay.* (S2pre)

My description of Aisha's 'flat' hands, and the context of our discussion about 'spreading,' 'floating' particles suggested that she held a similar visualisation to Sarah. However, as noted above, both girls had described gas particles as relatively fast in the show card episodes (S1; S2). The persistence with which they held this slow particle concept seemed inconsistent with their previous descriptions. For example, I noted,

> *Okay, but at the beginning of this conversation you weren't moving your hands so slowly as you were just now, when you were doing the gas. Why is it you are moving them slowly now but not earlier?*
>
> I don't know (laughter) it just came into my mind. (S1)

Sarah even appeared to contradict herself only moments before the discussion on gas movement through the room:

> *So why doesn't it [gas] stay in the bottle?*
>
> Because they [gas particles] are moving a lot. (S1)

Given their consistency in describing states of matter, Aisha and Sarah nonetheless continued to show 'slow' gas particles when applying the GTM to diffusion.

8.2e Developing an alternative conception of particle speed through slow-motion BAPs

Sarah and Aisha may have been informed in their conception of 'floating' particles through BAPs of gas particle movement. During the intervention, all students participated in four simulations of particle movement, two of which employed gestural models (the GTM demonstration and the dissolving simulation) and two that employed BAPs (‘The Chocolate Bar Story’; ‘The Spy’s Perfume’). In the gestural tasks, students modelled gas particles moving at a relatively fast speed in relation to liquid and solid particles, by moving their fists randomly much further apart and more quickly than for solids and liquids. However, during ‘The Chocolate Bar Story’, students used slow motion to convey ‘super-human’ speeds: I briefly stopped preparations and asked how the students aimed to express the relative speed of gas particles. After a response from several students stating that they should run quickly around the classroom, I then asked whether anyone had seen alternative ways in which television and film productions had revealed super-human speeds. One student noted that slow motion could be used (V3:32:04). I said that the students might consider using this technique. All groups then used slow-motion to express gas particle movement. During the BAPs, Sarah continued to use the slow-motion movement, in her role as a gas particle; she was observed by the teacher, who critiqued her in a stimulated recall episode, in reference to the seeming incongruity of her slow movements, and waving arms,

> And I wonder if that's her expressing her understanding or of it’s just somebody getting carried away and dancing.

In interview with Sarah, she omitted a sense of metacognitive understanding of slow-motion. For example, during stimulated recall, she observed only that, ‘I just moved around,’ and did not suggest her movement was figurative.

8.2f Anthropomorphic imagery

An analysis of utterances suggested that anthropomorphisms were evident before and after the intervention (§11.1). In the pre-interview, Aisha and Mark suggested that particles were living (S2pre; S3pre). Mark espoused a belief that particles were biological entities, and they 'die' at high temperatures (S3pre). Aisha observed that energy, such as provided by the sun 'fed' the particles (S2pre). Aisha continued to retain this perspective through to the delayed interview. Mark however, seemed to have a moment of awareness, that this view conflicted with particle theory, in describing the effect of heat on particles,

> The particles, pretend there was like, millions, well lots of them here…Every time that somebody put a heater up, and heats up, a couple of the particles go… whereas I think is they are a living thing - I think they will all die.
>
> *You think they will die… So it will just all disappear?*
>
> Some will still be left though. (S3del)

Mark, in the last line, appeared to hedge his statement that the particles would, 'all die' by suggesting that not all would die. As his TE response indicated (§8.2b), it appeared that Mark had developed further understanding of particle interaction, seemingly regardless of the living status of the particles. For Mark, whereas previously the gas had wanted to breathe (S3) and was a continuous substance, now the focus was upon the characteristic of individual 'teeny tiny things' (S3). By the delayed interview, Mark declared that he did not believe that particles were alive. He provided a rationale for his previous belief, that he had confused ‘microbes’, which they had learned about in Biology lessons, with ‘particles’.

> Microbes were like, were like, were like gas particles. That's why I, can, I think I've changed my opinion, because I always had got microbes and particles mixed up. (S3)

These examples of anthropomorphic utterances suggested that competing alternative and scientific conceptions of diffusion coexisted in Mark’s responses, but that over time he began to rely less upon the alternative conception.

8.2g Affective characteristics

A striking feature of the lesson was the high level of student participation: all students performed in all tasks, as the teacher noted,

> Impressive in the sense that all the students were actively involved, all the students were able to focus on the theme. And someway connect with it. Also because of the actual sort of nature and the lesson all of them were able to find some relevance to build upon their own experience. (T)

These students were considered low achieving, with one member of staff observing in an email beforehand that they [the class], ‘can’t remember anything with conventional teaching’ (email correspondence). In Mark’s case, a sense of low self-esteem appeared to be evidenced in his own perception of himself: Mark contextualised his lack of knowledge in interview by noting that he was in the bottom set, and indicated that expectations were lower for them than for other students (S3). Despite the teacher's perception of low achievement, and Mark's indication of the potential for students' low self-esteem, both of which may have suggested a weak sense of motivation in Science, the students nonetheless were interpreted to reveal focus and motivation during whole class and group work. The teacher's informal and formal comments corroborated the perception that the students were focussed, and confident to engage. In particular, he cited the response of quiet students,

> What I saw, I would say. I saw students who, in a normal lesson, who would normally sit quietly, would normally look to the person next to them for the answers and the ideas. And I saw them becoming actively involved in the lesson; and actively involved in trying to sort of express their understanding of concepts. (T)

An example of this atypical behaviour for the class could be seen in relation to one of the interviewees: Sarah was an introverted student with a voice so quiet that transcription of the interviews proved difficult. She not only participated in all the tasks, but during the performance of a gas particle in 'The Spy's Perfume' she moved with arms outstretched and spun slowly while moving across the floor, which suggested a high degree of confidence.

8.3Discussion

8.3a Promoting TE-type visualisations

Interview responses and drawings suggested an improved ability amongst interviewees to delineate sub-micro and macro level descriptions in post interviews, and a greater tendency to assert the particulate nature of some solids, liquids and gases (§8.2a). Mark appeared to have progressed from holding a primarily macro perspective of dissolving and diffusion to telescope between sub-micro and macro levels of thought while describing a TE-type visualisation in the post-interview (§8.2b).

8.3b The impact of action on conceptions of movement – slow-motion particles

Aisha and Sarah employed gestural metaphors in the pre-interviews, but switched to use GTM-type gestures, along with Mark, in the post and delayed interviews. This suggested the students' comfort with these models. However, Sarah's and Aisha's use of open-hand gestural metaphors in respect to diffusion begged the question – why did this new expression come into mind when there was already an authoritative teaching model that they could rely upon? A possible answer was that other images and explanations were competing with the teaching model. One possible stimulus for this challenge was a mis-hearing or misunderstanding of the model-based nature of the slow motion technique used in 'The Chocolate Bar Story'.

The lesson highlighted a potential problem when using slow motion as a simulation technique to convey the concept of high speed particles in a gas. Sarah and Aisha's descriptions of gas movement in the context of diffusion seemed to be informed by their 'slow motion' actions in the two BAPs within the intervention, and an inability to recall the metavisual context in which the slow-motion idea was initially discussed. In this situation it appeared that the students forgot that 'slow moving particles' was a modelling choice. The evidence suggested that the students could retain embodied images more readily than their metacognitive perspective, with the result that the images became disconnected from the original context. The teacher noted that students would have been ‘made aware of modelling…’ (T), but this wider awareness was not apparent in this example. As a subsequence of these episodes, I used the technique with a greater degree of caution in the next case, with different results (§9.2).

Students’ conceptions were sometimes informed by previous events and images, such as biological explanations for energy, ‘bouncing’ ball analogies of particles and a simulation of particles in a solid. Previous experiences also appeared to provide strong central images (similar to *anchor metaphors* (§7.3b)) such as ‘squashed particles’ and confusions of ‘microbes’ and ‘particles’, which potentially supported anthropomorphic conceptions. Interestingly, it was observed that Mark maintained an animistic conception *while also* developing a scientific conception of diffusion simultaneously, suggesting that the animistic conception did not hinder his understanding of diffusion.

The issue of ‘living particles’ highlighted the question of to what degree students may be expected to assume that particles have the capability of movement, without questioning how this movement is caused. It is worth noting that this suggests a gap within curriculum teaching, in that the (quantum) *cause* of motion of particles is not a teaching objective within the KS3 or KS4 stages.

8.4 Summary of Case 4

This case focussed upon the teaching of states of matter, diffusion and dissolving. The lesson progressed from the warm-ups to a whole-class GTM of states of matter, group

BAPs of diffusion, and group gestural metaphors of dissolving. This low ability class engaged in extended group TE tasks in larger groups than they typically used. The post and delayed interviews suggested that the GTMs and the memory of the activities provided shared metaphors with which to discuss and extend topic concepts in the short and medium term. Slow motion signifiers for high speed gas particles appeared to support post interview conceptions of slow, floaty gas particles. Students were interpreted to show increased visualisations of the sub-micro level, and one boy revealed that he had engaged in a TE of diffusion. Animistic conceptions which explained particle movement were retained by two interviewees.

9.0

Case 5: Student-Centric Expressions

> 'Using drama, like its two ways which are good; one is they are moving about, it's more enjoyable. And the second thing is that some things in science can't be explained by words. They can be explained by diagrams, acting and stuff like that.' (S3post)

9.1 Case Description

This case study took place with a mixed gender and mixed ability class of twenty-three Year 9 students at a state secondary school in Cambridge. The students regularly followed a circus format by which Biology, Chemistry and Physics topics were taught in successive two-week schemes of work. The students had begun their Chemistry scheme of work in the previous lesson, in which the teacher reviewed particle theory and demonstrated diffusion with potassium permanganate crystals in water. The classroom layout was similar to cases 3, 4, 5, 7 and 8, with long tables moved to the side, leaving four stations in the centre (Figure 9.10). This one hour forty minute intervention occurred in the last two lessons on a summer's term day.

9.1a Learning objectives

- To review a sub-micro level description of states of matter
- To introduce a sub-micro level visualisation of diffusion
- To introduce a sub-micro level visualisation of dissolving

9.1b Lesson description

The lesson began with a lecture on the abstract nature of atoms. This led into the four drama warm-up tasks (§4.4). These were followed by a teacher-demonstration of the Gestural Teaching Model (GTM) of states of matter. Next, the whole class performed their GTM's in response to changes in temperature that I called out. Then, four students were asked to demonstrate states of matter. Next, I divided the class into four groups for the task, 'The Chocolate Bar Story'. After a brief question and answer session on states of matter, four new groups prepared and performed 'The Spy's Perfume'. All were briefly evaluated in a forum discussion. Next, a question and answer session on diffusion led to a teacher directed demonstration of a drama technique for interacting with imagined objects. Next, four new groups were asked to create a Human Analogy Model (HAM) for dissolving; they were to simulate the sugar particles when a sugar cube is dropped into a glass of water. Each simulation was performed and evaluated separately. The lesson ended with a brief discussion of the topic concepts.

9.2 Analysis

9.2a Pre-interviews

Students tended to describe matter in relation to macro properties, to ascribe a substance's properties to its particles, and to describe static, rather than dynamic particle systems. In the pre-interview, prior to seeing the show card terms such as 'particle' and 'atom' (Figure 9.1, below), a boy named Gabriel described what his table might look like, at the 'highest' magnification with 'magic goggles', as revealing, 'some small sources of bacteria'. When asked to imagine what he might see if the table was under further magnification, he declared, 'I don't know' (S3). A second student, Amelie, described the air above us as composed of 'little things' and 'nothing', then of 'chemical things' and 'not chemicals'.

> Well, I don't know, the air is made up of little things as well is it? No,

maybe it is made up of nothing. No it is not.

Okay which way do you want to go with this?

Something. The air is like, different chemical things. No they are not really chemicals, like, it's oxygen and carbon dioxide and other stuff. (S1)

The third interviewee, Maddy, provided a sub-micro level description. She described states of matter at the level of particles, which were, 'like little circles' that were so small that, 'you can only see them with magic goggles' (S2pre). When presented with the show card term, 'particle', interviewees described changes in state with reference to relative particle proximity, such as, 'in a liquid there is like space between the particles' (S1pre), and in a solid, particles are 'squashed together' (S2pre). However two interviewees' responses continued to lack any reference to particle movement. Amelie and Gabriel gave static descriptions of particles as 'spaced out' (S1; S3) in a gas. The weak focus on particle movement was manifest in their explanations of diffusion: Amelie noted that gas, 'does not move by itself but needs people … walking around in it which makes the air move' (S1). Maddy did suggest *some* movement of particles to the extent that heated particles 'move a bit more' [than solid particles] (S2), and described diffusing gas particles as 'spreading' (S2), which suggested some particle movement. No student used the term 'random' or 'attraction' to describe particle behaviour, although they would in post interviews (§9.2).

Amelie was given a TE-type question to draw and describe how a balloon stayed inflated, she responded with an anthropomorphic explanation:

> Yeah, but you've blown loads of air inside of it, and the balloon doesn't want to be that big. It kind of wants to be small, and that's, it was small in the first place, but it is kind of being stretched and it wants to stretch back. But it can't because there is air in it. (S1)

Amelie was not working from a conception of dynamic air particles. Instead, the balloon was presented as an agent of action, suggesting a teleological explanation in which the balloon's desire 'to be small' and to 'stretch back' implied a passive role for the air.

9.2b Post and delayed interviews

The post interviews suggested an increased tendency for students to provide consistent sub-micro level descriptions and to express consensus-like descriptions of proximity and movement in relation to heat energy. For example, while Amelie had previously defined energy as 'stuff that living things need to stay alive… and like… electricity and stuff' (S1pre), and she had not used the term 'attraction' nor related particle movement to relative particle speeds in different states of matter (S1), in the post interviews, such as in the passage below, she described energy as a mechanism for movement (lines 1, 7 and 9) and included references to attraction (line 7) and relative speed (line 5).

1. No, they get like energy, it's, so they kind of like move-
2. *Okay, a bit of energy* --
3. Yeah and because they have more space between them-
4. *Than what?*

5. Than a solid which has practically no space between the particles, so they are very tight together, and so instead it hasn't as much energy, so they can't move around, so a solid is like hard.
6. *So, why are solid particles so close together?*
7. Because they don't have very much energy, so they are like attracted to each other.
8. *Okay, and are liquid particles attracted to each other?*
9. They are, but they have lots of energy which kind of pushes them apart and moves them around more. (S1)

A key feature within this passage was the consistency by which Amelie retained a sub-micro level description. Her focus upon linking energy, motion, and attraction supported dynamic descriptions of particle behaviour.

A further example of this new attention to movement and energy was in Maddy's reference to collision theory, below. This featured in a discussion which preceded the HAMs, in which students prepared and performed analogies of sugar dissolving in water. No interviewees had made reference to collisions in the pre-interviews, but in the post interview, Maddy employed collision theory to explain dissolving. Her language revealed some non-science terminology, as in her use of the terms 'bash' and 'breaks'. However, she subsequently clarified the latter term by noting that the solute particles 'separate'.

> Well when it is a solid the particles are together, when it is a liquid the particles are moving and every time they bash, the particles bash together,

it breaks it off and gives it more energy --

Breaks it off. A bit of a particle?

No, it just like keeps bashing and gives it more energy…I don't know what way to say it but like, I don't know how to explain it, but they bash together and it [the water particles] give it more energy and the particles separate. (S2)

Maddy emphasised a dynamic process, with 'moving' particles, and high-energy collisions in which they 'bash', and 'give energy' as well as break bonds ('breaks it off'). Maddy's expression here contrasted with that in the pre-interview, in which her narrative of events did not suggest a mechanism for particles to separate:

> The particles are all like with each other in the sugar cube. After a time the particles spread around the water, in the water I mean. They keep spreading. And eventually all the particles will become apart, spread in the water. (S2pre)

A feature of this pre-interview description was not only the absence of a cause for particle separation, but also that Maddy appeared to lack any awareness that a mechanism for separation was needed.

9.2c Post intervention scope for thought experiment visualisation

After the intervention, in the delayed interview, Maddy and Amelie were interpreted to express visualisations of complex, dynamic, multiple particle systems as they responded to a TE-type question: What happens at the particle level during the heating of magnesium? This was drawn from a demonstration that that they had witnessed in a previous lesson (S1; S2). Their responses suggested a richer visualisation than they expressed in the pre-interviews, indicated in part by the clarity of their narratives, and the degree to which this clarity foregrounded gaps in their understanding.

They described the physical reaction up to the point at which bonding occurred (S1del; S2del). These students had not yet been taught about bonding, and would not encounter it for another year (T). Amelie appeared to rely upon the concept of diffusion to explain the reaction. She focussed upon the physical process of mixing gases,

1. And then, I don't know. Just unless you heated up [the magnesium] so much that it becomes a gas.
2. *And now, what are you thinking for that?*
3. Because that's the only way it's going to mix with the oxygen.
4. *Okay, and once it's mixing with the oxygen what are you saying?*
5. Diffusing with the oxygen. (S1del)

The passage above, beginning with ‘I don’t know’, suggested that Amelie could not initially conceive of how the solid magnesium might interact with the oxygen.

However, she next seemed to overcome this obstacle with a new hypothesis, 'it [the magnesium] becomes a gas'. In the final sentence she appeared to frame this idea within the concept of diffusion, and that particles 'mix' (line 3), suggesting that her conception was based upon the mental model of a physical, not a chemical reaction.

Maddy was interpreted to come closer than Amelie to describing a chemical reaction when she described particle collisions. She described an environment of interacting particles ('they like hit the magnesium'), and provided a description of resultant products ('they made like different things').

> I mean that the particles in the air were like whizzing around and around and then they like hit the magnesium and bumped it about and they made like different things.
>
> *Okay, so they bumped in the air. Has anything happened to magnesium...?*
>
> I am not sure. (S2del)

Despite providing the image of colliding air and magnesium particles, and then stating that 'different things' were made, there was no expression of how the compound was formed. The juxtaposition of these events foregrounded a gap in her understanding. Maddy seemed to hold the belief that the magnesium remained a solid throughout the process, even as it seemed to behave like a gas, 'whizzing around' -- a belief that appeared to be related to previous macro observations.

1. *…Okay but it is very interesting, they [Mg] particles move around a bit more and a bit more. Do they stay solid?*

2. Yes.
3. *Okay.*
4. Like, they are in individual bits of ash rather than in one big lump of magnesium.
5. *Okay, how did they become individual if they are stuck together in a solid?*
6. I'm not sure, I think it is that with the attraction between them, they have too much energy when they heat up and move apart. (S2del)

Here, Maddy surmised that heat gives ‘ash bits’ enough energy to ‘move apart’, but unlike Amelie, she did not appear to consider that magnesium itself was vaporised by the heat. I interpreted her reasoning as informed by previous experience, i.e. in seeing ‘ash’ formed with heated magnesium (S2del).

Both Amelie and Maddy visualised dynamic, physical systems. Both appeared to have presented TE type visualisations, according to Gilbert’s definition (2005, p.65): Their *goal* was evident in their aim to respond to the question of what happens at the particle level, and their *experiential*, i.e. previous knowledge of physical reactions, was evident in explanations such as, Amelie’s comment, ‘That’s the only way it will mix with the oxygen (S2del),’ and Maddy’s understanding that, ‘[Oxygen particles] like hit the magnesium [particles]’ (S2del). In both situations the girls appeared to develop new hypotheses as part of their explanations. The *internal coherency* of their responses was interpreted in the clarity of their narratives. These thought experiment responses occurred during the delayed interviews, four months after the intervention, which included the summer holidays, and with no intervening lessons on particle theory (S1del; S2del; S3del). As such, this reflected a degree of durability in that their ability to visualise the sub-micro world appeared more lucid, still, than in the pre-interviews.

Interestingly, the interviewees appeared to be aware of the discontinuity of their expressions. By contrast, the pre-interview teleological descriptions in Maddy's description of dissolving and Amelie's explanation of how a balloon stays inflated had allowed them to maintain their narratives despite missing the key features of particle bonds (§9.2a).

9.2d Evidence of the acquisition of more science literate expressions of particle behaviour

Post and delayed interviews suggested an increase in the richness of expressions across gesture and drawing. Two examples are presented to support this interpretation: Gabriel's initial gestural metaphors were informed by the GTM in the post interview, and Maddy's drawings appeared to progressively afford greater detail, with a greater range of signifiers, over the post and delayed interviews.

In the pre-interview, Gabriel had initiated a gestural metaphor for states of matter. He began by holding his fists tight together while describing a solid. When asked where he got his idea from, he said he 'made it up' (S3). In the passage below he held his hands open-palmed and apart to describe gas:

> *Does gas have particles?*
>
> Yes, but they are very loosely spaced out.

Yes but they are very loosely spaced out and you put your hands out like [apart] do you mean like the particles look like that?

Yes. (S3pre)

Here, his gestural metaphor, like his verbal description, did not include movement. By contrast, in the post interview below, Gabriel described a more dynamic representation, in which he gestured the vibration of solid particles. I allude to this in line 5. The passage is extended here to illustrate his comfort in representing the GTM in conjunction with verbal discourse.

1. *In terms of the particles, what makes the particles, change state?*
2. Is it a solid, like I said, like that --
3. *Okay. Your fists together* --
4. If you heat it up then they can move.
5. *Okay, they have gone from vibrating to, into the liquid one. Yes.*
6. Then gas,
7. *Yes, and the attraction?*
8. There is no attraction.
9. *Okay you are moving your fists around.* (S3post)

Whereas in the pre-interview passage above, Gabriel's gesture suggested a static system, while he described the proximity of gas particles as, 'loosely spaced', in this post interview passage his gestures suggest motion in 'vibrating' (line 5) and 'moving your fists around (line 9), as he verbally described that heat causes movement, and responds that attraction reduces in a gas (line 8). Unlike Maddy, neither his gestures nor his speech described collisions between particles.

9.2e An increasing sense of science literacy: one student's pre post and delayed drawings of dissolving and diffusion

The increased detail in expression, suggested by Gabriel's GTM, was evident across interviewees' drawings over the course of the interview stages. For example, Maddy's pre-interview diffusion drawing seemed to emphasise a macro level perspective, principally in her use of a design reminiscent of spiral-like smoke, to represent the gas emitted from an opened jar, which suggested a continuous rather than particulate representation (Figure 9.1, below).

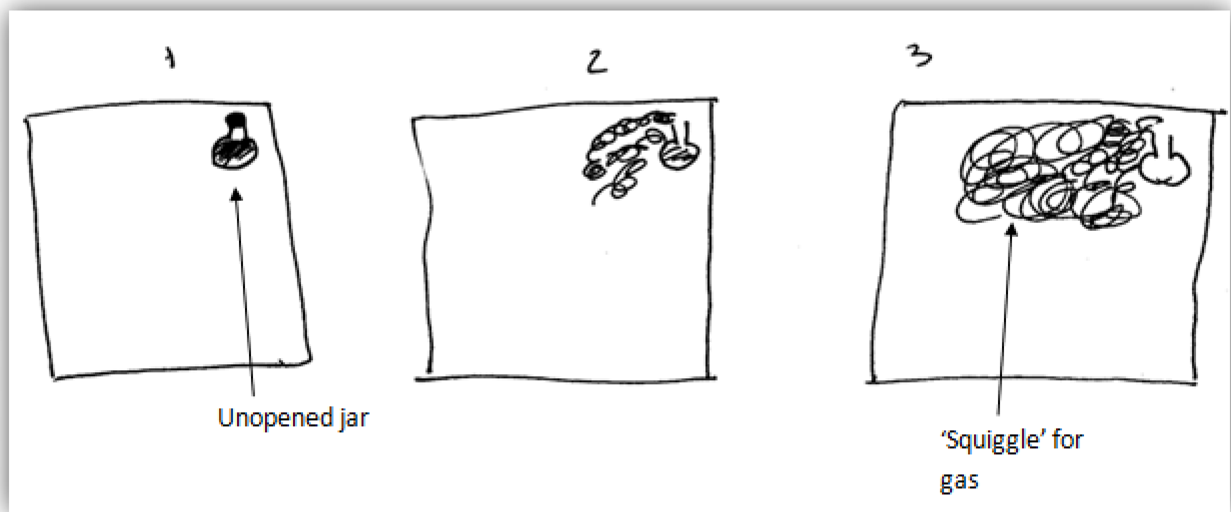

Figure 9.1 Pre-interview drawing of diffusion (Source, S2pre)

In interview, she seemed to affirm this continuous gas perspective (line 1), but then strikingly argued that she had represented 'particles' (line 3),

1. And when you open it the gas comes out of it a bit more than you can like smell it from across, all the way around the room. And then you go

out a bit further and it goes further around the room.

2. *So you have squiggly lines to show the gas, I presume. Yes? Is, should I see that as, sort of, like, visible smoke or should I see it as particles or --*
3. Particles. (S2pre)

The contradiction between the drawing and her intention for 'visible smoke' to suggest particles suggested a confusion of macro and sub-micro levels. This was echoed in her description of dissolving (Figure 9.2), in which a water-line squiggle in the flask suggested a continuous substance, while the presence of one type of dot suggested that only the solid was a particulate substance (Figure 9.3). Again the drawing contrasted with Maddy's verbal description in which she identified two types of particles, one that was, 'something else… smaller than grains of sugar' and 'water' (S2pre).

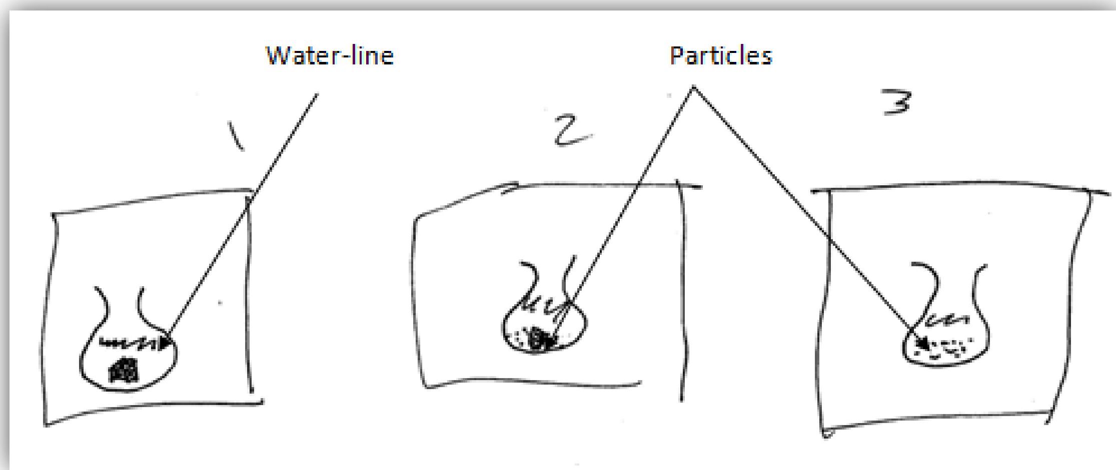

Figure 9.2 Pre-interview drawing of dissolving (Source, S2pre)

By contrast to the pre-interview drawings, Maddy's post interview drawings for diffusion and dissolving changed in detail and breadth of representational levels. In the post interview diagrams, Maddy included the device of a magnifying lens in order to signify magnification (Figures 9.3; 9.4), and in doing so, she now delineated the micro and macro features more clearly. Also she identified types of particle by either changing their size (Figure 9.3) or their colour (Figure 9.4; see opposite page). The initial smoke-like swirls from the pre-interview diagram remained, referring in this instance to the colour of potassium permanganate diffusing into water. In providing both macro and sub-micro descriptions, the images together presented what I interpreted as a telescoping between these representational levels.

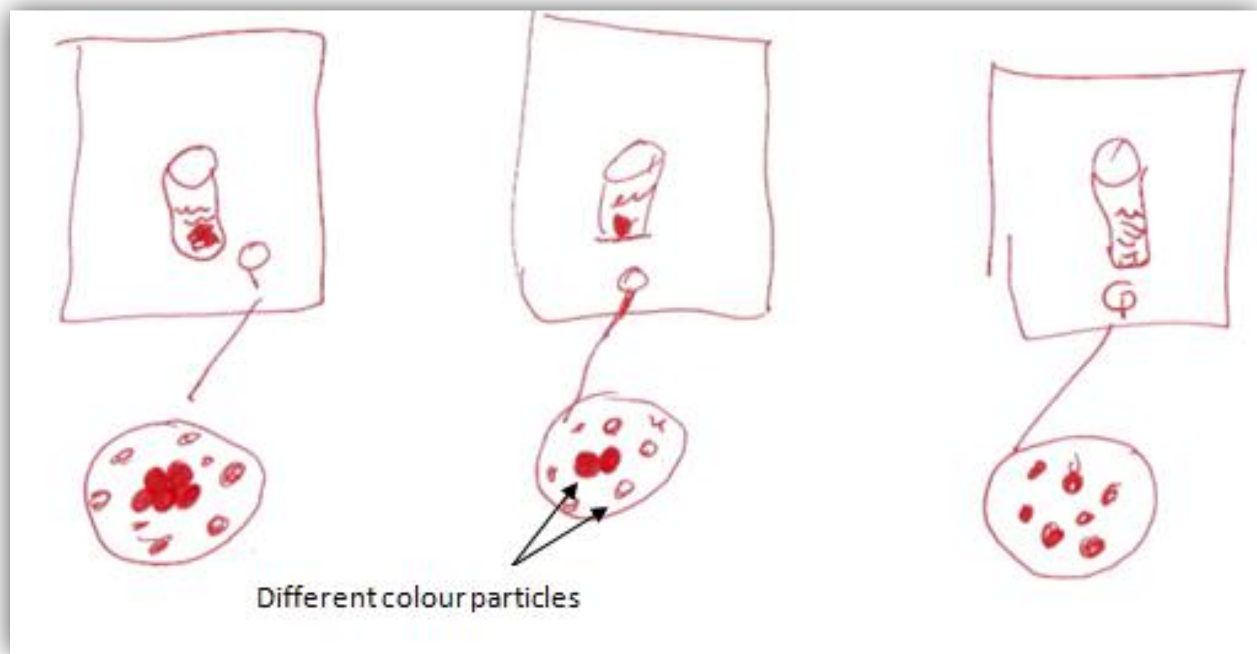

Figure 9.3 Post interview drawing of dissolving (S2post)

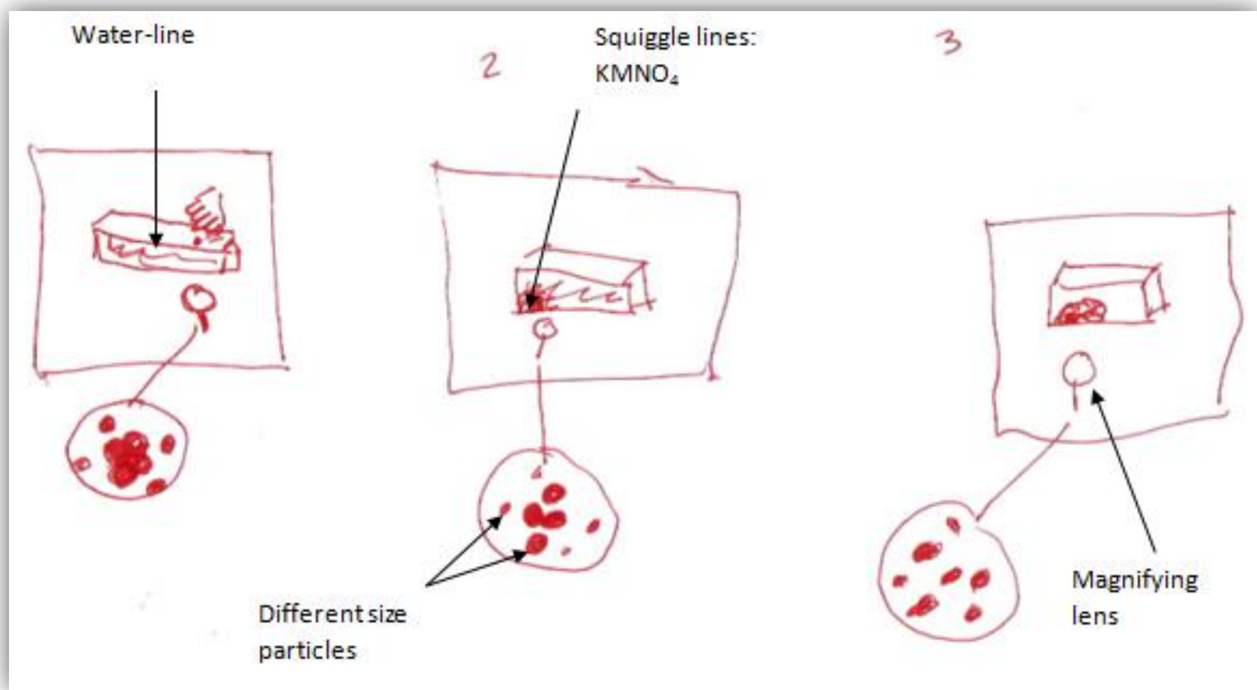

Figure 9.4 Post interview drawing of diffusion (Source, S2post)

Maddy's delayed interview revealed her further clarification of representational levels. Whereas previously the magnifying lens was separate from the substance, now the magnifying lens had been simplified to a 'mini zoom' that was linked directly to a circle over the substance (Figure 9.5 and 9.6). In the dissolving diagram, the liquid and solid particles are delineated by differences in proximity (Figure 9.5), as Maddy noted of the liquid particles, they 'have a bit more space between them' (S2del). There were no squiggly smoke-like lines, and furthermore, the diffusion example provided a more abstract expression of macro and micro-level phenomena than previously: with the two 'mini zooms' at different sites in the room which appeared to convey the effect of spreading at the macro as well as sub-micro level.

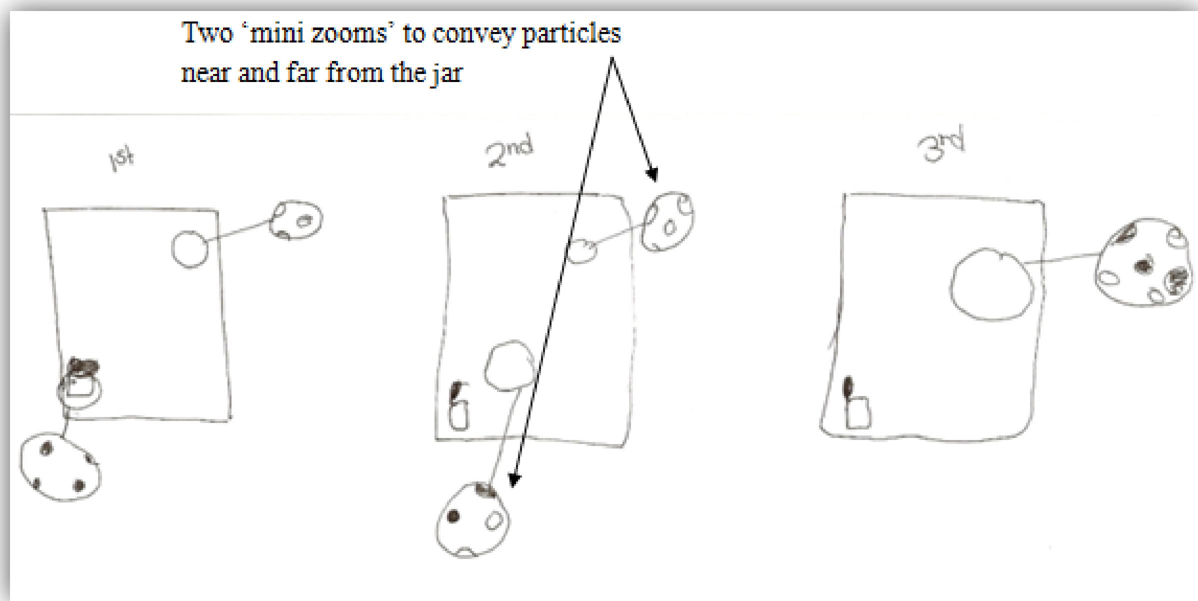

Figure 9.5 Delayed interview drawing of diffusion (Source, S2del). Note the two types of particles, distinguished by colour, and the spacing between them.

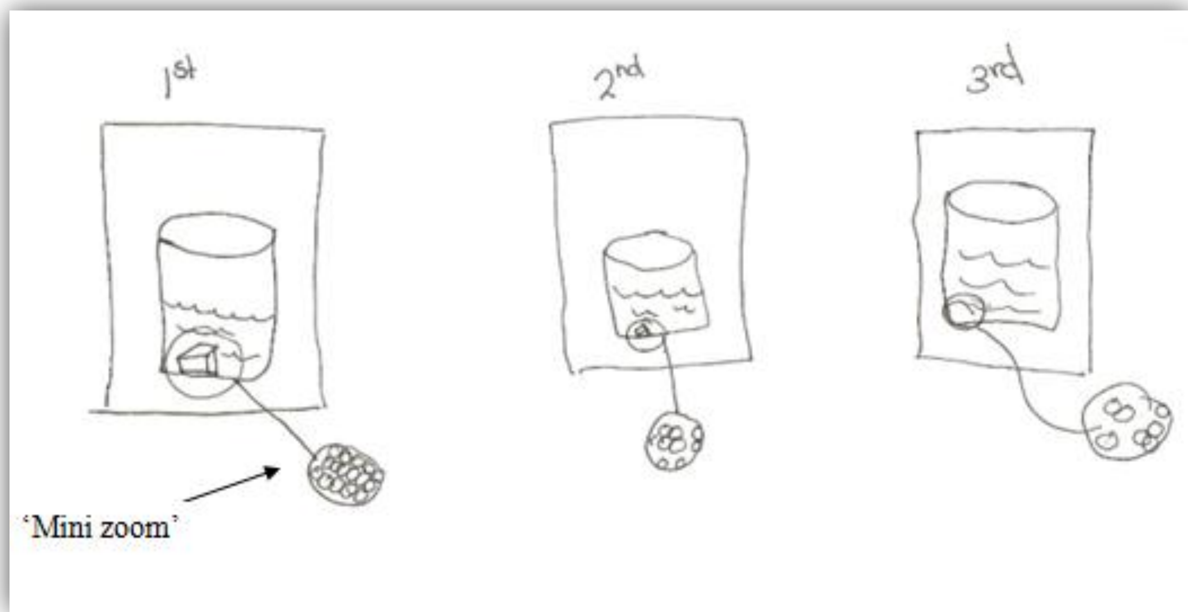

Figure 9.6 Delayed interview drawing of dissolving (Source, S2del). Note the mini-zoom of the sugar particles in the first frame. Note also the increased spacing between particles within the subsequent frames.

9.2f Developing modelling talk: making the implicit explicit

As with the drawings, the interviewees appeared to develop consistent verbal and non verbal expressions suggestive of increased metacognitive and collaborative science-oriented talk through the lesson. An objective of the warm-ups was to develop students' skills at making the implicit explicit: to be able to justify specific meanings by relating these to specific signifiers, such as body language, facial expression, of proximity. In the warm up tasks, students' initially tended to describe the implied meanings, such as in line 2 below. At this stage I directed students to describe how the model was constructed, as in line 3.

1. *Teacher: What's the first thing that you notice?*
2. Student 1: Looks a bit like a bit like a sofa…

3. *Excellent, but what is telling us it is like a sofa?*
4. Student 2: It is double the height here than there. [Student gestures towards the front and back rows]
5. *Teacher: Good so it is longer than it is deep, and you picked up the arm rests there too …*

(V1 22:06)

Figure 9.7 Sofa: group 1. (V1 22:06)

As the tasks progressed, I continued to direct students to justify meanings with reference to features of the models. By the fourth warm up task, ‘the uncomfortable sofa’, students’ responses were increasingly complex, for example, highlighting multiple signifiers such as levels (line 5), proximity (line 3), body language ('crouching'), and juxtaposition of patterns (line 10):

1. Student 1: Well it sort of like, you can see the shape of it but you know, that-
2. *How can you see the shape? Deconstruct it.*
3. Student 1: Like you have the back bit like and then you have the [sliding gesture] armrests with Kevin, Nora, and Karin.
4. *How are they showing armrests?*
5. Student 1: Well they are sort of like crouching over, sort of like [gestures vertical hands symmetrical] making it like two or three deep.
6. *Hey sweet. Yes moving out towards three deep. But there's something interesting here. You said they arched over. Now I arch over. Do I look like an armrest?*
7. Student 1: No.
8. *Why do they look like an armrest and I don't look like an armrest?*
9. *[New student, hand raised] Go for it.*
10. Student 2: All the people are doing different things together. (V1: 40: 23)

A teaching rationale for *making the implicit explicit* was that students would begin to develop a structure of talk which they could use to construct their own group simulations. For example, in the passage below students responded to the question of how they might extend their modelling of interactions of particles in a three dimensional space. We had just finished watching a group's Human Analogy Model (HAM) of sugar dissolving in water.

1. *Excellent, round of applause [students applaud]. What would make it a better representation of particle movement?*
2. [Student 1 raises hand]
3. *Yes?*
4. Student 1: If you like [curls up] crouch?
5. *Ah Yes. We are moving in three dimensions now. Crouch to show that the particles go down... Where's another place we could go if we could?*
6. Student 2: Up high.
7. *Up high, is where we could go. If we only had the capability to fly we could turn this into a really good model.*
8. Student 3: We could get a few more people to move around and show there's more [particles] there. (V1: 61:00)

Based upon my prompt to describe 'better …movement' (line 1) the first student focused upon particle shape (line 4); this seemed to inspire the second student to promote a three dimensional perspective with a contrasting level ('Up high', line 6). The third response suggested modelling movement ('move around') within a multi-particle system ('a few more people') (line 8).

9.2g Student focus and motivation

At one hour and forty minutes, this was the longest of all the case interventions. It was also, from my teaching perspective, the most rewarding (Obs). The potential for students to lack interest was assumed to be high. It was a warm sunny classroom, on these last two lessons of the day. Some students yawned frequently during interactive/authoritative talk (V2: 16:15-17:35). Furthermore, the teacher noted that there were some students who may have been difficult (T). Despite this, I interpreted a positive affective environment during the lesson: There was full participation throughout the performances (V1), with examples of intensity, such as in Figure 9.8, below, and student gaze that suggested self-regulation and attention (Figure 9.9). The teacher noted that the potentially disruptive students' behaviour 'impressed' her (§9.6). The class focus was emphasised in an impromptu question and answer session near the end of the lesson. The teacher noted,

> … so you know at that stage in the lesson, they should be tired but they were really, really wanting to ask about things... (T)

It was not only the students' eagerness but their choice of questions that was particularly striking: they asked idiosyncratic but scientific questions, such as whether ice dissolves or melts (V1 43:37) in water, and whether 'any' solid can dissolve (V1: 44:15). The teacher explained further,

> Oh there's the questions about a solid melting, which, you know, that's one of the misconceptions that a whole lot of them have. … And so, you know, using the particle theory to think about why it was that sugar wasn't melting when she put it in a glass of water [during a previous class practical] and … and the difference between chemical and physical reactions… (T)

That these questions were asked suggested a positive emotional atmosphere that supported science talk. That the students, late in the lesson, should initiate and support an extended discussion about questions that were relevant to them, was perceived by the teacher and myself as evidence of students' interest.

9.2h Visible thought

Discourse during the intervention was sometimes accompanied by illustrative gestures or action. This multimodal aspect of the lesson was noted by the classroom teacher in the post interview. In particular, she highlighted a discussion between a boy and myself in which he first gestured water particles with his arms extended, which I mimicked, reflecting his gesture,

> I thought it went really well; I was really impressed with how well they behaved; but then how much they got out of it as well. And you see them thinking these things, like I said to you about Ben doing this [gestures] as he was talking to you. (T)

Figure 9.8 Using gesture to inform dialogue between student and teacher. (V1: 27:21)

The comment that, 'You see them thinking these things', implied that action could be a proxy for thought. Within this context, the following episode suggested the potential for a teacher to misinterpret thought by solely assessing action. During a performance of ‘The Spy’s Perfume’, one group used gestured particles (i.e., fists moving) while also using their bodies as particles (Figure 9.9). Amelie, who had been one of the members of the group, described the behaviour of herself and others,

> ... we were [previously] doing the thing with our hands together, and then with our hands, and moving and stuff like that [the GTM demonstration]; we decided that when we were running around, maybe it would be good if we had our arms going out like this. [Holds arms extended on a dihedral; hands in fists]. (S1)

Figure 9.9 Superimposition of gestural metaphors and BAPs for gas (V1 1:10:43)

This seemed redundant and incongruous. To the observer, the gesture and body language could potentially have been interpreted as two competing representations of particles, one gestural, one a BAPs. This appeared to suggest some confusion as to what they aimed to signify: was one on top of another? If their bodies are particles bumping into imagined particles, are the fists bumping into the same particles? Did they perceive that particles have appendages? With such issues in mind, I questioned Amelie during the post interview. She explained,

> Well it would show, because, the class had done that [learned the gestural model], so they knew that meant the gas [particles]. So if we did that and then, like, we would be the gas particles. (S1post)

In Amelie's view, the group members chose to put their arms out in order to draw a parallel to a previous representation of gas particles in the GTM task. This appeared to be an attempt to enhance the identity of the particle description, by using a metaphor that they believed would be familiar to the class. This episode therefore suggested that students constructed a simulation that seemed incongruous but had an *internal coherency* (Gilbert, 2005, p.65).

Figure 9.10 Gas particles in 'The Chocolate Bar Story' (V1 39:52)

9.3 Discussion

9.3a Dynamic visualisations

The physical simulations in this case were interpreted to promote conceptions which emphasised random movement, attraction, the effect of heat upon particle speed, and, for Amelie and Maddy, the transfer of energy in particle collisions (§9.2b). All three interviewees appeared to be able to delineate macro and sub-micro levels of representation more clearly than in pre-interviews. This was despite 'The Spy's Perfume' task in which particles and human characters interacted within the same representational space.

The utility of the resultant conceptions was suggested in Maddy's increasingly detailed drawings of dissolving and diffusion across interview stages, and Gabriel's adoption of the GTM over his own gestural metaphor for gas. These examples suggested an increased awareness of scientific literacy. The utility of conceptions over time was further suggested by Amelie and Maddy's thought experiment visualisations in the delayed intervention. In their descriptions of the reaction for MgO, the students described the process up until the point at which bonding would occur, relying on visualisations of particle collisions developed within the intervention.

As with Case 2, these students were unable to bridge a key mechanism in the reaction (bonding). For both Amelie and Maddy, the 'bonding' gap affected the continuity of their developing narratives of the process, whereas in the pre-interviews, a gap in knowledge did not affect the narrative. For Maddy, a second issue was that the white ash from a previous classroom demonstration of heating Mg seemed to provide an *anchor metaphor* which informed a conception that solid magnesium would not vaporise.

9.3b Odd models and bad representations

Amelie's group expression of simultaneously gestured and bodily particles in 'The Spy's Perfume' was interpreted to parallel an episode in a previous case, in which the teacher commented on a student who had used a similar expression. During a stimulated recall episode of the BAPs task that teacher noted,

> … And [a girl named Sarah] ended up in the final performance moving through with her fists. And I wonder if that's her expressing her understanding or if it's just somebody getting carried away and dancing… and… one of the big misconceptions that students have about states of matter is the idea of expansion... Could it be that they are getting mixed up in their heads between the idea that I am just one particle or I am all particles and I am the object expanding. So is there, is that an explanation for the moving arms? (T: Case 5)

The teacher's assumption was supported by observations in the literature that note that students' expressions of 'expanding particles' had been common (Calyk et al., 2005). However, in this case there was no other evidence that supported their perceptions of the *expansion of a particle when heated*. On the contrary, Amelie indicated her understanding in the post interview that expansion was a result of 'more space in between particles' (S1post). In this context, the group members' expressions can be viewed as metacognitive attempts to emphasise a range of conceptual features.

9.3c Adult modelling bias

That seemingly inappropriate models may in fact be useful to students informs the issue of what defines an appropriate, effective model. The evidence here has indicated the potential for adult observers to misconstrue useful student models as evidence of misconceptions. Science educators may at times be biased towards adult centric models (Bruner, 1974; Goswami 1992; Gilbert & Boulter, 2000). However, I am not aware of research that has investigated how a teacher's modelling biases may affect their assessment of students' own models. This may be an area for more research, especially now that student-centred modelling is increasingly promoted as pedagogy (Edmiston & Wilhelm, 1998; Aubusson & Fogwill, 2006; Justi & Gilbert, 2006).

9.3d Mixing multiple representations within the same simulations

There is much literature on the confusion of macro and sub-micro features in conceptions (Taber, 2001a; Treagust, Chittleborough, & Mamiala, 2003). For example, Jewitt et al. (2001) have suggested that contradictions in models may enrich conceptions by allowing the student to hold meanings in more than one domain (for example, social domain and science domain meanings). There is little research on the *affordances* of these combinations when they are intended by the modellers.

9.4 Summary of Case 5

This case focussed upon the teaching of states of matter, diffusion and dissolving. The lesson progressed from the warm-ups to a whole-class GTM of states of matter, and to group BAPs of diffusing gas, and then to group HAMs of sugar dissolving in water. The activities were observed to promote a high degree of motivation, autonomy and collaborative talk. GTMs were reproduced by interviewees without prompting in post and delayed interviews. In the post interviews, two interviewees engaged in extended TE responses which suggested a strong narrative structure to their visualisations of sub-micro processes. The case suggested that the teacher may misinterpret some students' models as evidence of misconceptions; this highlighted the importance of engaging students in justification of their models.

10.0
Case 6: Conceptual Conflict and Playground Behaviour

'Okay, and would you use role-play as a teacher in the way I did.
Yeah, because it's kind of like people remember things if it is more exciting. So like I remember trips to Alton Towers and stuff, it is, so like your memory stores it easier, so like kids will remember it better.' (S1del)

10.1 Case Description

This case took place with a Year 9 class in a large comprehensive school in Cambridgeshire. The class included twenty-eight mixed ability students including one boy with Asperger's Syndrome. This was the most culturally diverse class of all the cases. The classroom layout consisted of fifteen tables which were moved to the sides and front, a fixed teachers' desk and four fixed 'islands' in each quadrant of the students' seating area. Their teacher, in the lesson before the pre-interview, had reviewed states of matter.

10.1a Teaching objectives

- Review particle theory
- Introduce terms 'attraction' and 'energy' as features of states of matter
- Develop sub-micro visualisations of diffusion

10.1b Lesson description

As with previous cases, the intervention began with a brief lecture on atoms and the utility of particle models. The talk was followed by the four warm-ups (§4.4). The topic tasks began with a demonstration of the Gestural Teaching Model (GTM) for states of matter, wherein students stood in a line and mimicked my gestures, then applied their GTMs to express particle behaviour as I called out different temperatures. Students next formed five groups to prepare bodies-as-particles simulations (BAPs), and then they simultaneously performed, 'The Chocolate Bar Story'. After an evaluation, the class was arranged into five new groups. Each prepared 'The Spy's Perfume' for performance. Then they joined into two larger groups of fourteen students. After a second period of preparation, the two groups then performed, 'The Spy's Perfume', which was followed by forum evaluations. The lesson ended with a question and answer session, and then a final exercise in which students were asked to repeat key terms loudly in different tones of voice.

10.2 Analysis

10.2a Pre-interview, post and delayed interview comparison

Early in the pre-interviews, students' responses revealed a range of particle conceptions. All three interviewees' responses suggested a strong degree of awareness of the show card terms, except Cameron, who did not define *diffusion*. However, when asked to use 'magic goggles' to imagine the table and the air at the highest possible magnification, two students, Jenny and Cameron, asserted that one would see biological phenomena: 'bacteria' (S3) and 'DNA' (S2). This suggested micro-level rather than sub-micro level perspectives. A third student, Mike, described the substances through a sub-micro level perspective, noting that air would look different to a solid and liquid due to the different types of particles, such as, 'CO_2, oxygen, argon, nitrogen. Lots of stuff' (S1).

The following evidence suggested that after the intervention, students appeared to more readily apply sub-micro level visualisations, and increasingly focus upon attraction and the relation of energy to particle interaction. For example, the concept maps reflected an increasing tendency in the post interviews to focus on energy, with less attention to features of particle proximity. For example, the term ‘energy’ became the central node in post interview concept maps for Jenny and Cameron (Figures 10.2; 10.5), in contrast to pre-interview maps that fore-grounded ‘particle’ (10.1) and ‘liquid’ (10.4), respectively. The number of connections to ‘energy’ in both post concept maps increased from two to five in Jenny’s map (Figure 10.2) and from three to six connections in Cameron’s map (10.5). Jenny and Cameron’s delayed interview concept maps also retained an increase in connections to energy (Figures 10.3; 10.6), supporting an interpretation that this feature was incorporated into these students’ wider conceptual frameworks.

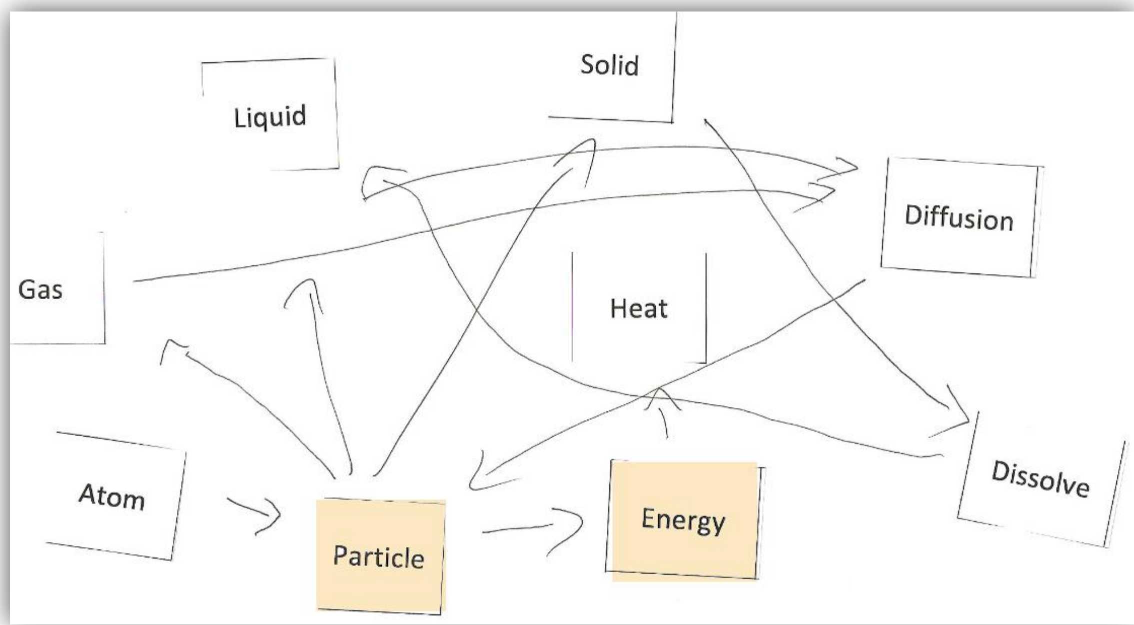

Figure 10.1 Jenny pre-interview concept map. (Source, S3pre) ‘Particle’ and ‘energy’ are highlighted.

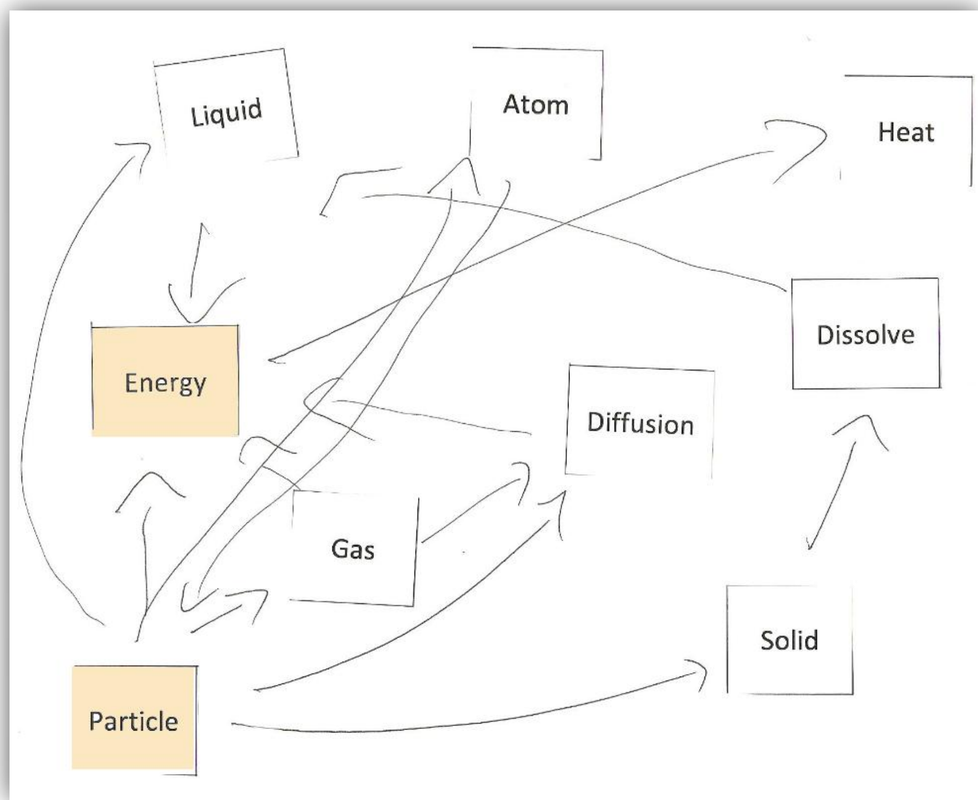

Figure 10.2 Jenny post intervention concept map. (Source, S3post). 'Particle' and 'energy' are highlighted.

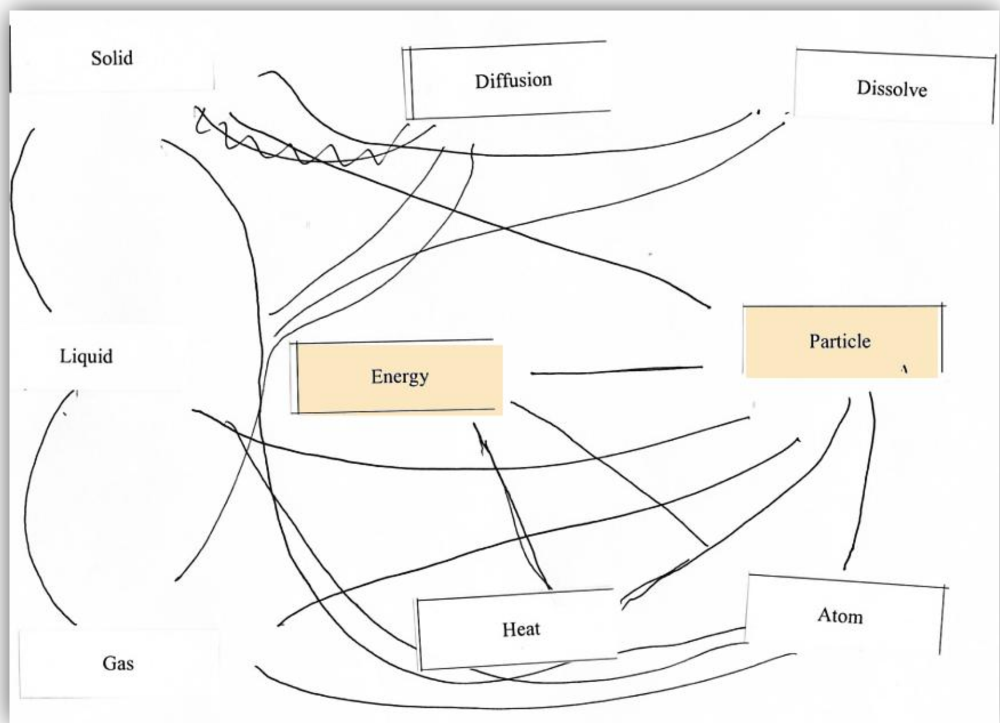

Figure 10.3 Jenny delayed concept map. (Source, S3del). 'Particle' and 'energy' are highlighted.

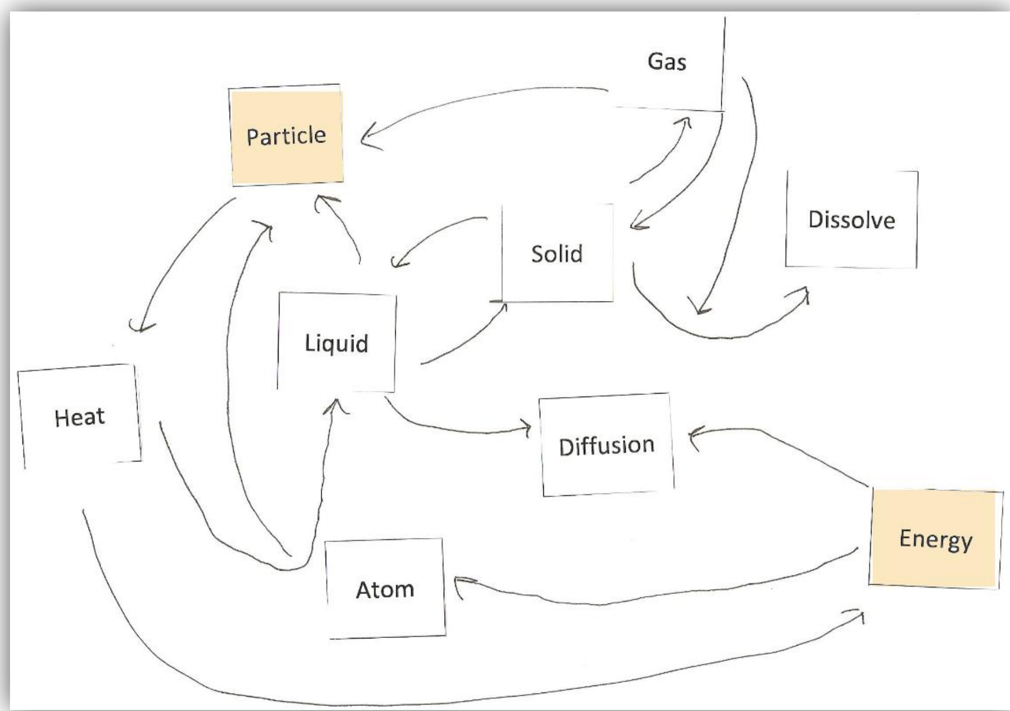

Figure 10.4 Cameron pre-interview concept map. (Source, S2pre). 'Particle' and 'energy' are highlighted. 'Liquid' has a greater number of connections than 'energy'.

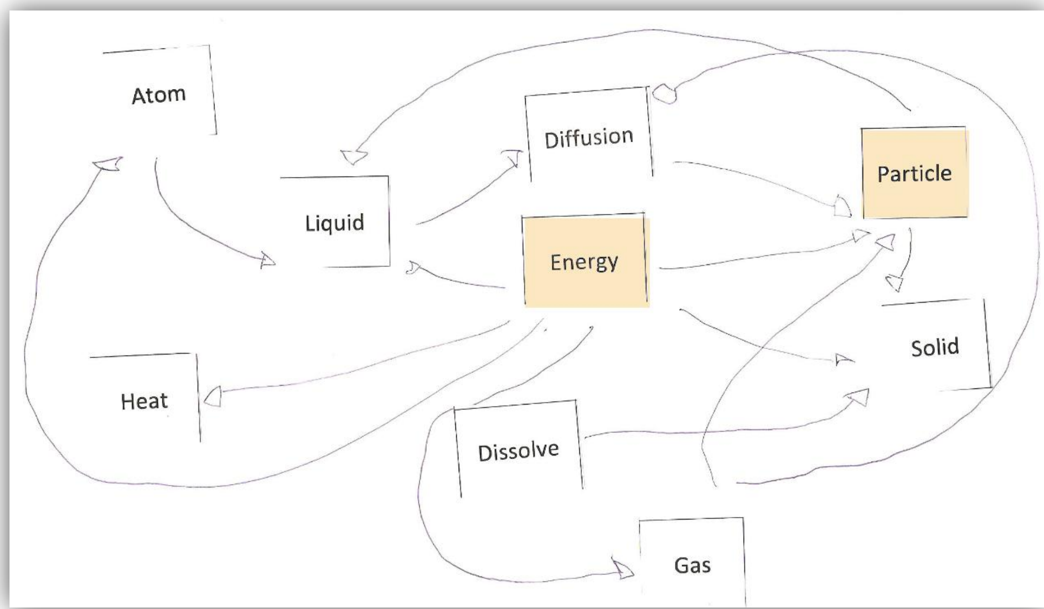

Figure 10.5 Cameron post interview concept map. (Source, S2post). 'Particle' and 'energy' are highlighted.

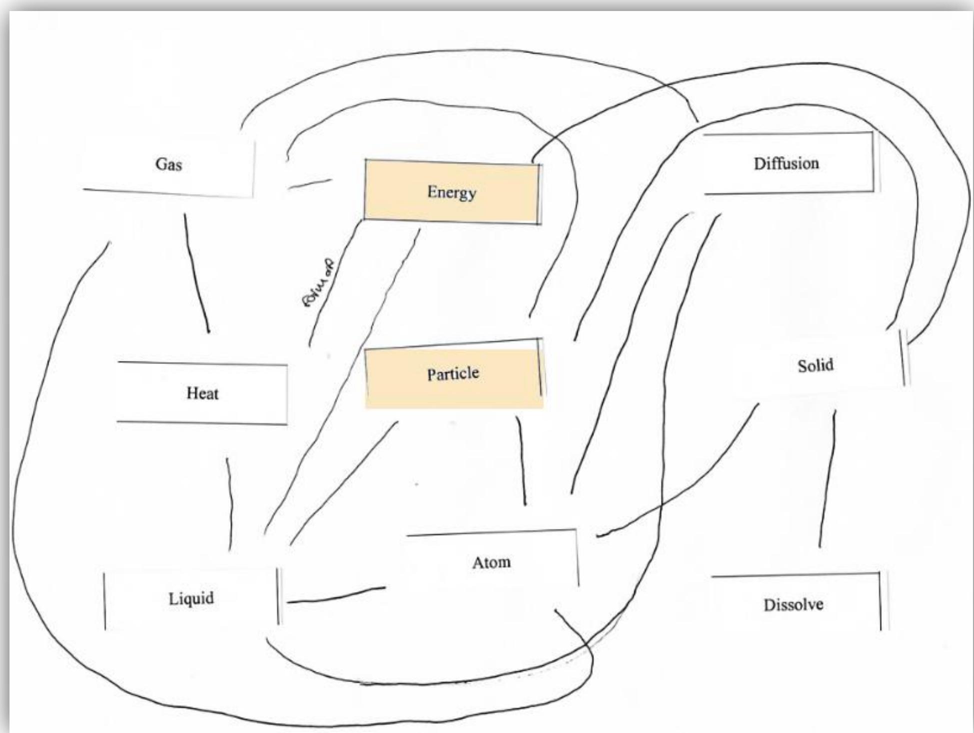

Figure 10.6 Cameron delayed concept map. (Source, S2del).'Particle' and 'energy' are highlighted.

Overall, the maps tended to increase or retain the same number of connections between the pre and delayed interviews. The maps also echoed interviewees' increased focus upon explanations for movement and process. For example, Cameron's post interview explanations for heat and energy were more consistent, consensus-type definitions than in the pre-interview, in which he had explained during the show card session that, 'Heat is a particle. It expands. ... Heat is in energy. An atom is energy' (S2pre). This seemingly random amalgamation of definitions suggested a confusion of the terms. Cameron's post interview descriptions revealed a more discrete understanding of the link between energy and particles.

1. There are, energy is in particles: energy is in solids. And energy [is] in gas.
2. *What does the energy in solids and gases do? How can you tell there is energy in those things?*
3. If there wasn't energy, the gas [particle] would stay still because if there was no energy; it wouldn't be able to move. (S2)

Here, energy was in solids and gas particles (line 1). Furthermore, in hypothesising what would happen without energy (line 3) Cameron implied that energy causes particle movement.

None of the interviewees had described particle behaviour in relation to *attraction* in the pre-interviews, yet after the intervention, Jenny and Mike initiated the term. For example, Jenny used the concept during the show card task, when she noted that, 'A solid is something that is like, has got, like, loads of particles or atoms that are attracted to each other' (S1). This description contextualised the system as composed of multiple particles, and suggested that attraction was a mechanism for their proximity. Mike described attraction (line 3), and also movement (line 1) and energy (line 3), and expressed these simultaneously with the Gestural Teaching Model (line 2).

1. The solid is like when the particles are vibrating very fast.
2. *So you have in your hands together, you are rubbing them together.*
3. Very, very fast. And like they are attracted but they don't have as much energy. And as you start to, as you start to notch up the heat it becomes a liquid, like – (S1)

Mike and the other interviewees noted that in contrast with solids, in a gas that particles, 'are not attracted' (S2), 'not as attracted' (S3) and 'break away from the attraction' (S1).

Interestingly, in the delayed interviews, no interviewee initiated the term attraction. Rather, Mike described solid particles as 'close together'(S1del), Jenny initially employed the term, 'put together'(S3del), and Cameron similarly noted, 'Something is pushing them together. It's just they haven't got enough energy to move away' (S2del). These comments supported an interpretation in the delayed interviews that the students visualised the particles but could not recall the mechanism for their interaction, as if there had been a decoupling of image and context.

10.2b From smell particles to air particles

Some images within the students' drawings appeared to remain consistent throughout the interview stages. Yet, while this image-consistency was strong, the labelling and verbal descriptions differed across interview stages to a degree that suggested that students re-contextualised and re-labelled the images over time. This is evidenced with examples of Jenny and Mike's drawings for *diffusion*, in which the aim was to convey the concept of diffusion of an odorous gas within a 'before', 'middle' and 'after' frame.

In the pre-interviews, Jenny drew small circles to denote particles of gas emitted from an opened jar. In Figure 10.7, in the second frame, she appeared to draw movement lines. In the third frame, these disappeared, and beside the circles she drew wavy lines. Jenny said that the lines were the 'smell'. The lines were relatively similarly spread amongst the circles; this suggested that 'smell' was being portrayed at a sub-micro level. In discussion, she appeared to perceive the smell as a distinct, discrete feature, which may be 'released' when particles collide (line 1).

1. Diffusion is like when the particles like move around and they hit each other and that then releases the smell.
2. *It releases the smell. Excellent so I don't want to put words in your mouth. So, I will sound stupid: so what are these two lines here?*
3. They are like, the release of the smell. (S3pre)

The lack of smell in the second frame seemed to reinforce the idea that smell was caused by particle interaction and collision, rather than a feature of the substance itself.

After the intervention, Jenny created a similar drawing for diffusion which included wavy lines (Figure 10.8). Jenny's accompanying verbal descriptions suggested that these features were supported by a richer conceptual framework: She said that 'compressed' gas in the jar (in the first frame) would 'accelerate' into more space and would 'collide'. She said that the room in her drawing, 'obviously has more, other gases that I didn't draw', and indicated the random movement of gas as it moved towards equilibrium (line 4). Notably, Jenny now also described the wavy or 'squiggly' lines as 'air' (line 2).

1. *A, you have got a squiggly line there.*
2. That's air.
3. *You have drawn three circles in the jar. What* --
4. I think they will still be some atoms inside the jar that haven't come out yet. (S3post)

The features of the drawings remained similar; however, the overall conception appeared to change dramatically in that non-scientific 'smell particles' were now 'air particles.

In the delayed interview (Figure 10.9), key features of the initial pre-interview image were retained, but with more consistency across frames, or with changes in composition. The jar remained in the bottom right corner, but retained more gas particles in the final frame. In between the circles, Jenny used only arrows rather than a mixture of arrows and wavy lines to signify movement and direction. Jenny denoted particles as circular, however these were now coloured to represent air and gas particles.

Similar patterns of change occurred within Jenny's interview comments. For example, she had continued in the post interview, to use the term 'releasing', as when she noted that atoms outside the jar 'will continue diffusing, and releasing the smell' (S3). This suggested that Jenny still believed smell to come from the collision of particles. However, the term 'diffusing' was now associated more with a process of movement, as she subsequently described, 'The ones outside are like, diffusing, so they are moving around really fast' (S3). Four months later, there was no indication that smell came from particles. 'Diffusing' was directly associated with the movement of particles:

> And the others are diffusing.
>
> *Now what do you mean by diffusing?*
>
> Moving around randomly. (S3del)

Jenny's drawings and comments over the three interview stages revealed consistency in her representation of central images, while her labelling and descriptions increasingly delineated conceptual features and enriched their potential for meaning.

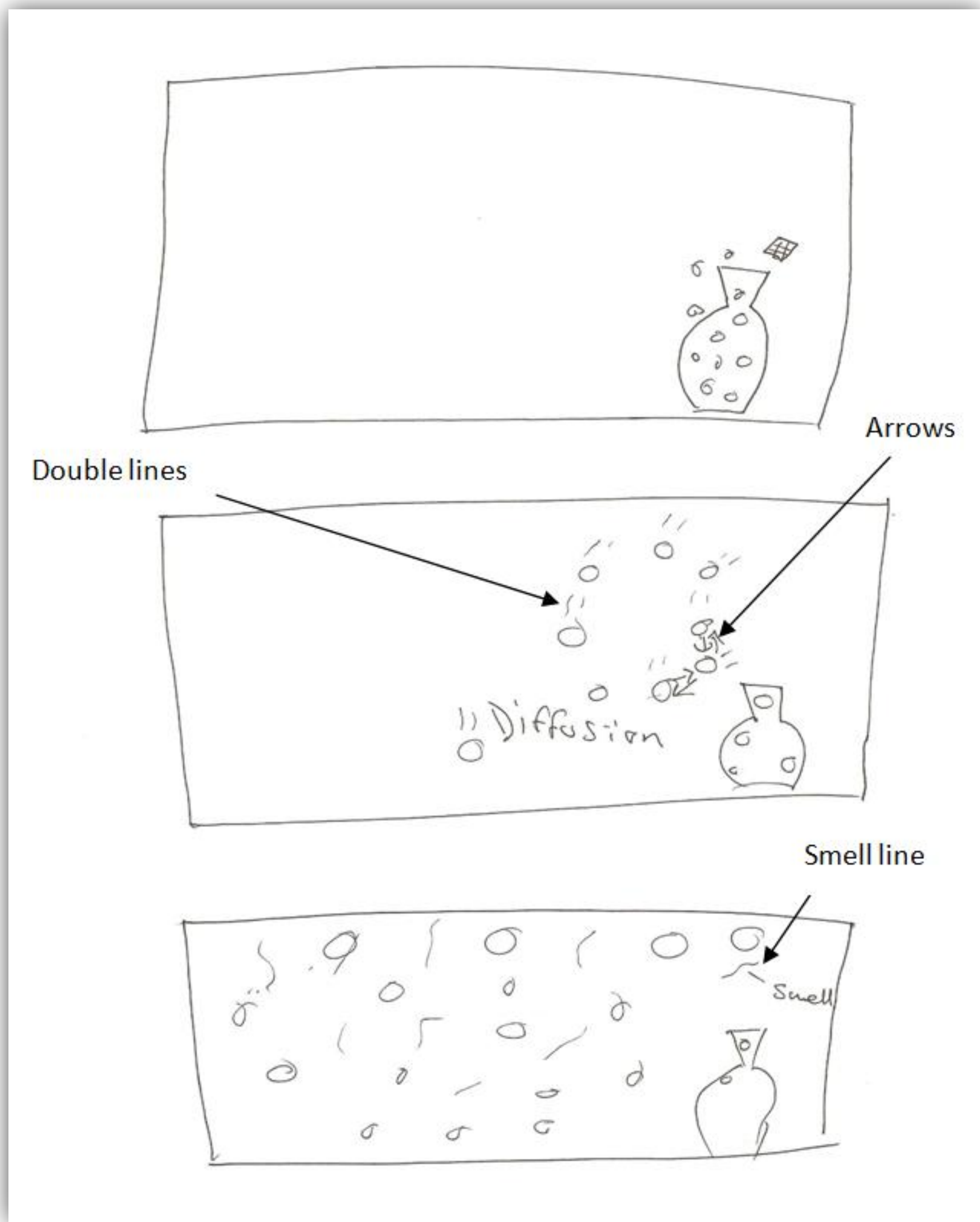

Figure 10.7 Jenny's pre-interview drawing of diffusion (source, S3pre)

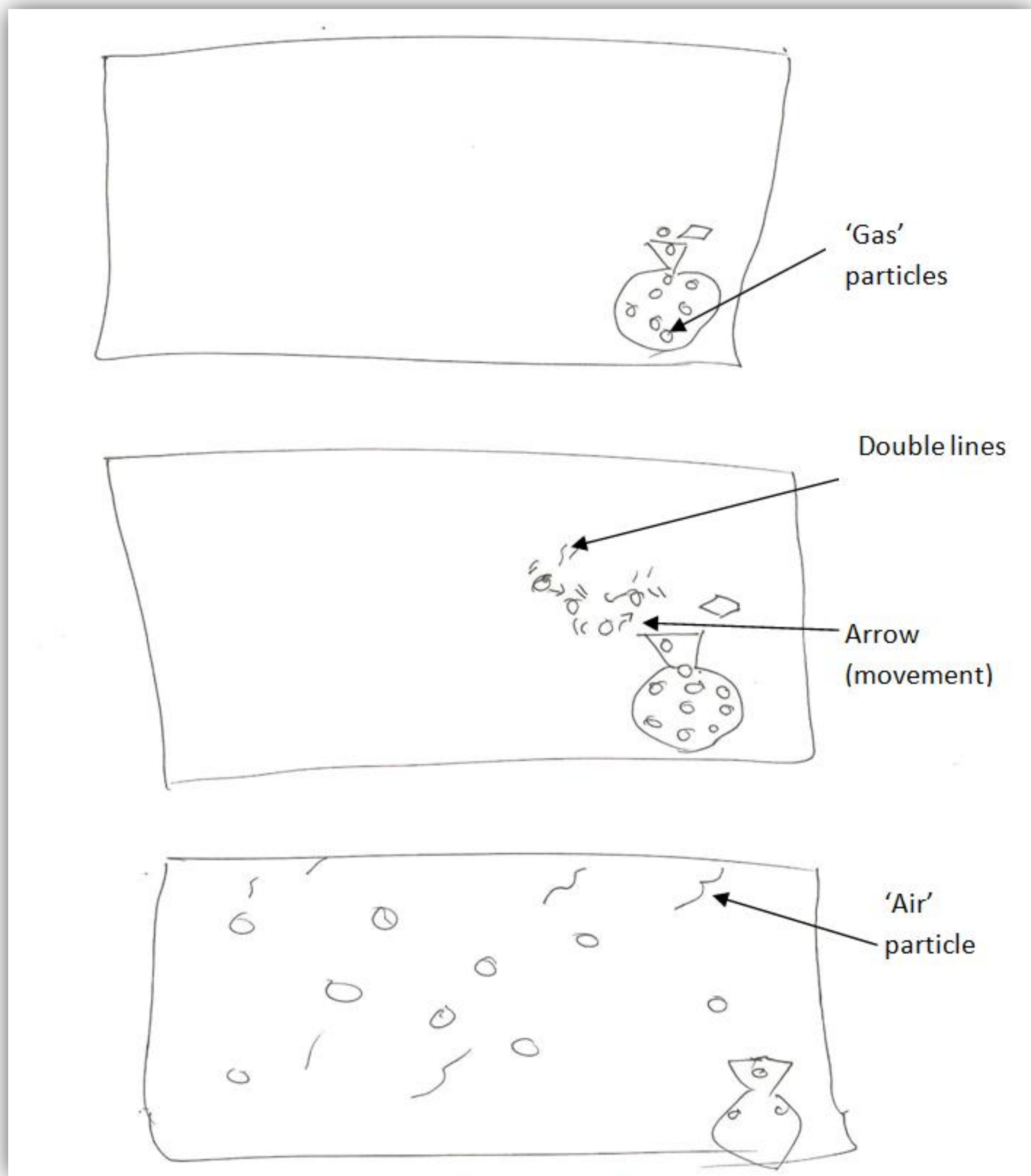

Figure 10.8 Jenny's post interview drawing of diffusion (Source, S3)

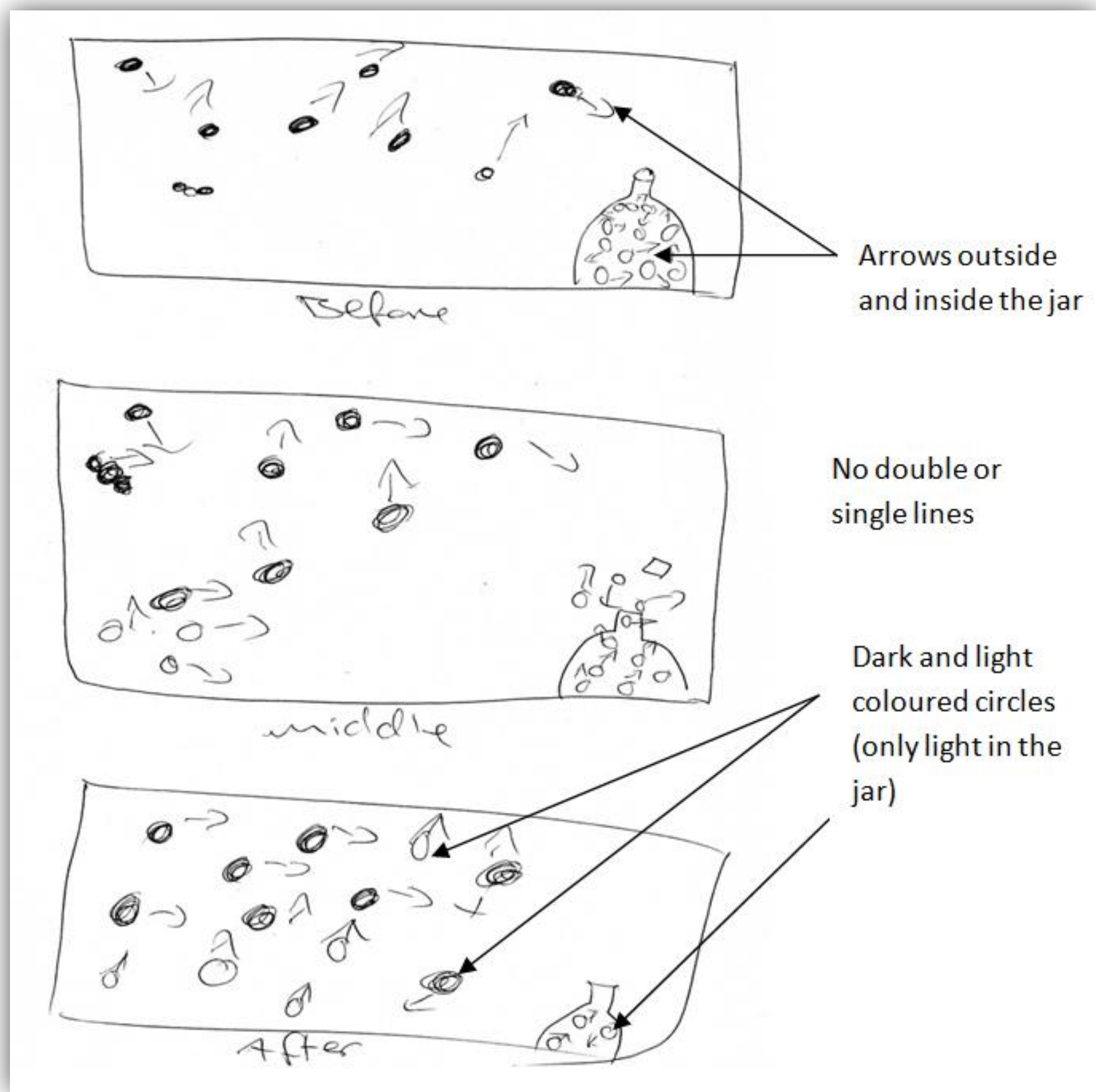

Figure 10.9 Jenny's delayed interview drawing of diffusion (source, S3del).

This sense of a consistency of image, but a plasticity of meaning over time, was also evidenced in Mike's diffusion drawings. For example, he too first included a 'smelly stuff' expression (Figure 10.10):

> Okay, so, the big particles, the bigger particles, they are the air. The smaller dotty ones, they are the smelly stuff. (S1)

Over time, as with Jenny's diffusion drawings and comments, key features remained similar while still moving the conceptual landscape towards a reflection of a more consensus description of diffusion: In the post interview Mike's 'smelly stuff' had been removed from his drawings. Now the dots represented air particles:

> Okay, the smaller particles are the gas and the larger particles are the air.
>
> (S1)

In the delayed interview (Figure 10.12), the air and gas particles were coded with colour (black pen for small dots, blue for large dots). Mike described an increasingly complex image in relation to the pre and post interview drawings:

> [Black marks] is like, so this could be like methane, you know like the methane gas. [Blue marks] is like just the air, the oxygen, argon, all sorts of stuff in it. (S1)

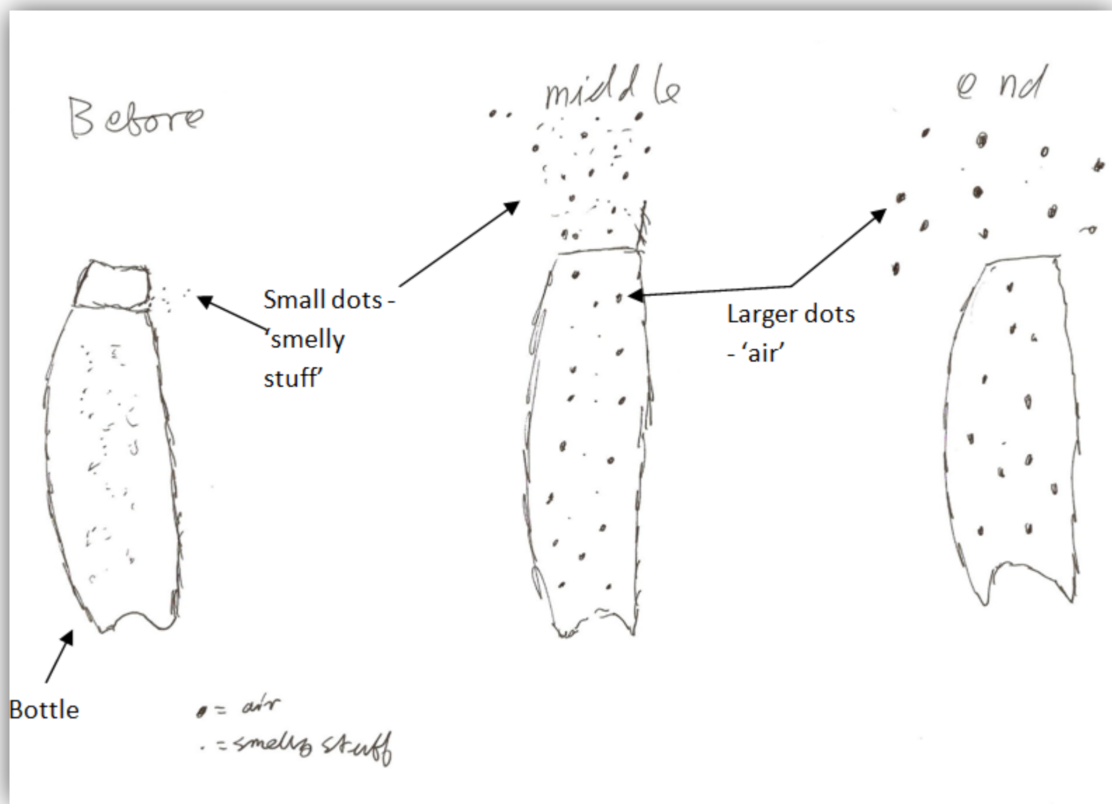

Figure 10.10 Mike's pre-interview drawing of diffusion (Source, S1pre)

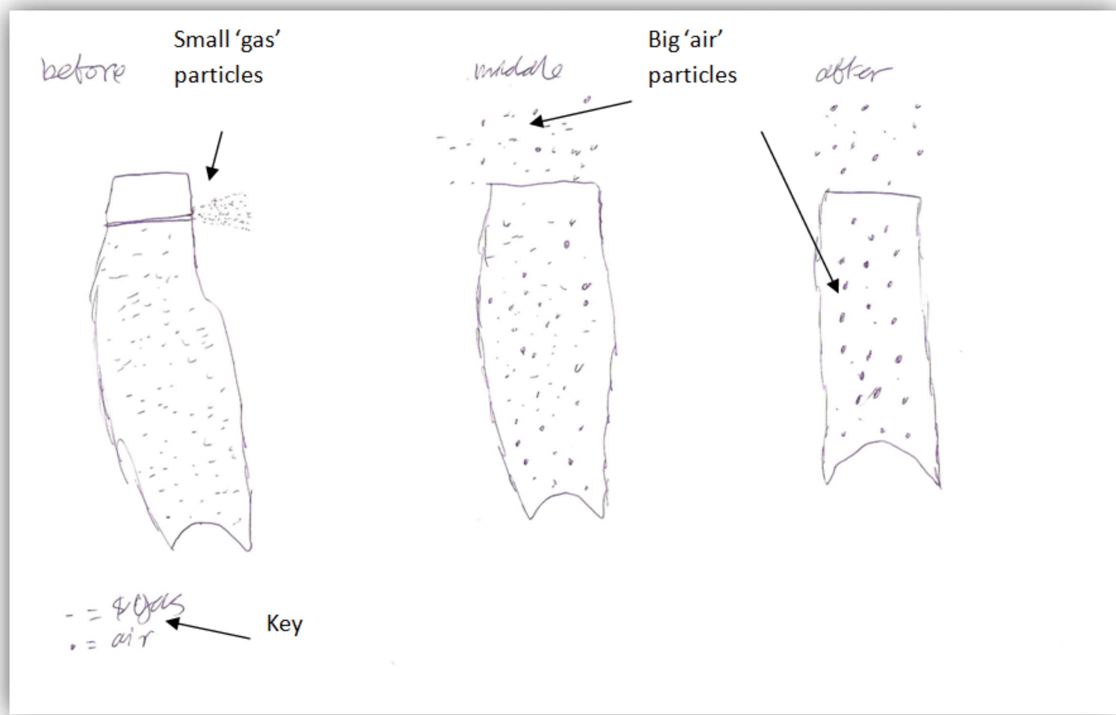

Figure 10.11 Mike's post interview drawing of diffusion (Source, S1post)

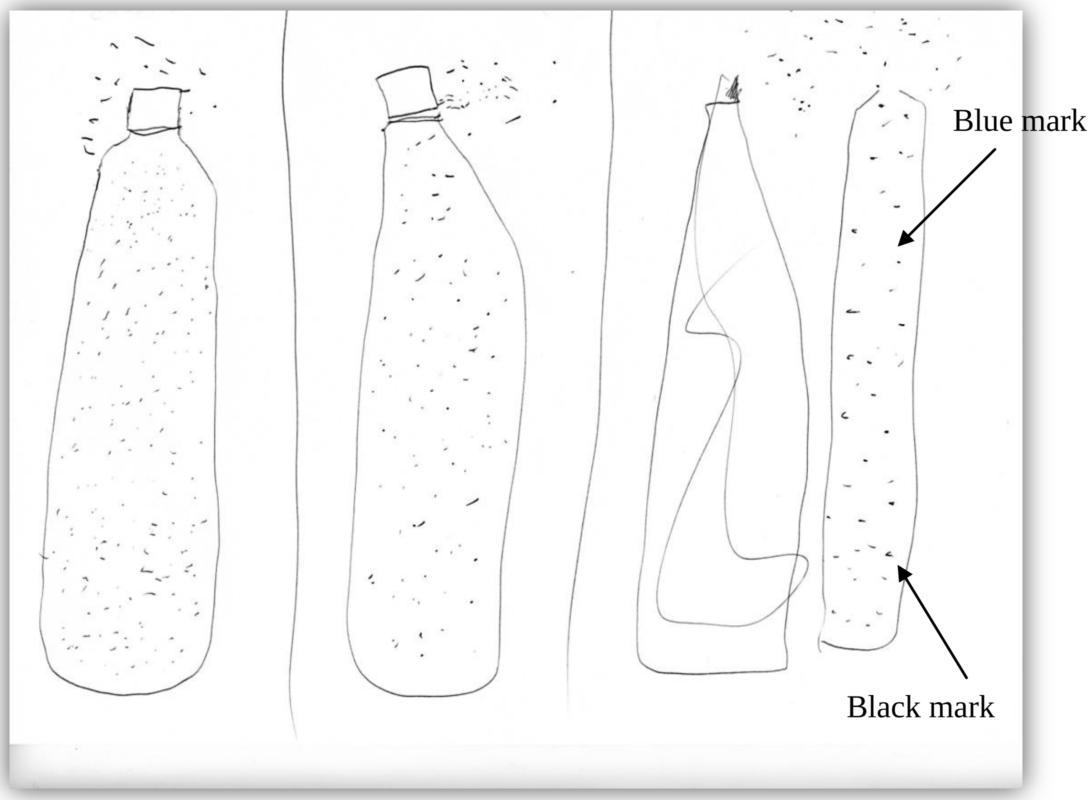

Figure 10.12 Mike's delayed interview drawing of diffusion (Source, S1del)

10.2c Enriching talk: using descriptions of students' actions within physical simulations to aid visualisation of particle movement in diffusion

Two episodes suggested that physical simulations might support students' science talk within the lesson, and afterwards. In the first episode, a student with weak verbal skills explained diffusion by referring to students' movement within a simulation to describe gas particle movement. In the second episode, the Gestural Teaching Model (GTM) was interpreted to provide Jenny with a means of expression that complemented her verbal discourse, and also prompted an episode of conceptual conflict.

During the debriefing session at the end of the lesson, one student, Ken, could not seem to find the words to express his understanding of diffusion. The teacher singled him out from the video during her stimulated recall task in her interview, describing him as a reticent participant normally, and weak verbally as well as academically (T). I had just declared that particles 'moved from high concentration to low concentration' (V2:59:48). I called upon Ken, and with the aim to offer him an easy answer in order to support his self-esteem, I asked,

> *You sir, what is diffusion?*
>
> When they spread they split up.

I aimed to draw a clearer explanation,

> *Brilliant. And particles, what happens?*
>
> [He sat silent.]

Presuming that he might be trying to remember the term, 'concentration' I said,

> *You don't need the word.*
>
> [He sat silent.]

Inspired by his initial statement, I aimed to frame the question in respect to the performances,

> *Can you describe what happened over here? Was there one particle?*
>
> No. Loads.
>
> *And they moved?*

> Spread out, they spread out in the room. (V2:59:54)

In my participant notes, I perceived that Ken's response was supported by our ability to discuss the particles in relation to human actions, rather than focus upon particles. The teacher corroborated this view with,

> And I, I actually felt towards the end, like, oh, when Ken couldn't say high concentration, low concentration, he knew, he actually knew what you wanted, he just couldn't quite use the words. (T)

Her suggestion that Ken 'knew' the idea but couldn't 'use the words', suggested that the gap between his understanding and his expression of that understanding might be bridged through discussing the acting out of the BAPs.

10.2d Using the conflict between Jenny's verbal description and her gestural teaching model to promote conceptual conflict

A second episode in which physical simulations supported discourse was in respect to Jenny's use of the GTM in her response to a thought experiment question. All interviewees in the post interviews had been asked a question designed to elicit a thought experiment-type response: What happens to an iron bar upon heating? The two other interviewees responded that an iron bar would 'expand' (S1; S2) when heated. Jenny said that it would 'shrink' (S3). The interview evidence suggested that her conception of the process was hindered by social domain beliefs and that the Gestural Teaching Model afforded a site of conceptual conflict through which to challenge her misunderstanding.

10.2e Base-line understanding: Jenny's description of a heated iron bar in the pre-interview

Jenny was first asked about a heated iron bar in the pre-interview. I had already introduced the idea of using gestural metaphors by the time the passage below occurred; Jenny initiated her own gestures to describe solid to liquid transition, which she illustrated in real-time with her verbal explanations.

1. *Okay. What are those particles doing in an iron bar?*
2. They are all compact --
3. *I like that, you put your hands together* --
4. Yeah … And they try to move and all they do is vibrate.
5. *And you are vibrating your hands.*
6. Yeah. (S3)

In this initial passage, when Jenny described the solid particles as 'compact' (line 2), she illustrated this by putting her fists together, beside each other. At the time, she gave an anthropomorphic explanation that, 'they *try* to move' (line 4). She moved her hands (line 5) in a manner that I interpreted as suggesting that the two particles were near, but independently moving.

As the discussion continued, there was a sense of confidence in her concise response as to what would happen just before the bar melts: 'It will shrink' (line 4, below). Jenny noted that this was so because the particles would 'break free' (line 8) which she seemed to equate with the destruction of a rigid structure, in the sense that the structure itself might reduce in size if its parts separated.

1. If it is heated to the right temperature it will melt.
2. *It will melt. Excellent. Something might happen to the length before it melts.*
3. It will shrink.
4. *It will shrink, so, if it is shrinking what is going on. Do the particles have anything to do with that?*
5. The particles are heating up and with the heat they get more excited and they move around, and then, I think, as the iron is melted it starts to be able to escape and move. So, yeah.
6. *To escape, to move, so how do you scale that up to the iron bar?*
7. I mean if the particles are like this [gestures fists together (Obs)] the hotter it gets the more it like [gestures fists shaking (Obs)]. And then they just kind of break free.
8. *They break free and that makes the bar grow smaller?*
9. And that makes the bar, like, go smaller. And eventually melt. (S3)

Jenny appeared to consider that a heated bar retained the same average volume as before heating, until the point at which rapidly moving particles ‘break free’, with no intermediate stage of expansion. Jenny, however, in using the GTM according to its use in the intervention did not illustrate a jarring, fast movement of her fists away from each other, but rather a progressive separation (Obs).

10.2f Jenny's post interview: conflict between talk and a gestural teaching model engenders conceptual conflict

In the post interview, Jenny provided a more lucid expression of solid and liquid states, for example, in her inclusion of the concept of *attraction* (line 6, below). She did not use anthropomorphic terms as in the previous passage above, but rather, used more scientific language: instead of particles that 'tried to move' she commented instead that they 'are not as attracted to each other... so they start to break away'. However, despite this increased depth of expression, Jenny appeared to reiterate her pre-interview belief that an iron bar contracts, again responding concisely, 'It will shrink'. Her response was quick, suggesting a rote-like, propositional statement, rather than a result of a thoughtful visualisation (Obs).

1. *What happens when an iron bar heats up?*
2. It melts.
3. *It melts. Before it melts what happens? Does anything?*
4. It shrinks.
5. *It shrinks. Why does it shrink?*
6. Because the particles, like they are not as attracted to each other and they turn into a liquid so they start to break away.
7. *They start to break away. Now-*
8. Yeah.
9. *As your hands broke away they made more space between them.*
10. Yeah. (Pause)
11. *If there is more space between them what happens to the, the object?*
12. No, it wouldn't shrink, would it? It would expand.

13. *Okay.* (S3)

Jenny used the GTM to illustrate her talk. Jenny appeared to change her mind when I stated: ‘As your hands broke away there was more space between them’ (line 9). Within the context of the discussion, I interpreted the student’s response, ‘Yeah,’ (line 10) to be evidence of affirmation and confusion, so I asked her how increased particle spacing related to its size (line 11). To this, she changed her response from previously: ‘No it wouldn’t shrink would it, it would expand’ (line 12). I interpreted the role of the GTM as an artefact of evidence. It seemed to reflect this role when, in the continuation of this discussion, Jenny retracted this conception (line 1, below). In doing so, Jenny drew upon previous empirical experience (line 1). She argued that iron contracts, and based this argument upon her own experiences of heated materials. Furthermore, she stopped using the GTM, but rather gestured in illustration of these macro objects shrinking when heated (line 2).

1. They were all starting to, I think - When you melt something it starts to shrink like when you try to burn something it starts to shrink, then it melts.
2. *I, I see, okay so you have got your hands showing the shape of this thing shrinking, and then it melts.*
3. And then it melts. So I thought. You know.
4. *Interesting, can you think of the things that you might have been thinking of when it shrinks and melts, a particular thing?*
5. I don't know. Ice?
6. *Yes, okay. It possibly was ice that you're had in your mind.*
7. Yeah.

8. *Okay so we have a metal bar and it is not melting, we have heated it up, and you have got yourself* --
9. *Yeah,*
10. *And you have given your particles energy,*
11. Like so they move around, and then the vibration makes them break away from each other.
12. *Your hands, yep, vibrating more and more. And so we scale that up. And then what happens to the iron bar?*
13. It is, I don't know. (S3)

In this post interview Jenny's final conclusion came as the result of an arc of thought that began with contraction, considered expansion, but then returned to the initial conception, supported by personal, empirical experience.

10.2g Students at play: the atypical nature of student discourse within the preparation for devised BAPs

Preparations for 'The Spy's Perfume' were preceded by a description of a brief lecture. During this interactive/authoritative discourse, the students sat cross-legged, remaining relatively still for the entire time (V1:32:03-33:24). While there were sporadic smiles and laughter, presumably at my humorous comments, nonetheless, a minority of students stared at the floor. The attention in the lecture seemed high, as evidenced by student stillness, gaze, and silence (Figure 10.13). Five students spoke during the lecture; three because I directed questions specifically at them.

Figure 10.13 A Lecture (V1 32:03-33:24). Students sitting attentively.

By contrast, the preparation phase of ‘The Spy’s Perfume’ revealed a learning environment that was also conducive to student attention, but a first impression was that the room was crowded and noisy. Close proximity, touching and unintentional blocking of other groups’ actions was indicative of the behaviour (Obs), but there was also a high degree of self-regulation. In one group, for example, three boys and two girls stood initially in a tight circle; the girls at times reached out and grabbed two boys’ arms. In an exuberant moment, one boy stepped back and momentarily danced outside the circle before returning to the group (V1:45:55). The circle dissipated as they spread themselves across a wider space in order to rehearse, and stood in a line down the centre of the room. The room was cacophonous (Obs; V1:44:31). In the video**,** students in other groups blocked the eye-line of the King-actor and his companions, but the King merely looked around the other students towards his group members. Still partially blocked, the group enacted the first scene, in which the Spy released the gas and the Bodyguards and the King fell down sequentially as their distance increased from the Spy (Figure 10.14).

Figure 10.14 (V1 44:59) A sequence from the initial Spy's Perfume preparations. This is the macro scene in which particles are not acted out; the students are falling sequentially based on their distance from the spy (labelled). The girls at the front and students to the right are in two other groups (a third and fourth group are out of frame). A teaching assistant sits at the back (the teacher is out of frame).

Despite the potential for disruption the students did not tend to move away from their group and engage with other students, but rather focussed upon their group tasks. For example, during a stimulated recall episode while watching an example of *exuberance*, their teacher observed a boy who, 'has a tendency to dominate, but within the group he couldn't' (T). This comment was made in reference to an episode in which the boy mimed firing a machine gun at the student in his group playing the 'King'. Members of the group looked towards him, and then turned back to the group (Obs). The boy stopped, and the group drew him into their focus again.

Close proximity and touch were evident to the degree that the latter was noted afterwards by the teacher as a potential problem, but which in this situation revealed a positive outcome. She noted that one of the girls normally did not like being touched, and was surprised by her observations of the girl's enthusiasm to engage fully in her group (T). She explained this attitude in respect to the warm-ups,

> And then a couple of girls. They were Asian girls, but there's a girl here with a white headscarf. Very bright, but very quiet and very self-conscious of people being near her and touching her. But she didn't seem to, when you did the whole sofa bit.
>
> *Would she have been the sort of person who would have said if she really wanted to sit out? Would she have felt, Oh, I must do it anyway?*
> No, she would have tried to do it anyway. But she would have tried, I think, in a usual situation she might have taken a lesser part rather than be the one that is on the end of the chair, bent over, trying to do something. (T)

The student's engagement in the lesson was emphasised in that she took the key role of the spy in her group's preparations for 'The Spy's Perfume' (Figure 10.15). She was one of three students which the teacher commented upon as students who acted atypically, either in becoming more extroverted, like the girl above or the boy, or in adopting an attitude of complicity to the group, such as two boys, Ted and Ali,

> And it was really nice to see them actually standing up and taking part. Because Ali is very much like,' I don't want to do it, I won't do it, I don't want to work with him'. So that was really nice, that was completely different. And I think he didn't feel embarrassed because he could see that everyone was so involved in what they were doing that he didn't feel like people were watching. (T)

Figure 10.15 V2 (44:38) A normally shy girl in-role as the spy in 'The Spy's Perfume', miming binoculars.

10.3 Discussion

In the intervention, students' levels of participation in performances suggested a high degree of comfort despite being placed in a position of vulnerability, such as acting in front of their peers (Heathcote, 1971; Odegaard, 2003). The teacher noted that otherwise quiet students, including girls, or those who were weak verbally behaved with atypical motivation and engagement in the intervention task (§10.2g). This echoed findings by Aubusson et al. (1997) who also observed atypically engaged behaviour from a normally shy girl, and by Tvieta (1999) who observed that girls felt comfortable with this modelling resource (§2.2d).

10.3a Image consistency, context inconsistency

Some interviewee's drawings were found to repeat key images from the pre-intervention in post and delayed interviews (§10.2b). Over time these were reconceptualised with more accurate and detailed labelling (or verbal descriptions of the drawings). In the pre-interviews, Jenny and Mike's drawings included *smell particles,* and verbal descriptions suggested that they believed that smell was a separate entity caused by gas particle interaction. This smell-particle idea has been observed in responses from secondary students (Stavy, 1990). However, whereas Stavy presented a cross-sectional description, this study has provided a longitudinal lens in which Jenny and Mike seemed progressively less inclined to signify smell as discrete objects in their drawings, nor to conceive of smell-particles. Following the theory that each drawing was an episode of recall of the topic concept, and therefore a new site of reconstruction and re-encoding of the concept (Kokinov & Petrov, 2001; Taber, 2003), the evidence highlights the consistency of the interviewees' images, and also the malleability of their associated labels and definitions.

10.3b The GTM: a model of authority

While this interview was not aimed at teaching Jenny, the 'iron bar' discussions nonetheless suggested the rhetorical force of including the GTM in science talk. Jenny appeared to be in a situation that Bouwma-Gearhart, Stewart, and Brown have termed a dual-model approach (2009, p.1167), in which a student holds two models that conflict, but does not realise that there is such a dichotomy in her understanding of the concept. The scope for the interviewer to draw attention to features in a student's own GTM suggested its impact as an authoritative heuristic for challenging students' alternative conceptions, while also supporting extended discussions across sub-micro and macro levels of thought.

10.4 Summary of Case 6

This case focussed upon the teaching of states of matter and diffusion. The lesson progressed from the warm-ups to a whole-class GTM of states of matter, to group BAPs of diffusion and then half-class group BAPs of diffusion. Students' behaviour was atypical for the class in regular lessons, in that it resembled playground behaviour; however, it was interpreted to reveal a high degree of self-regulation. The pedagogy appeared to support the engagement of students who the teacher perceived as typically quiet or shy. Interview data suggested that GTMs held a rhetorical authority which aided in an episode of conceptual challenge. Interviewees' drawings suggested an increasingly rich expression of the sub-micro level, and concept maps suggested that interviewees foregrounded the idea of heat and *energy* in their conceptions of the relation between heat and particle movement.

11.0

Case 7: Concretising Pretend Objects, and Balancing Equations

> 'It was good. I remember about protons and neutrons. And it was good. I really liked the fact, when we were all sitting in a circle and we were doing balancing equations. And it was really good because like, all, basically everyone got involved in that. Because everyone was kind of like helping contribute. It was really cool.
>
> *Excellent. So, what –*
>
> Because a lot of the time in a class, obviously you just ask the question and one person gets to answer, but [here] we all participated.' (S1post)

11.1 Case Description

This case took place with a Year 9 class in a secondary state school in Cambridgeshire. The class included twenty-four mixed-ability students (T) aged 13-14. The late-morning lesson took place in the school hall, a gymnasium-sized space, with a proscenium arch stage at one end (Figures 11.1- 11.4). This was the only intervention to occur outside the classroom. The teacher had not used role-play previously with this class (S2; S3; T). The intervention lasted an hour and ten minutes.

11.1a Teaching objectives

- Review atomic structure
- Introduce a particle-based visualisation of molecular structure
- Introduce a particle-based visualisation of balancing equations
- Solve a balancing equations problem

11.1b Lesson description

The lesson began with a brief lecture on particles as models of atoms. Over the next twenty minutes, two groups of twelve students performed the warm-up tasks (§4.4). I then demonstrated a BAPs of an ideal atom, which students then devised and performed in eight groups of three. I described their collective simulations together as a roomful of hydrogen gas. After a brief lecture noting that hydrogen exists in the air as diatomic molecules, four groups then performed their responses to a thought experiment of how two ideal atoms might form a hydrogen molecule. These were performed simultaneously, followed by an evaluation, and then I directed the groups to perform a hydrogen molecule of my design. Next, I directed a whole-class BAPs of a balanced equation for water synthesis. Students then engaged in a whole-class simulation for NaCl synthesis. A debriefing ended the lesson.

11.2 Analysis

11.2a Pre and post interview descriptions of molecular and atomic features

The pre-interviews suggested that students had a weak understanding of simple atomic features. Only Ben in the pre-interviews initiated the terms *electron* and *proton* (S1pre). None of the interviewees could define the terms *neutron* or *positive charge* when prompted within the context of the show cards task, and only one, Ben, defined *charge*, which he described in relation to electric current (S1pre).

The post interviews provided a more consistent description of subatomic features: All interviewees associated positive and negative charges to protons and electrons and all interviewees noted that neutrons were neutrally charged. For example, Ben asserted that, ‘the, neutron is, I guess, the particles in atoms that have got a neutral charge’ (S1), whereas Tracy, who could only imply the positive and negative charges by saying that, ‘One was yes and … one was no’ (the words that the electron and proton actors used), nonetheless also noted the neutron ‘was neutral’ (S2). Kate could point to a neutron in her drawing and say, ‘That is neutral’ (S3).

While no interviewee discussed the concept of *attraction* between particles in the pre-interviews, Ben and Tracy described attraction between protons and electrons in which both students used the terms, ‘connection’ and ‘connecting’, for example, Tracy explained that during her atom simulation she was the proton,

> And I was keeping eye contact with a neutron, no, no, the electron.
>
> *Why was that?*
>
> Because they have a *connection*. (S2)

And Ben observed that,

> I know that there is a force *connecting* it with the nucleus in the way that it [the electron] just spins around the nucleus. (S1)

Only Ben could attempt to balance an equation in the pre interview, in which he balanced the equation for water with the following equation: $H_2+O_2 \rightarrow H_2O$, which he completed as, $H_2+O \rightarrow H_2O$ (S1pre). Tracy and Kate could not complete the task.

11.2b Post interview balancing equations tasks

Only with guidance could the interviewees balance a water synthesis equation in the post interviews (S1; S2; S3) for the reaction of sodium chloride. All interviewees at first attempted to divide the chlorine reactant (S1; S2; S3). However, all of the interviewees adopted the rule to add particles once reminded. Tracy and Kate did not initially understand the notation of coefficients and subscripts until they received guidance (S2; S3). All three interviewees checked their work by counting the number of particles on each side of the equation (S1, S3). An attempt to visualise these reactions appeared to form part of Kate's response, suggested in her use of circles to denote particles, drawing them above the corresponding formula (S3).

The simulations appeared to support students' ability to engage in extended discourse in relation to their balancing equations questions: in particular when describing the equation in terms of directing an imagined class of students acting-out a simulation (S1; S2; S3). For example, in the post interview, Kate, who had been described as lacking confidence (T), surprised me with her engagement in an extended, sixty-line dialogue on the balancing of a water equation. This began with my question in respect to the equation: $H_2+O_2 \rightarrow H_2O$,

1. *Okay is that a balanced equation or not?*
2. No.
3. *No, justify that. What were you thinking of?*
4. Well, there is, like too few there and there is only one there.
5. *Okay. So what does that mean? There are too few?*
6. There should be more on that side or one less on that side.
7. *Okay, so could you tell me how you might direct that? If you were having people stand up.*
8. You would have, like two girls and then two boys, and then two girls and two boys.

9. *Okay so you'd want two boys and two girls over here?*

10. No just one boy. (S2)

A key aspect of the passage above was Kate’s use of gender as a proxy for the elements, as in line 8: the girls signified hydrogen and the boys signified oxygen atoms.

Kate had been given the written, unbalanced equation in front of her. Through reference to the simulation that she had done in class, Kate seemed to quickly translate the chemical symbols and subscripts into the imagined model of students enacting the equation. She was able to engage in conversation despite using relatively little science terminology: For example, she described an oxygen symbol as ‘zero’ later in the passage (S2). Kate’s relatively lengthy responses suggested her comfort with the problem, an increased skill at visualisation and an increase in her sense of self-esteem, given that she could and would continue with the problem for so long. (S2).

11.2c The effect of what isn’t there: the use of imagined roles to inform subatomic particle proximity

The ideal atom simulations were ostensibly *thought simulations*: visualisation tasks that exist without an explicit hypothesis or answer, such as replications of a teacher’s model (Georgiou, 2005; Irvine, 1991). I had initially assumed these to be a less cognitively challenging task than a thought experiment since the objective was merely that students reproduce, not devise, a model.

The initial teacher's demonstration incorporated real and imagined images. Students watched as I inhabited three roles consecutively. I coded for these roles by stepping out of the place in which I created the first role, then stepping out of that place to produce the next role (Figures 11.1; 11.2; 11.3, 11.4). I reminded the students of the imagined roles by turning towards the place where I had just been standing and framed my previous position with my hands held out as if to hold the sides of the imagined me. The trios, however, translated the imagined me into concrete features by using all three students simultaneously to play particle roles (Figure 11.5). Students did not seem to be hindered by this task. The students' full participation and speed in creating the atomic simulations reflected a comfort with the modelling task, as one interviewee, Tracy, noted:

> Well it was quite easy, about what to do, because we had already seen it.
> It had just been demonstrated. (S2)

However, they had *not seen* the model that they then created. The two models were not replicas; students were not reproducing a *1:1 representation* (Grosslight, Unger, & Jay, 1991). The students saw only the concrete demonstration of a *part* of their atomic models. By contrast to my single-person model, three students took separate roles. Signification of particular features differed between the teacher and student simulations. For example, I did not demonstrate attraction by holding my gaze with anyone. Rather, when in role as a proton, I stared into the middle distance and turned my head, as if looking at an orbiting object a metre away (Figure 11.1). Then in role as electron, I stared into the middle distance towards the space in which I had stood as a proton, and at a height of around two metres, while I moved in a circle around an empty space (Figure 11.4).

By contrast, the three-person student models were visibly different, with features associated to their more concrete nature: for example, Kate noted that her group looked to relate their different heights to the size of atomic particles (S3), with the shortest girl playing the electron. In the post interview, Ben's explanation of the use of *gaze*, suggested that the student models differed in a qualitative sense too, in the emphasis on the relationships between the actors as a source of meaning,

> *Okay. And how did you show the electron?*
>
> … I walked around, spinning around, holding my gaze to the proton --
>
> *Why the gaze, why holding the gaze?*
>
> I think because the connection between the nucleus and the electron is, well the proton, the proton and the electron are connected and that is why, because in some way, that's why, I think it is with the charges. That is why, that is why the electron stays spinning around that particular atom. (S1)

The enacting of gaze for attraction suggested a heightened emotional tone, as it was an action that might potentially make people feel vulnerable. For the participants involved, the point of view afforded by gaze was potentially different in its emotional quality in contrast to watching me stare into the middle-distance. This further highlighted the difference in representations between the teacher and student simulations of an ideal atom.

Figure 11.1 Teacher demonstration of an ideal atom: proton (V1:28:05)

Figure 11.2 Teacher demonstration of an ideal atom: electron (V1:28:52)

Figure 11.3 Teacher demonstration: neutron (V1:28:39)

Figure 11.4 Teacher demonstration: orbiting electron (V1:28:58)

Figure 11.5 Group simulations of ideal atoms. There are three groups in frame. Note the lower level of the centremost boy (electron), and the held gaze between him and the girl opposite (proton). (V3 31:43)

11.2d Molecular models: failure first

The inclusion of the molecular model task was inspired by the teacher's assertion that her previous students had difficulties in recognising that some gases were diatomic, and that this had confused them when they were first introduced to balancing equations. Indeed, the pre-interviews suggested that the interviewees had a very weak understanding of molecules, as exemplified by drawings of a molecule as either a single circle (S1; S3) or none at all (S2). Only the most able interviewee, Ben, revealed an awareness of molecules as dynamic particles, albeit with movement described in anthropomorphic terms, as '…atoms and molecules and stuff… Just, like, dancing about' (S1). However, Ben revealed his confusion over the size and nature of the particles:

> I know that molecules are smaller than atoms. But I am not sure where particles come into it. (S1)

However, in employing the terms ‘atom’ and ‘molecule’, and describing their movement, Ben showed greater awareness than his peers; one of whom, Kate, summarised her understanding in the post interview that, ‘I didn’t know anything before. I didn’t know what a molecule was’ (S3).

I felt that the task included some risk in that if the rest of the class shared the interviewee’s lack of understanding of molecules they might therefore become demotivated; it was important to provide a familiar base analogy. However, I provided this only to the extent that I asked them to try to use their understanding of the atomic models. Despite the complexity of the task, the students appeared comfortable with the task, although they were given only thirty seconds to complete it.

Figure 11.6 Students' molecule performances (V3 36:21)

After an initial phase in which they stood in tight groups and spoke briefly; action followed quickly: The video revealed that students from different groups watched each other prepare (Obs). One group to the left of the field of view appeared to change their model after three members watched the group to their right, so that they changed from standing in a circle facing inwards, to facing outwards as their circle rotated (Figure 11.6). Tracy described her ease at co-constructing what for this class was a highly abstract concept:

> Well we just gave each other our arms and we knew, that, what we needed to do. And we did say something like, 'Oh, put your hands up like this', or 'Let's keep eye contact'.
>
> *Yes, yes.*
>
> Other than that we knew what to do. (S2)

The task was to simulate a system for which I assumed they had little understanding, and therefore posed a high cognitive challenge. Also, I assumed there was a high affective challenge due in part to students being placed in large groups with others with whom they did not ordinarily work (S3). I nonetheless interpreted a high degree of student complicity and interest in the simulation construction, shown in part through student *exuberance*. For example, during a stimulated recall session, I asked the class teacher to watch and comment upon a video of a group of boys just before they were to perform their molecular simulations to the class. During a stimulated recall session, the teacher later reflected upon the behaviour of Ben briefly kicking out as if doing the Can-Can while his group held arms and stood facing outwards in a circle:

> They were so keen. I think they were keen to get started. Ben had cottoned on to what you wanted. That is my impression from that. (T)

The classroom teacher indicated that this exuberance was in keeping with appropriate learning behaviour for the class. When Ben was asked if he could discuss his behaviour at this point he too indicated that it was drawn from a sense of motivation.

> I think, I think it was just showing, I think it was because we were really enjoying ourselves… I don't think; I suppose it's kind of not acceptable… I don't think it is a significant problem. (S1)

The features of these molecule simulations indicated that students were reliant primarily on their understanding of their atom simulations. This was suggested in their replication of signifiers: For example: each student represented one subatomic particle, conveying its features through facial expression, with smiling protons to signify charge. They employed spatial orientation, and stood as individual particles beside each other; and they conveyed attraction through electron and proton-actors staring at one another. Three of the resultant group models were like rotating rings, which seemed to echo the atomic models' orbiting electrons. In two groups, students also locked arms and in three groups students stood beside similar particle-actors, suggesting symmetry within their molecules. A final group had four students with interlocked arms and two students walking around the outside, as if orbiting (Figure 11.6). In this group, they said that the atomic nuclei were separate from one another. These responses supported an interpretation that these were thought experiment-type responses in which the *goal* was to describe features of an ideal diatomic gas molecule, the use of analogical relations used in the atom simulations suggested *experiential understanding*, and the consideration of proximity and attraction suggested a *coherency* to the simulations.

When I began the activity, I did not know what the students' resultant models would look like. Since I did not know how they would use their physical simulations skills, I did not prepare an ideal model of a molecule in mind. Rather, I aimed to see if I could work with their chosen modes and signifiers. In doing so, my resultant teacher-directed model separated the paired nuclei-actors and the electron-actors, and I had the electrons running in a figure-eight between each nuclei (Figure 11.7). While the activity aimed only to provide students with the idea that hydrogen was a diatomic molecule, nonetheless, some improved visualisation of molecular structure seemed to be developed. For example, in Ben's response in the post interview, when asked what he would see while looking at the table with 'magic goggles', he said,

> I guess you would see just individual molecules. I guess, molecules and atoms, yes atoms inside molecules. (S1)

This statement contrasted with his pre-interview statement, 'I know that molecules are smaller than atoms' (S1). Furthermore, while the pre-interview drawing of a molecule consisted only of a circle, Ben's drawing of a molecule in the post intervention provided a range of details (Figure 11.8). Whereas the pre-interview drawing consisted of two circles, he now signified atoms, electrons, protons, and neutrons. The electrons' orbit was signified by a large circle. Double lines from electrons to protons signified the attraction. Although the model was incorrect, for example in uniting the nuclei of the two atoms, and suggesting a cell-like structure, nonetheless, it presented the diatomic nature of the molecule which was not evident in the single circle drawing in the pre-interview. He identified the particle types by the personification of their charges, drawing different facial expressions. In this use of happy, angry and neutral expressions on the subatomic particles, Ben appeared to provide a student-centric, rather than formally expressed description of a molecule. Students were not exposed to diagrammatic representations of molecules within the intervention lesson.

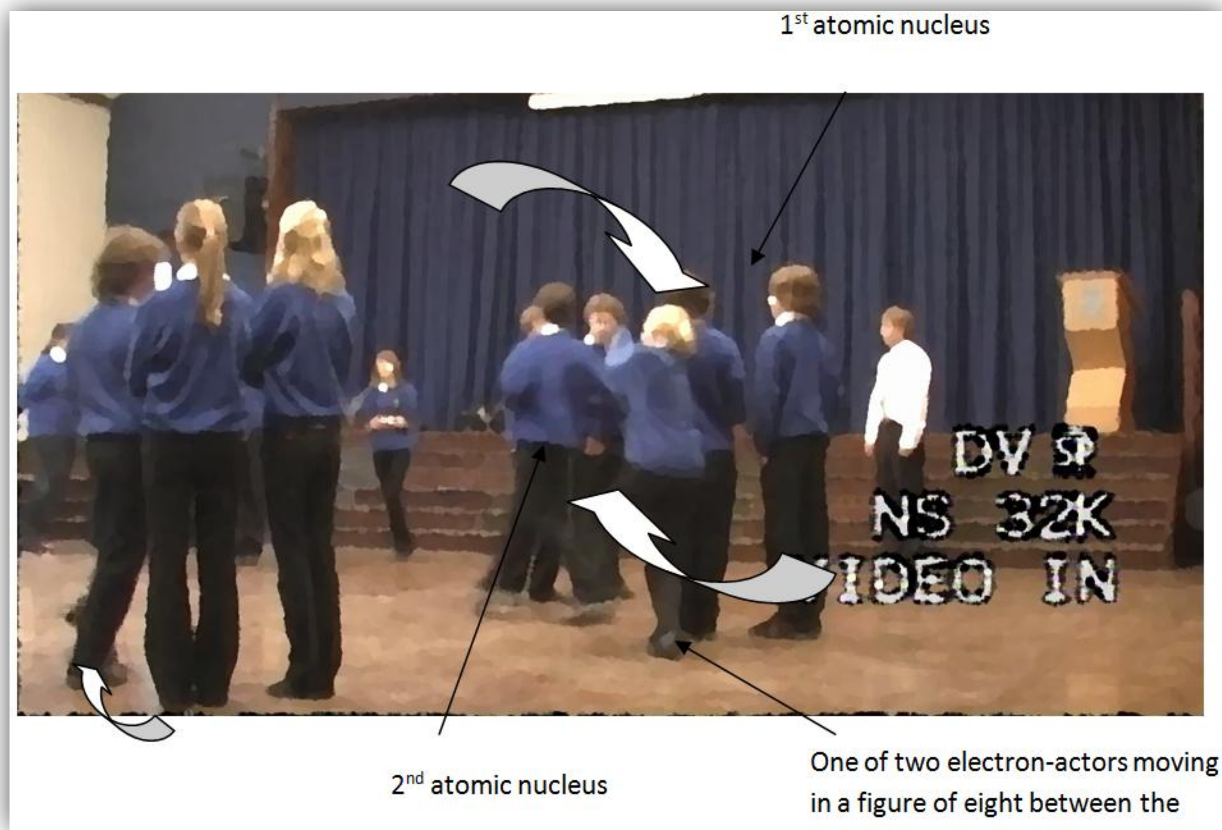

Figure 11.7 Students performing teacher-directed models after evaluation of their TE-type expressions. Three groups are in frame. The large white arrows show the direction of movement of the two electron-actors as they run in a figure-eight pattern around the two nuclei pairs. (V3: 37:17)

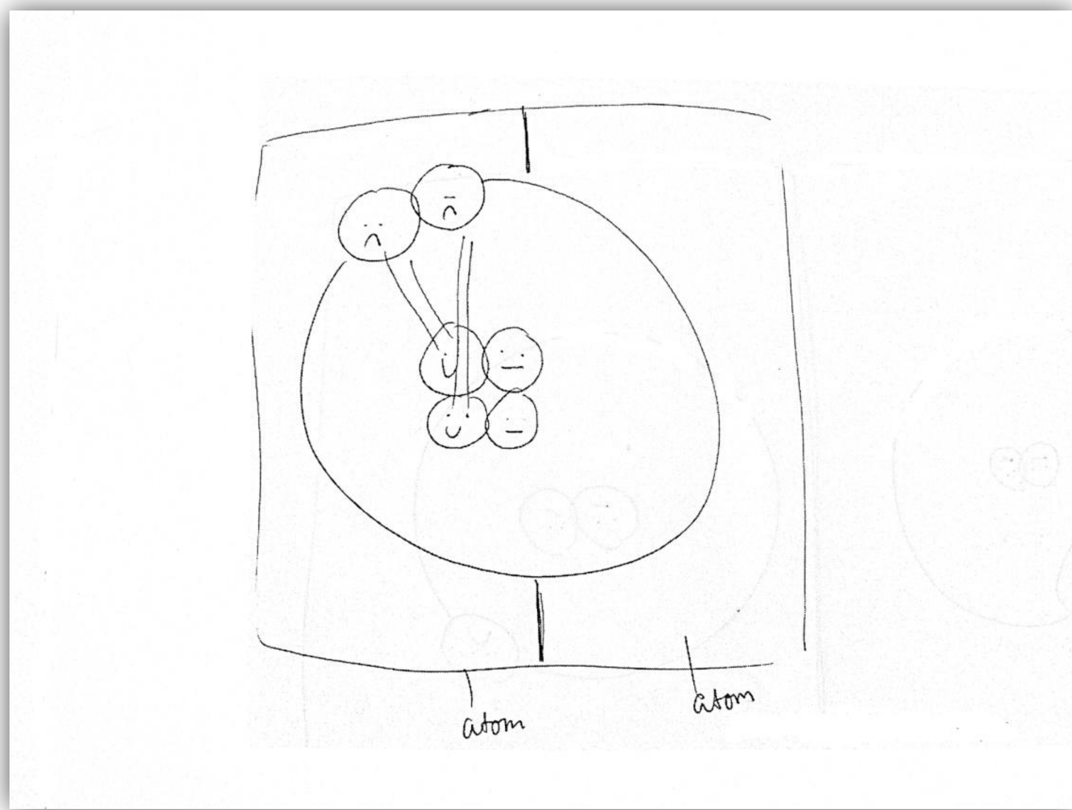

Figure 11.8 Ben post interview drawing of molecule (Source, S1post)

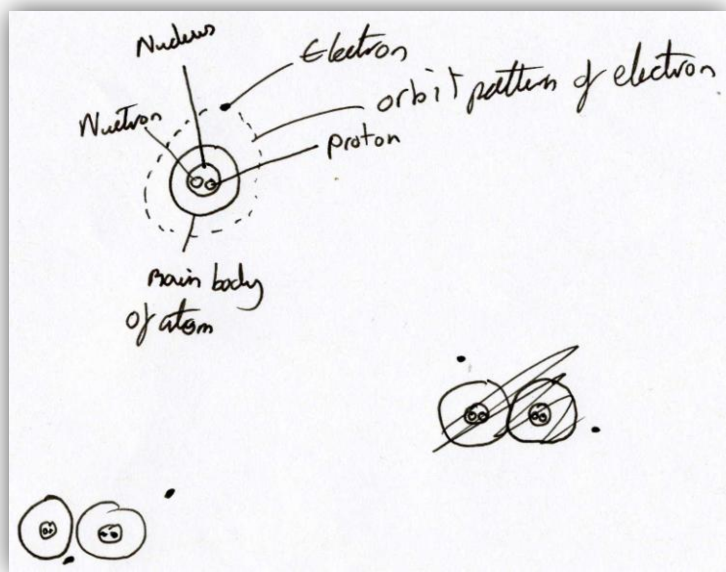

Figure 11.9 Ben’s delayed interview atom and molecule (Source, S1del)

The teacher noted informally that she had not taught molecular structure before the lesson, nor during the four months afterwards, which the students corroborated in interview (S1; S2; S3). Even so, Ben's subsequent molecule drawing appeared more scientifically literate, in the delayed interview. This diatomic molecule was closer in semblance to the teacher-directed simulation of a diatomic molecule, to the extent that his drawing was suggestive of a bird's eye view of the physical simulation. Here he revealed the principal features of two nuclei close together, separated by a gap through which, as he described in interview, the electron paths intersected in a figure-of-eight orbit around both nuclei (Figure 11.9, bottom left hand corner). Ben, in describing the features of his drawing said that he remembered the modelling task from the intervention (S1). However, there was also a suggestion that the model was informed by knowledge outside Chemistry: The circle that surrounded the nuclei above seemed to suggest cell structure, which Ben had studied in a recent Biology class (S1del).

Improved visualisation was also suggested through Kate's use of language. Although she did not initiate the term 'diatomic' she seemed to circumvent her lack of terminology when she described oxygen as, 'an element, a gas element,' which is composed of 'oxygen and oxygen' (S3). Whereas Kate did not appear to have the term, 'diatomic' in mind, she could still describe a visual image of it as two oxygen atoms.

11.2e Balanced equation tasks: three-tiered concepts and forum theatre

The balancing equations episode consisted of two activities: a teacher demonstration of balancing the equation for H_2O synthesis, and a student-centred balancing equation task for NaCl synthesis. This was a difficult activity to design as this was the first task in the study in which a teacher had asked that students include a symbol-based dimension to their learning. I aimed to devise an activity which provided scope for more teacher control over the model. I aimed to use the bodies-as-particles (BAPs) approach that students had experienced already in the lesson. To avoid having my attention divided between groups, I aimed to create whole-class models.

I was inspired by the concept of 'balancing' to consider an approach called Forum Theatre, a feature of Augusto Boal's Theatre of the Oppressed (2000). In this, scenes were presented by actors to simulate societal inequalities in which there are oppressors, oppressing the oppressed. An audience is then invited to direct, and act-out themselves, a *more equal* society onstage. Adapted for this lesson, the approach provided a format for staging the problem-solving in a circular, democratic forum, using the whole class as one modelling group, under the constant supervision of the instructor.

The balancing equation tasks were framed with the scenario that I was a mad scientist who aimed to react hydrogen and oxygen to create water, and to do so in sufficient quantities as to cause havoc by flooding the country's schools, so that children would be given time off and would then run amok in the towns. In order to save on waste and cost, the scientist wanted an exact amount of hydrogen and oxygen.

The first task was a teacher-directed simulation: After laying a printout of 'H_2+O_2→ H_2O' on the floor, I directed fourteen volunteers to create a BAPs of the equation in the centre of the circle (Figure 11.10), including two students as the symbols '=' and '→'. Gender-based coding was introduced: two boys were instructed to stand together as a hydrogen molecule, and two girls were directed to stand apart from them, but beside each other, to represent an oxygen molecule. In the space between the two pairs of reactants, I asked another student to sit and hold her hands crossed in front of her, to indicate a plus sign. One boy, as the *arrow* symbol, was directed so that he laid down on the floor with his head pointed in the direction of the products and feet towards the reactants; two boys and one girl were directed to stand together in order to represent the product. From this point, I directed the addition of an extra actors to balance the equation.

After the teacher-led demonstration had been completed, the students were instructed to balance and express a second equation ($Na+Cl_2 \rightarrow NaCl$) on their own using the techniques modelled in the previous demonstration. The students were allowed to ask questions. Employing the signifiers of the previous demonstration, together they co-created an unbalanced, and then a balanced equation.

Figure 11.10 Balancing equation, teacher-led task (V1: 47:37)

11.2e.i A comparison of talk between the teacher-led and student-centred balancing equation tasks

Due to the whole class design of the balancing equation tasks, this was one of the few activities for which extended discourse could be clearly transcribed (4.8c). This provided the opportunity to explore talk at a finer grain level than in previous cases. The dynamics of teacher and student talk differed markedly across the two tasks. Through initial analysis with respect to The Communicative Approach (4.8c) I interpreted the teacher-led task to be interactive/authoritative, whilst the student-centred task was interactive/dialogic. The differing patterns of talk in these tasks echoed evidence in my Masters study which questioned whether teachers' perceptions of control over the learning environment actually corresponded with students' conceptual development (Dorion, 2007, pp.122-123). Now, given the opportunity of two tasks which were ostensibly identical in respect to the form and problem solving protocols, I aimed to explore the dynamics of discourse and teacher control. To increase the sensitivity of my analysis, I drew upon Mercer's features of traditional classroom talk (2000) and Alexander's criteria for dialogic discourse (2006) (4.8c). The benefit of employing both classification schemes was that it juxtaposed Mercer's focus upon the teacher's control of the developing arguments with Alexander's focus upon the different relationships between teacher and students when they are viewed as co-participants in a lesson. The definitions for their categories of talk are included in the tables below (11.1; 11.2). The tables also show examples from the video transcripts which corresponded to these criteria (see Appendix 8 for transcripts).

In relation to Mercer's categories, the demonstration employed five common oral techniques (Table 11.1, see following page) for building new understanding. The data suggested that in the second task there was no evidence of teacher *recapitulation* or *elicitation. Repetition* was used, but not, as Mercer defines it, to further a cognitive process, but rather to support the students' autonomy and motivation. In relation to Alexander's dialogic criteria (Table 11.2), the first task provided no evidence of *collective, supportive* or *cumulative* language, and only a teacher-centred *reciprocalism*. The second, student-centred task revealed evidence for all dialogic criteria.

Table 11.1
Examples of Mercer's features of talk

Oral Technique	**Definition**	**Task 1 (Data from transcript of first task, Appendix 8)**	**Task 2 (Data from transcript of second task, Appendix 8)**
Recapitulation	Summarising and reviewing previous information	Instructor - Okay so, oxygen plus hydrogen reacts to become the product. [I stand up and gesture as if to frame each unit of the equation as I narrate] Hydrogen plus oxygen reacts to become the product water.	None
Elicitation	To ask a question designed to stimulate recall	Instructor - You guys, in a millisecond, balanced this equation. And how can you tell that you've balanced an equation?	None
Repetition	To repeat a pupils answer, either to give it general prominence or to encourage an alternative	Student- An oxygen. Instructor - An oxygen.	I will be the arrow. You will be the arrow, great
Reformulation	Paraphrasing a pupil's response, to make it more accessible to the rest of the class or to improve the way it has been expressed	Student- There's the exact same number of molecules on this side. Instructor- There's the exact same number of hydrogen molecules on this side.	You have two sodium atoms on the other side
Exhortation	Encouraging pupils to think or remember what has been said or done earlier	Instructor - And how can you tell you've balanced an equation?	Now I said there was chlorine gas

Table 11.2
Alexander's dialogic criteria

Dialogic talk	Definition	Task 1 (Appendix 8)	Task 2 (Appendix 8)
Collective	Teachers and students address learning tasks together	No example	The model required 14 students to decide or negotiate their positions, the teacher relinquished control
Supportive	Students help each other to reach common understandings	No example	A girl stands, You will do that? Great
Reciprocal	Teachers and students listen to each other, share ideas	Students do not help each other, but the teacher does	Video evidence of students negotiating their positions as the stand in the equation Teacher: Okay, so the next problem is sodium chloride
Cumulative	Teachers and students build upon each others' ideas	No example	Ben says: Okay, so who's the sodium? Boy next to him raises hand, he moves quickly near the girls, as a chlorine atom Blonde boy tells reactants where to stand Ben says: We need a plus sign.
Purposeful	Teachers plan and steer classroom talk with specific goals	Discourse aimed towards introducing balancing equation and forum theatre skills	Discourse was aimed towards balancing the equation

11.2e.ii The demonstration task: multimodal and authoritative discourse

The demonstration was consistent with what Scott, Mortimer, and Aguiar have described as interactive/authoritative discourse, whereby 'the teacher leads students through a question and answer routine with the aim of establishing and consolidating that point of view' (2007). This initial task was dominated by teacher-talk. Over the entire task, the ratio of student to teacher talk was approximately 58:851 words. In the initial 499 words spoken, the students provided three words. In analysis of the first task, each response had also been considered according to *initiation (I)*, *response (R)*, and *evaluation (E)* coding (Mehan, 1979).

1. *[How] do we change this? We cannot cut things in half. So what else can we do?* [I]
2. Student 1: We could slice an oxygen. [R]
3. *Well that's interesting. [E] But let's say that we can add more. We can add more oxygen, we can add more hydrogen, or we can add more water to this equation. Any ideas what we might have to add more of?* [I]
4. Student 2: We need more water. [R]
5. Student 3: More hydrogen. [R]
6. *Okay, well, let's add more water.* [E]

(Transcript of first task; see Appendix 8)

The passage above illustrated a resemblance to what Alexander has described as a teaching style offering low cognitive demands, by which questions remain closed and praise is 'bland' (Alexander, 2006, p.14). This was particularly illustrated in the weakness of my praise in the lines coded for *evaluation*, evident in, 'Well, that's interesting' (line 3), and 'Okay, well, (line 6)'. The passage suggested that I directed the class towards the answer by side-stepping the two students' responses. In particular, after I said that, 'we cannot cut things in half', Student 1 offered that we could, 'slice an oxygen [molecule]' (line 2). Rather than explore that issue, I merely offered another possibility (line 3). Likewise, when someone called out for more hydrogen, I chose to advise adding water, without dealing with the 'hydrogen' response (line 6).

Verbal discourse was supported by other modes. For example, I discussed the model with students from *within* the simulation in order to foreground specific conceptual features, such as when I stood up and mimed divisions between units within the equation:

> [I stand up and gesture as if to frame each unit of the equation] Okay what is she? She's the plus! Okay so, oxygen plus hydrogen reacts to become the product. Hydrogen plus oxygen reacts to become the product water. Marvellous.
>
> (Transcript of first task, Appendix 8)

The deixis implied in 'What is she?' above, supported my framing of the different units of the simulation through gesture, as I moved across the floor from reactants to products as if isolating and narrating the images.

11.2f The student-centred task: multimodal and dialogic discourse

In the second task, the class briefly saw a printout of a new, unbalanced equation, for sodium chloride synthesis. The students' dialogue in the first few lines reflected their initial, seemingly unconfident behaviour, suggesting a heightened sense of vulnerability. Note that there was no clear IRE structure, but rather an initial mix of initiation and response. Their tentative behaviour and my reticence to provide guidance (in keeping with the research model) suggested an atmosphere of potential failure.

> [Silence]
>
> *You have two minutes to create that equation. You can ask me any question.* (I)
>
> [First student quickly raises her hand] 'Are we allowed to talk?' (I)
>
> *You are allowed to talk.* (R)
>
> [Silence]
>
> *What might we need to do?* (I)
>
> [Second student raises his hand] 'People get up.' (R)
>
> (Transcript of second task; see Appendix 8)

From this point onward, the students controlled more of the discourse. One student in particular (Student 4) took a leadership role in the central discussion. A striking contrast with the first task was the shift in patterns of IRE, in which there was little or no verbal evaluation within the conversation.

1. *We have NaCl on one side- now I said there was Chlorine gas.* (I)

2. Student 3 - I will do that. (R)
3. Student 4- Who'll be the arrow, to the reactants. (I)
4. [A girl stands up.] (R)
5. Student 4 - You will do that? Great. [To me] How many to be the sodium? (I)
6. *One*. (R)
7. Student 4 – One. Okay, so who is the sodium? We need a plus sign.(I)
8. Student 1 - I will be the plus sign. (R)
9. Student 4 - I guess we need more of them over [points to the products]. Do you want to [looks at a boy and girl beside him. They quickly get up and stand next to the others in a group]. I will go add to the sodium. (I)
10. Student 3- [To the boy and girl] Over here. (I)
11. *Okay, so we have got two sodium chloride on one side. You have two sodium atoms on the other side. Is it balanced? How many say yes? Yes. It is balanced. That's spectacular. (E)*

(Transcript of second task; Appendix 8)

This discourse reflected a dialogic, student-centred activity. Whereas the previous task revealed a student/teacher ratio of 58:851 words spoken, this subsequent task revealed a ratio of 116:300, albeit excluding isolated conversations of the particle-actors and the non verbal discourse. This task revealed all five of Alexander's dialogic indicators (Table 11.2). The language often attended to a social function, such as the supportive, 'You will do that? Great.' A *de facto* leader can be identified, but nonetheless, there was a communal effort to the modelling. This was expressed across verbal and non-verbal modes, such as when one student stood up to volunteer, ostensibly to show eagerness to take part in the simulation (line 4). Brief conversations and non-verbal communication among the role-players in the centre occurred throughout, suggesting a sense of social regulation in support of the group modelling process. One interviewee implied that students' behaviour was so co-operative as to be novel for the group,

> [Students could be] quite chatty [in regular lessons], so it was weird because everyone was really quiet and listening. (S3)

This co-operative behaviour, however, was a feature of both tasks, according to the teacher, who did not distinguish between the two, and who opened her scope to the whole lesson:

> There was a lot of co-operation between them to be honest... I thought they were engaged throughout. (T)

Whereas in the first task, the students were passive participants, the second task reflected Gilbert's definition of a TE. Here, the *goal* was to balance the equation for NaCl. *Prior experience* included students' knowledge of the warm ups and atomic structure models; and their experience of the demonstration model for the previous balanced equation. *Internal coherence* was revealed in the correspondence of features in the BAPs model to the written equation symbols.

11.3 Discussion

11.3a The molecule simulations: analogies out of nothing

This case suggested the potential for imagined objects to be used as a feature in teacher-led demonstrations, and highlighted the ease with which students translated the teacher's one-person simulation into a multi-person model. Students in the atomic modelling task immediately 'made concrete' the imagined particles that I had demonstrated. Expressions of key signifiers were then returned to in subsequent tasks, in which they were rearranged in an aim to describe new concepts. In this way, the initial imagined objects provided an initial modelling resource which would be used in later activities.

The diatomic molecule modelling activity was inspired by a curiosity as to how the students might draw upon their previous experiences to visualise and express an abstract concept that they had not previously visualised. The students constructed their models with attention to features that they had used in the atomic modelling task. There was no evidence to suggest that they developed an understanding of the covalent structure of hydrogen. The teacher noted that these students would not encounter covalent bonding within the curriculum for another year. Nonetheless, the aim was not to have students immediately master the ideas (Varelas et al., 2010, p.307), but to allow them to experience intermediate models (Clement, 2000) and extend their repertoire of scientific metaphors (Wilson & Spink, 2005). Indeed, the students tended to express a greater visualisation of molecules in the post intervention, and they continued to be aware of the diatomic nature of molecules over time.

11.3b Complex visualisations

The balancing equation features and the role-play codes for science notation, seemed to provide what Gilbert and Treagust have described as a tripartite representation of macro, submicro and symbolic representations (2009). The complexity of the balancing equations task could be seen in the task requirement to not only superimpose real and pretend worlds simultaneously in the mind (Somers, 1994; Wihelm and Edmiston, 1998), but also to engender a dialectic between 3D (students in the space), 2D (particle representation), and 1D (scientific notation) worlds (Gilbert, Reiner, & Nakleh, 2008). Within this context, the relative ease by which the students interacted to create their simulations for NaCl synthesis, and the interviewees' qualified success in the post interviews, appeared to suggest that students might have been helped rather than hindered by this multi-dimensional, multi-modal visualisation approach. This resonated with students' success in other tasks that employed complex analogies, such as the HAMs in Chapters 5 and 10. These activities suggested that it was plausible that some complex alternative analogies were more effective, or at least no worse, for conceptual learning than some more simplified, traditional teaching analogies.

If this is the case, then *why* is this the case? One possibility, emphasised in the post interview dialogues, in which students discussed balancing equations as if directing their own class, was that students may have a metacognitive response to the role-plays by which they are inclined to view them strongly as models open to manipulation. This is supported by theory around Forum Theatre, which as a type of didactic theatre, aims to distance the audience from being drawn into the drama, and aims instead to highlight key features in the process or system upon which the audience can focus critically (Counsell, 2001). Science educationalists have long questioned the degree to which students understand that they are working with metaphors (Jungwirth, 1975; Grosslight, Unger & Jay, 1991). The distancing effect associated with Forum Theatre may help students to see physical simulations as explanatory models.

The comparison of the demonstration and TE task revealed that talk in the demonstration was dominated by me to a greater degree than in the TE. Furthermore, the type of discourse, both verbal and multimodal, seemed to be interactive/non-dialogic in the demonstration whereas the TE task discourse was interactive/dialogic, using Mortimer and Scott's CA matrix (2003). The students also appeared to express a greater degree of self-regulation in the TE. These features suggested that the demonstration was less conducive to meaningful learning than the TE. Certainly, research elsewhere had suggested that peer collaboration (Howe, McWilliams, & Cross, 2005) and dialogic environments (Frijters, Dam, & Rijlaarsdam, 2006) support learning. However, the focus on talk perhaps downplays the effect of the demonstration's *social* and *multimodal* aspects, by which fourteen students had negotiated a multi-representational expression of NaCl synthesis.

I must question my reasoning for including the demonstration: One of my key aims in using the teacher demonstration was to control and focus students' access to conceptual information, so to use a limited amount of time *efficiently*. This was a ubiquitous aim with the Science teachers who used role-play in my previous research (Dorion, 2009). This approach appears to be supported too in arguments that call for teachers to use precise communication of Chemistry concepts in class in order to save time with respect to dealing with students resultant misconceptions (Bucat &

Mocerino, 2009). However, my previous research, and that of others (Butler, 1989), makes me question whether part of my motivation was to maintain a sense of teacher control for fear of confusing the students. I may have been correct in doing so, as two of the three interviewees (S2; S3) opined that their class would not have been able to complete the TE without the initial demonstration. It could be argued that the TE task was achievable because the demonstration model provided a scaffold for students to work collaboratively; i.e., they did not have to focus on constructing the symbolic resources for the model, but rather could focus on manipulating the metaphors that they had acquired from me. However, both the atomic structure and molecular modelling tasks revealed that even with limited conceptual knowledge, and limited experience in the warm-ups with role-play, students had a wealth of skills, knowledge, and comfort after only twenty minutes of warm-ups, and were able to produce *coherent* models of abstract scientific concepts. Given that this study was based upon the contemporary constructivist perspective that conceptions are complex and evolve over time, such an argument leads me to question, whether or to what degree the initial demonstration would be required in a class in which drama is used continually as ‘a classroom resource,’ (Neelands, 1984) in which students knew how to construct their own analogies, and were given time to do so.

11.4 Summary of Case 7

This case focussed upon the teaching of atomic structure and balancing equations. The lesson progressed from the warm-ups to group models of ideal atoms, group TE modelling of diatomic molecules, and then teacher-directed and group-directed BAPs of balanced equations for H_2O and NaCl. Physical simulations were interpreted to support students’ visualisation of atomic and molecular structure in post and delayed interviews, and to provide shared metaphors for extended discussions in interviews. Students were observed to adapt the signifiers from the previous teacher demonstrations. Students could use and concretise pretend objects, which they subsequently remembered in the post and delayed interviews (as opposed to pretend objects in cases 1 and 3). In the balancing equations tasks, the evidence suggested that the pedagogy promoted a dialogic environment which supported a high degree of student autonomy and complicity to the group.

12.0

Case 8: Creating Attraction

> 'I particularly liked the bit at the beginning in terms of the, about the ability of the group to non-verbally intuit the nature of something from nothing more than a couple of words description, so like you have, you know, the make a sofa and a star; that's very interesting because it is something you are familiar with, and then going into the most uncomfortable sofa in the world, and that was fascinating and seeing how they would think, and then make an abstract idea and talk about it non-verbally, you know to share out information, I thought it was absolutely fascinating. And then using, later on, their own skits to do the, um, the idea of cold and hot dissolving, the differences between them; it was actually a matter of them rather than being led by you, to actually say, "Well, here you've got an idea about what's going on. Look, you show me how you would show how it works."' (T)

12.1 Case Description

This case took place with a Year 10 GCSE class of eighteen students in an independent school in Cambridgeshire. The teacher predicted that all of the students would gain an A or A* in their triple Science course. The intervention was delivered in the last two lessons of the day, with a similar classroom layout to those in cases 5, 6 and 8, in which tables were moved to the sides, leaving the teacher's front table, and four fixed stations in the middle of the room. The students ordinarily worked as individuals or in pairs (S1pre; S2pre). They had not previously used role-play in Science (S3pre; T).

12.1a Learning objectives

- Promote submicro visualisation of solute and solvent particles
- Introduce solid solubility at particle level
- Introduce gas solubility at particle level

12.1a Lesson description

The lesson began with a lecture briefly describing the utility of models for studying atoms. Role play was introduced as one form of modelling. The students were then led through the warm ups (§4.4).

The topic tasks began with a teacher-demonstrated model of a water molecule, and a simulation of the interaction between a polar molecule, played by the teacher, and positively charged particles, played by the students. This was followed by a student-centred improvisation in which students arranged themselves as if they were dipole molecules.

Next, five volunteers stood as five sugar molecules, while I modelled a water molecule colliding with one sugar molecule and attracting it away from the group. After this, three groups of six students created a bodies-as-particles (BAP) simulation of sugar dissolving in water, with one student in each group asked to represent a sugar particle. The other students simulated dipole solvent particles interacting with the sugar particle. The finished models were performed simultaneously as a whole-class representation of an eighteen-particle simulation of sugar and water in solution.

New groups of six prepared Human Analogy Models (HAMs) of sugar dissolving in water. The task was stepped: First, students were given thirty seconds to consider what human roles they might use to portray the solute particles. Second, students were asked to consider a social situation in which their human roles would interact analogously to particles in solution. Students were then given ten minutes to prepare two scenes in which they were to portray particles in ‘cold water’, and then in ‘hot water’. The simulations were performed and then evaluated.

The penultimate activities were two teacher-directed whole class BAPs of gas solvation at lower and higher temperatures. Each had one student as a lone gas particle, surrounded by three concentric rings of students-as-solvent particles, all with their arms out. I clapped to provide a rhythm for students to which they would drop then raise their arms on each clap. The lone student in the centre of the group was given the aim to escape this solvent maze, but could only do so when the other students' arms were down. Clapping increased or decreased in tempo to suggest heat energy.

The lesson ended with a review of dissolving with solid and liquid solutes.

12.2 Analysis

12.2a Multiple models

If one included the warm-ups, then the students enacted or observed at least twenty-four representations (of which sixteen represented topic concepts) during the course of the lesson. These employed bodies-as-particle simulations (BAPs), human analogy models (HAMs) and one gestural teaching metaphor (GTM). Within this context, the following analysis explored how particular conceptual features recurred across a range of representations. It suggested that conceptual features potentially acquired a range of different meanings. In particular the analysis focussed upon the multiple expressions for electrostatic *attraction*. The chapter first describes the students' baseline understanding of attraction, as evidenced in their pre-interviews. It then explores the demonstrations that provided an initial mix of semantic and conceptual resources, from which students were perceived to construct their own models.

12.2b Pre-interview descriptions suggest teleological explanations of particle attraction

Students had previously studied covalent and ionic bonding (S1, T). They had also previously studied dissolving at macro and symbolic level (T), but the teacher noted that they had not visualized a sub-micro level process,

> Yes. Solvation - And the fact is that they had not been involved with what is actually physically happening. It was very much, 'This is what happens with solids,' and working out how to figure out solubility of the substance – that something occurs and you have to know that, that solubility increases with temperature, and with gases,... and I added the extra depth that water is polar... we talked about forces between molecules, saying that you need enough energy between the solvent and solute so that the solute is attracted, but it was very basic.

The teacher suggested that the students had been taught solubility primarily as a mathematical problem. In the pre-interviews, when students were asked what happened at a molecular level, their responses suggested a weak visualisation of particle interaction. One student, Rose, provided an explanation in which 'bond' and 'mix' were interchangeable,

> I think like the sugar would start to like bond with the water.
>
> *Okay.*

> So like join next to it or mix in with the other like particles in it, and so if you heat it up and stir it, they will become more like energetic so you could fit more sugar in the water. (S3pre)

No interviewee initiated charge-related explanations of attraction in the pre-interview (S1; S2; S3). Another student, Kay, suggested a teleological explanation, such as in the sense of water particles as goal-oriented,

> The water just, I don't know if it like attracts them or if they kind of like, kind of go in between them, the bonds. I am not really sure. (S2pre)

Only after prompting with the show card term 'attraction' did interviewees describe states of matter in relation to attraction. When Kay was asked specifically if she could define 'attraction' in relation to particle theory, she responded,

> Atoms *use* attraction to stay together. (S2pre)

That atoms 'use' attraction suggested another anthropomorphic conception, in that attraction is employed by atoms as a tool for uniting atoms. The lack of understanding of a scientific mechanism for attraction was reflected in the comments of a third student, John, when he observed in retrospect, in the post interview, that before the intervention he had not considered attraction to be a feature in dissolving at all.

> [Before the intervention] I didn't know there was attraction or anything when sugar was dissolved. (S1post)

12.2b Developing the landscape of meanings for 'attraction'

Analysis suggested that the students were exposed to a range of potential meanings for attraction during the initial demonstrations and BAPs, and that these meanings were often adopted and adapted within students' resultant expressions. In order to draw some connections between expressions and resultant conceptions, this study initially explored the potential meanings inherent in the initial demonstrations.

12.2b.i Teacher demonstration of a water particle with arms-as-bonds

The first topic task was a BAPs demonstration that aimed to highlight three key features of a water molecule: That it is of a particular shape which is composed of two types of atoms which contain opposite charges. The demonstration began with me standing, with arms raised to chest height, angled outwards, and hands clenched in fists (Figure 12.1, below). I said,

> I am a water particle now, because I have got my hydrogen atoms [shakes fists] and I am an oxygen atom. We are all bonded together in kind of a triangle. That's how it looks. But [shakes fists] these have a [moves one hand over top of the other] a greater positive charge out here. [Gestures towards body] Now, *I* have a greater negative charge. (V1:31:07)

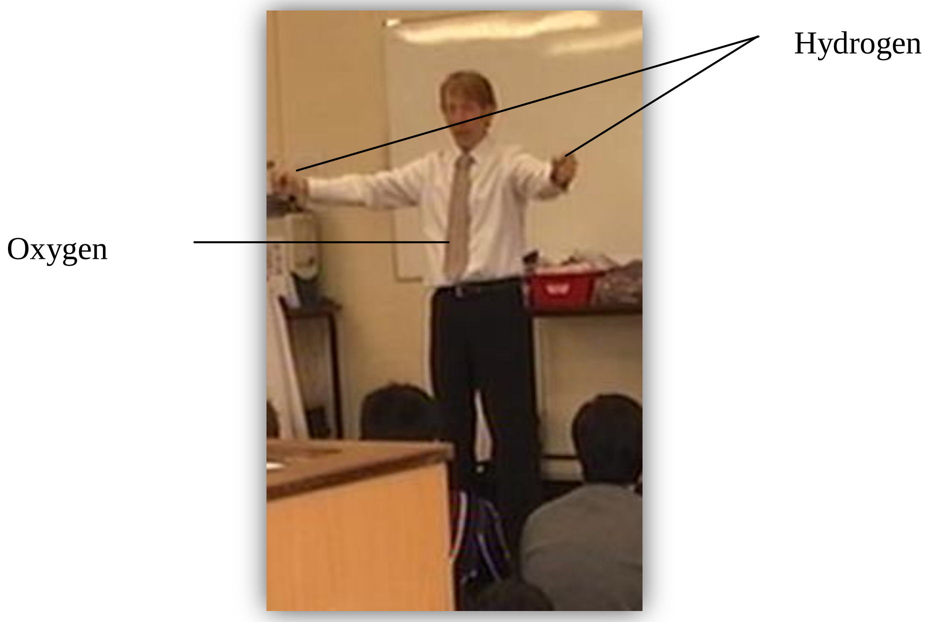

Figure 12.1 Polar molecule (V1: 31:34)

In the model above, students may have perceived that my arms represented an attractive force between the hydrogen (my fists) and the oxygen (my body). They may have associated the tube-like structures of my arms to molymod ‘sticks’ which may have supported the idea of attraction as constituting a physical structure (a solid ‘bond’) between the atoms.

12.2b.ii Changing the model for water, and simulating dipole molecule interaction with students as other charged particles

I progressed quickly into a second demonstration that aimed to highlight the polar nature of water molecules. I prefaced this second model with:

> Now this can get complex quite quickly so I will take my hydrogen atoms away and say I have a positive charge on one end and a negative charge on the back. (V1:31:41)

Figure 12.2 Positive charge on front (V1: 31:34)

Figure 12.3 Negative charge on back (V1:31:36)

Despite indicating that the model would be 'complex' I did not provide a description of why, or explain the changing signifiers. Furthermore, whereas the first model only presented a sub-micro level representation, this new model juxtaposed symbolic (charge) and sub-micro level features (water particle). The features of shape and charge now had different signifiers: the fist-arm-body model had become a body-gesture model (Figure 12.3): I mimed a 'cross' with my hands open-palmed and perpendicular to each other, on my front. I then turned my back to the students and with a flat hand gestured a 'minus sign, describing this as 'negative'.

I told the students, 'Now I would like you to be polar molecules'. The point of view now shifted, as the students were now positioned inside the phenomenon as participants rather than spectators. At this point, the space between us was potentially part of the model, in that attraction was defined in the interaction between myself and students within this space.

12.2b.iii Humour

I asked what happens when two positive charges meet (V1:32:20), one student called out, ‘They repel’. A second student with their hand raised said that I would ‘spin’. In response, I backed away and spun so that my back faced the students, and at my back I gestured a ‘negative’ sign, while I walked backwards towards the students. Following the answer that I would spin, I did so suddenly with exaggerated speed and arched my back away from my right shoulder as if pulled into the new position. At the same time I said, ‘Whoa, like that!’, and as I walked backwards towards the students, I said in a calmer tone, ‘And then I come back.’ The exaggerated spin and ‘Whoa’ were impromptu actions by which I aimed to use humour to foreground the ease with which water molecule shape and the orientation of charges could induce rapid changes in movement and position.

12.2c The initial improvisation, with students in-role as dipole molecules

The next task aimed to let students experience a multiple particle system. The students were asked to pretend that they had a positive charge on their front and a negative charge on their back. From their initial positions standing randomly as a group in front of me, they were each to act like a polar molecule (Figure 12.4).

Figure 12.4 Dipole organisation start (V1: 32:35)

Figure 12.5 Dipole organisation end (V1 33:19)

12.2c.i 'Like a computer simulation'

The task lasted thirty-three seconds. Initially, students moved in seeming disorder. Between eight and thirteen seconds a pattern emerged, a seeming ripple effect by which students moved into rows (Figure 12.5). The resultant grouping was of four rows facing forwards, with uneven numbers of students at the back. The teacher commented upon the dynamic with reference to computer simulations:

> …And it, it, suddenly reminded me of, um, computer modelling for artificial intelligence, for flock modelling-
>
> *Right,*
>
> Where with very simple rules you create flock behaviour; and it's almost exactly like a whole bunch of starlings, but the rules are for the little particles in the computer; [it is] so incredibly simple. (T)

According to the teacher the students were assumed to be obeying simple rules, such as 'like repels like' and 'opposites attract'. However, in video analysis, the students revealed that some individual actions suggested other or additional objectives: one exuberant student continuously spun, without interacting with the students he passed, while moving from the back left to front right of the group (V1:32:54). One girl followed another girl, smiling and hunched with her head touching the other's back (V1:32:50). As ordered rows began to emerge, a boy at the front of the group (which faced the teacher) directed a boy beside him to move to the back of a line of three students (V1:33:06). Such behaviour suggested that sometimes rules were followed, but also that students' own objectives were pursued.

Their actions suggested that individual perceptions of the model would not be homogeneous, since each student's positioning and interaction in the event differed. The experiences varied across a range of touching, blocking and bumping into fellow students, spinning, and laughing. This raised the issue of how such behaviour re-oriented or disoriented students' visualisations of the simulation, and whether their understanding of *attraction* was perceived in relation to propositional or holistic features.

12.2d Competing meanings for attraction

In the context of the observations above, potential meanings for attraction were varied: in this collection of dipole molecules, *attraction* was potentially perceived as a means of cohering particles in a group, as no students moved away from the group regardless of their kinetic energy. In students' continual turning towards and away from each other, *attraction* was potentially part of an attraction/repulsion dichotomy in which the interplay of attraction and repulsion promoted constant reorientation of the actor-particles. Some of the students touched each other, possibly suggesting a physical connection between particles. Finally, some students continued to gesture 'positive' signs on their front, implying that charge was a feature of attraction.

12.2e Orientation that suggested attraction in student-devised simulations

The first student-devised BAPs employed groups of six in creating a 'snapshot' of an ideal simulation of five water molecules and one sugar molecule. Students were informed that while sugar is a polar molecule, in an effort to focus upon the orientation of particles in an 'ideal solution', they would only deal with the sugar as negatively charged. Students were allowed to talk and prepare for one minute.

The three groups provided similar models, in which the water particles faced the sugar particles (Figure 12.6). Attraction now seemed to be implied in the students' orientation, as their 'positively charged' fronts faced the negatively charged solute particle (gestures indicated the charges). Repulsion between like charges was implied in the evenly spread positioning of the students, as water particles, around the student-as-sugar particle. The students pressed in so that they touched, or nearly touched the solute. The close jumble of bodies resembled the close proximities in the previous simulation task.

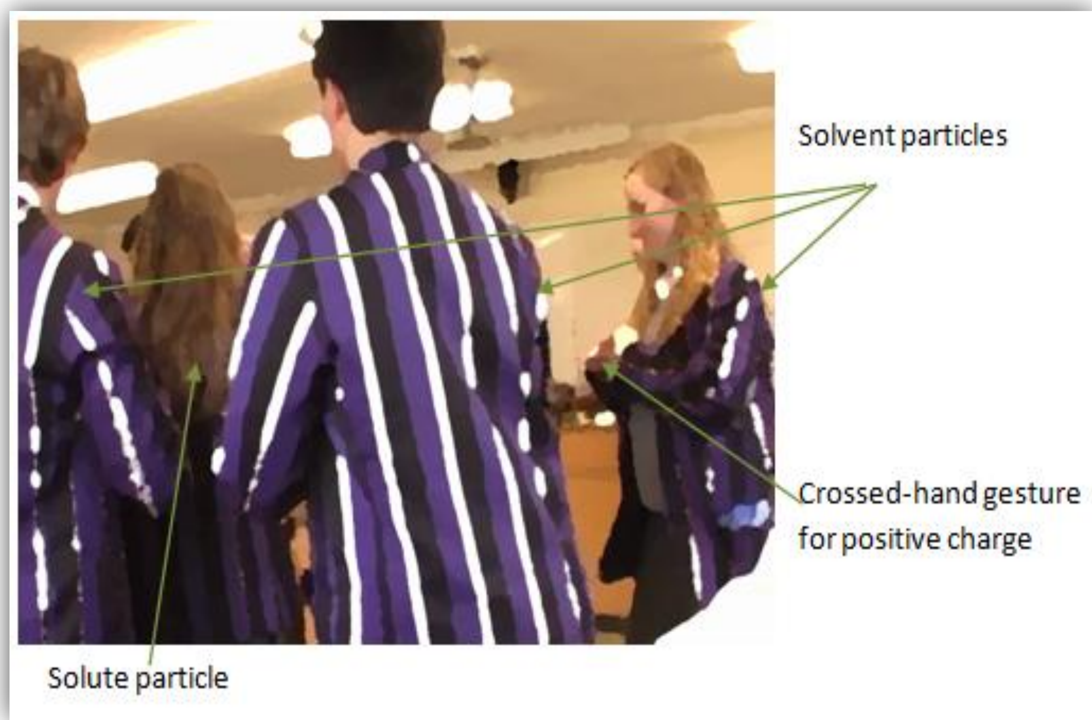

Figure 12.6 Student model of dissolving (V1 38:21)

Figure 12.7 Student simulations for dissolving - two groups in frame (V1 38:26)

On seeing their positioning, I asked solvent particles to take one step back (Figure 12.7). This new positioning was reminiscent of textbook-style images of solvent particles surrounded by solute particles. If transposed into circles and charge symbols, for example, the three groupings might suggest the following image (Figure 12.8):

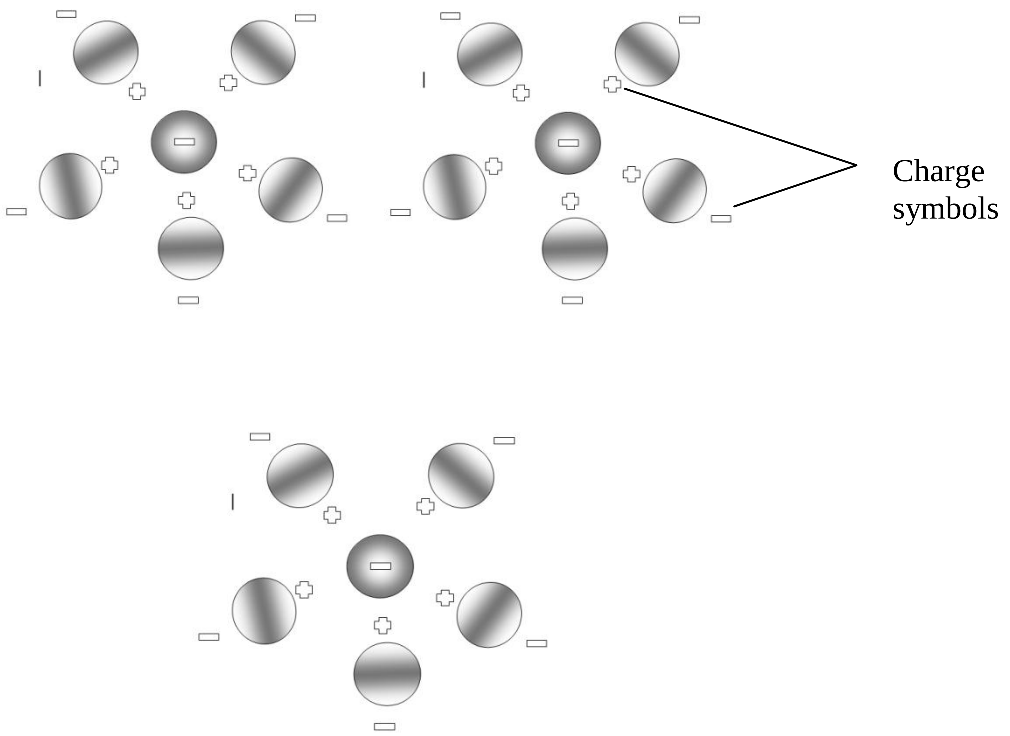

Figure 12.8 Diagram suggesting the similarity of students' proximity in their 'snapshots' of solute and solvent interaction to textbook-style images

Such a diagrammatic visualisation suggested a potential for confusion: The proximity of negative charges to those negative charges in the abutting groups of particles seemed to have no effect upon the orientation neighbouring particles. It could have suggested that solvent/solute groups were isolated from the electrostatic attraction of adjacent groups.

However, issues related to such an overview may not have been noticed. Individual students did not have such a 'bird's eye' or topographic point of view. Rather, as the photo and diagram above illustrates (Figure 12.7; 12.8), the students' perspectives were partial and blocked by other students. This perspective suggested a more localised perception focussed upon attractions between neighbouring particles.

12.2f Features of attraction conveyed through human analogy models

The HAMs task was designed as a group thought experiment, by which students were asked to visualise and express the differences in the dissolving of sugar in cold and hot water. The resulting simulations produced a range of expressions for solvent and solute particles, and attraction, in which base analogies were drawn from non science domains of knowledge. In particular, students focussed upon signifying these through relations between characters within particular situations. Three groups were designated A, B and C. During preparation, groups A and B initially decided to signify solute particles as two 'siblings'. These were either 'brothers' (S1post) or 'sisters' (S3post). The sibling analogy was elaborated upon by a student in group A.

> It was, first we thought that we could be like a mother and child. ... and then, yeah, and then we were going to be like two sisters, because then we thought they would be even more similar. (S3post)

For this group, the sibling analogy was subsequently discarded in favour of a return to a mother and child analogy, suggesting that similarity was not ultimately a primary interest for the group. However, group B retained a 'brothers' pairing. The brothers analogy afforded not only a morphological similarity, but also indicated a strong force of attraction, to the extent that they needed to be, as one of their members noted, 'ripped' apart:

The first key feature was how to separate the two, what were the two, brothers in this case.

Yes.

And why, you know, we just, we ripped them apart, you know, how we thought, that would happen, you know how we thought water would rip sugar apart, break the bonds... (S1post)

Here, the term ‘ripped’ suggested a quick, violent pull. As with, ‘break the bonds’ the language seemed to convey an impression of the destruction of a physical structure.

12.2g Mother-child attraction analogies for solutes

Groups B and C decided to use mother/child analogies for solutes. The expressions here did not focus on ripping and breaking but rather upon what I interpreted as a less violent process akin to ‘drawing away’.

Within this context, attraction was not a single ‘type’ of interaction, but rather an agglomeration of different meanings for attraction. For example, an interviewee for Group A highlighted her intent for attraction to be signified through an opportunity for ‘distraction’:

After that we thought, Oh we could do a carnival because like there’s a lot of different attractions there.

Nice.

Not just like a normal place, there’s like loads of different things happening...

And with the cold water, we just sort of like said that the mother and child

> were [sic], we'll make it harder for, to, like *distract* them, so they don't seem as *interested* **[**in the solute particles**]**. But still like paying *attention* [to the stall holders]. (S3post)

This passage suggested that the base analogy for attraction was related to the affective traits of human interest and attention. The terms, 'distraction', 'attraction', and 'attention' seemed to suggest a group focus on emphasising the chaotic nature of particle behaviour.

12.2h A comparison of group performances

An ideal performance might have shown dipole water particles moving toward and colliding with a solute group, which would separate, and individual solute particles would move off while randomly and briefly 'sticking and repelling' in respect to their orientation within a group of water particle-actors. Group A's performance resembled the first half of this ideal: The sibling solutes stood close, with sides touching, while the solute particles surrounded them (Figure 12.8). The group walked from the left to right and as they did, the solvent characters physically parted the solutes, with hands on shoulders, guiding them apart.

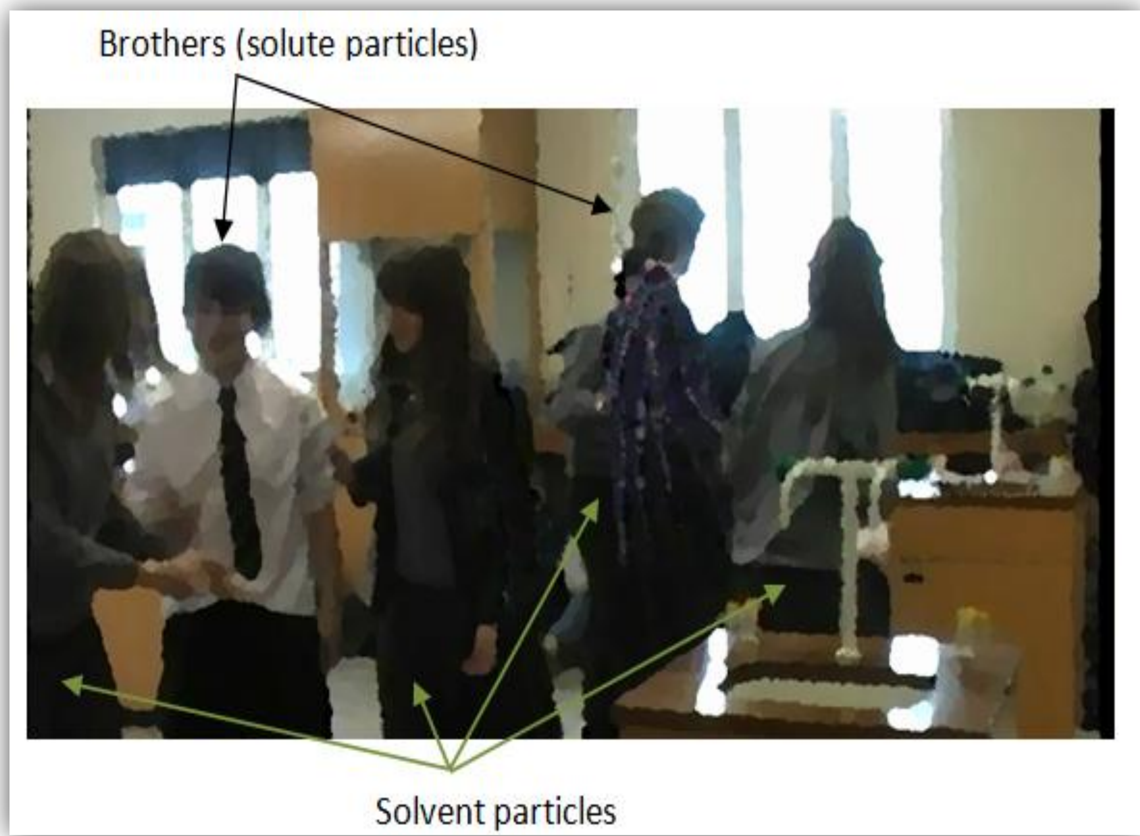

Figure 12.8 Group A (V2: 58:14)

Group B's performance began with the solutes and solvents on opposite sides of the room, moving towards each other (Figure 12.9). By contrast to Group A, the solvent-actors here surrounded the solute-actors. The group came together as a whole, with the mother and child staying side by side, then moved towards the solvent's side (left) of the room.

Figure 12.9 Group B (V1 1:00:08) N.B. The black arrows denote movement.

Group C's performance presented two students as mother and son, who had entered a store. As they moved from left to right, the 'mother' was invited to buy a jacket and purse from sellers who held the items forward. The son noticed two boys standing on either side of a third (echoing the three-part shape of a water molecule) who was kneeling with a 'Coco Puffs' sign. The son ran to him, then back towards the mother, and back again, while calling incessantly, 'Mummy, over here.' (Figure 12.10)

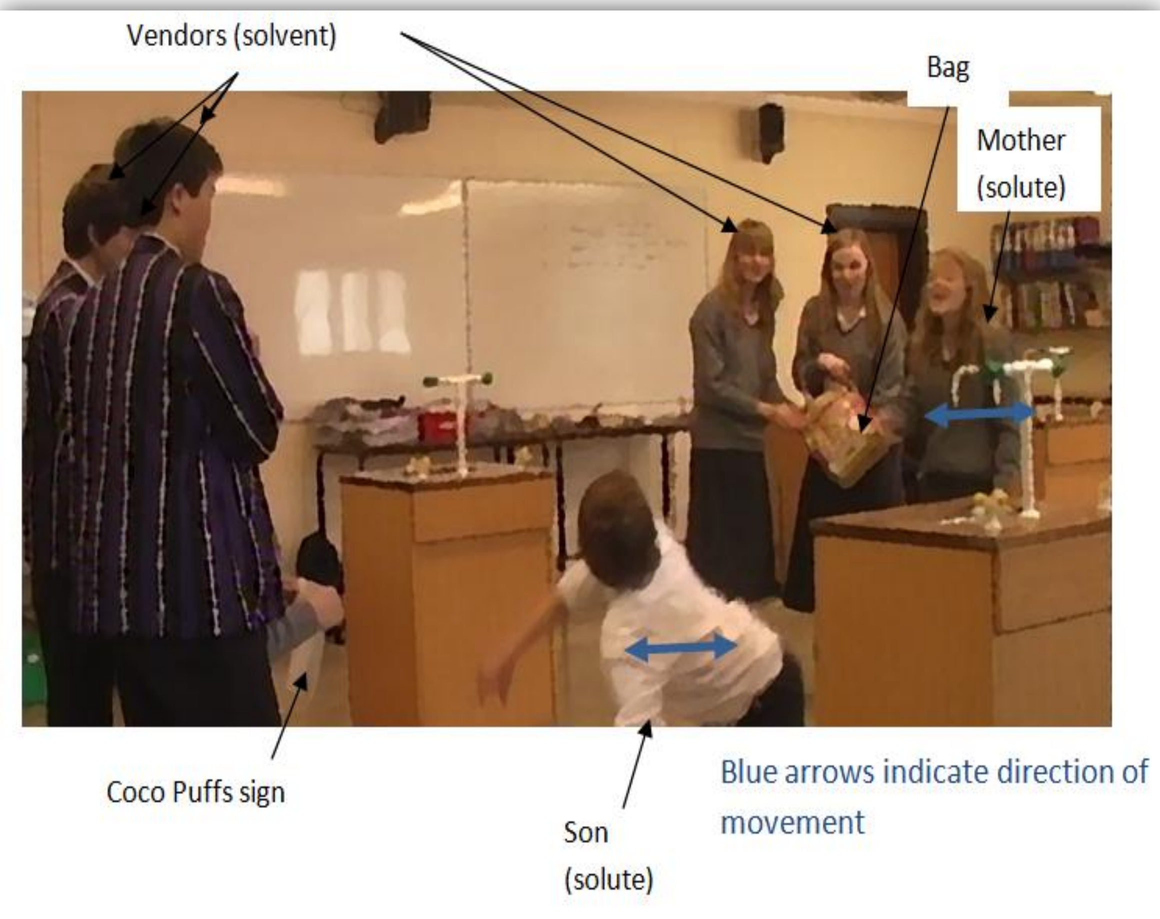

Figure 12.10 Group C first performance (V3 1:04:07)

12.2i Group C's forum evaluation and re-performance

The group C performance differed from the previous performances. A high tempo in this group suggested increased energy within the system, and the continual frantic movement highlighted the chaotic movement between particles in a complex system. However, an obvious issue was that the *solute* actors moved towards the *solvent* actors. The teacher corroborated this in stimulated recall, noting,

> The only thing that that group did which was different [from the other groups] - they got the idea of the attractive forces between the particles of water and the solute - but they had the solute going to, rather than the water coming to,

and pulling off the solute atoms, molecules, one by one. (T)

The teacher's observation was echoed by one of the student audience members during the post performance evaluation (Obs). An audience member queried the group's choice to have water particles in fixed positions. The performers were asked to repeat their performance. In this new improvised simulation, the solvent particles moved towards and around the solute particles, while the solutes also continued to move as they did previously.

12.2j Differences in attraction: familial solutes and collegiate solvents

For all groups, attraction seemed to have different qualities in the way it was expressed between solute particles, compared to between solvent particles. The solute sibling and mother/child pairing of the solutes suggested *familial* attractions: The initial close proximity of sibling actors in Group A, the proximity of family members in Group B, and the continual attempts of mother and child to return to each other in Group C, associated the relatively strong 'familial love' attraction as akin to the force between the sugar particles. By contrast, the 'solvent' actors stood near to each other, but did not move towards each other. Their attraction was analogous to the cohesion of colleagues. Proximity and shared interest (to attract a buyer) suggested a lesser attraction to one another than in the family analogy. Such group choices highlighted different strengths of bond, and relied upon understandings of archetypes in which family members (as covalent bonds) had stronger affective bonds than colleagues (as H-bonds).

12.2k Props which potentially confused the analogical relations

Group C's was the only performance that used props for the products (i.e. a jacket and a bag). In the analysis, but not during the lesson, the props seemed to lead to confusion as to whether the sellers or the products were the analogues for the solvent molecules. If the latter, then a seller might be construed as a separate particle. This potential for confusing the relation between the role, prop and the target concept appeared to affect at least one actor: In the second scene, representing a higher temperature solution, the 'mother' raced to the sellers and in her *exuberance*, she snatched the bag and began to run away. After four steps, she appeared to realise that she should return to the sellers, and so ran back to them with the bag. In this instance the bag, rather than the seller, represented the attracting particle.

12.2l Central meanings for particle attraction in the HAMs

Interestingly, none of the group performances highlighted charge as a cause of attraction, despite that in the first five activities charge had been described verbally and through gesture by both the teacher and the students. Otherwise, the HAMs suggested that students highlighted the following meanings for *attraction, it could*:

- Be visualised as a concrete feature (hands upon shoulders to pull 'siblings' away (§12.4a))
- Be portrayed as an invisible force (conveyed by students' movement towards students (§12.4 a; §12.4c; §12.4d))
- Provide a mechanism for direction of movement (conveyed in the movement of one students towards one another (§12.4c; §12.4d)

- Provide a mechanism for reorientation of a particle (in that particle actors 'faced' oppositely charged particles (§12.4b)
- Differ in strength between different particles (§12.4d)
- Be a force which is in competition with other forces (§12.4a)
- Be a force whose impact is mediated by changing kinetic energy of the particles due to heat (conveyed in the change in tempo between 'cold' and 'hot' water simulations (§12.4a)

12.2m Post and delayed interview expressions of attraction and charge

In contrast to the pre-interviews in which 'attraction' was not initially used by students in interview, all interviewees in the post interviews included the term 'attraction' (S1post; S2post; S3post; S1delayed; S2delayed; S3delayed). The term 'charge' was not used at all by Kay and Rose during the post or delayed interviews (S2; S3). Nonetheless, Kay described the interaction of charged particles in a manner that suggested a visual understanding of particle movement. Note her implication of water particles 'lifting' sugar particles up 'polar-wise (line 3), to each other' as the sugar dissolves,

1. Okay, so the black circles are sugar.
2. *Yes. And talk me through the story.*
3. Like when they get dropped in [the water molecules] start to catch up and then lift up them polar-wise, to each other.
4. *Okay.*
5. And then after [the solvent particles] are like completely, like, apart from each other. And you then can't see any more. (S2del)

12.2n Post intervention perceptions of the intervention pedagogy

When the interviewees were asked about the utility of the lesson, by way of, ‘Would you teach Chemistry using role-play?’ they argued that they would use role-play as a teacher (S1; S2; S3). Rose for example, suggested that the tasks held a strong visual quality which aided her memory:

> *Um, now would you use this as a teacher, the lesson, styles?*

> Um, yeah I think I would, because I remember, because I have got more of like a photographic memory than like listening or just reading, so I can remember it better than that, but, yeah I think I would use it. (S3del)

Rose appeared to suggest that she would use this approach because it aided students like her. She focussed upon its usefulness in enhancing memory. All students believed that physical simulations aided their memory of the topics (S1post; S2post; S3post), for example, Kay noted,

> Because, like it is easier to remember, it makes it more fun. (S2del)

Kay and Rose, however, were concerned that it took too much time to cover material through drama than through a more traditional approach (S2; S3). However, Kay observed that due to the ease of remembering the drama, she could spend less time revising, since solvation was now ‘easier’ for her to remember (S2post).

John echoed the importance of the visual quality, and also suggested that the anthropomorphic nature of the activities aided his understanding,

> Because adding it, yeah, in a human, in a human you know way of thought, in a human background I suppose let's people see it in a different light. Because I suppose that's why I didn't know very much. I mean I knew I knew basic solutions but now I can, I can see how it works and how because, I could see other people acting it out... (S1post)

John described an ability to 'see how it works'. This perceived ability to visualise a dynamic system, and find utility in the visualisation, was espoused by the other interviewees within a metacognitive, multi-model approach. For example,

> *…do you visualise little people as particles or do you visualise, see in your mind, particles looking like something else? How do you think you use that, in your mind's eye?*
>
> Like, if I thought about solubility I would think about, like, the plays, but if I think of particles in general then I would still think about the [atoms as] circles. (S2post)

So, rather than translate the people into circles, Kay seemed to argue that she would retain the image of people interacting. She would use these two models in different contexts. Rose too thought that she would adopt this multi-model approach,

> *Now do you picture atoms as little people?*

No, I can think of like, in my notes I have got this big page, like, I have got an Atom at the top and, like, what's inside an atom at the bottom. And I can just remember that.

Okay.

And how they separate; I would remember it as the people in the shop.

(S3post)

An interesting aspect of these statements was that the students' comments did not reflect a sense of being overwhelmed by over twenty different representations during a one and a half hour lesson. Rather, as the comment above suggested, the interviewees seemed to have felt comfortable with these analogies.

12.3 Discussion

This case provided evidence to support the view that social and affective domains are integral to the acquisition and expression of scientific concepts (Watts & Alsop, 1997; Harrison, 2006), albeit in the context of physical simulations. The will to engage and be complicit was a prerequisite in the successful preparation and performance of student-constructed simulations. The students displayed a high degree of motivation, attention and ownership, as evidenced by their full participation, intensity (indicated by an example of exuberance (§12.2.c.i)), and their creative use of analogies within large-group models (§12.2e).

The wider field of drama in Science echoes these attributes (Odegaard, 2003; McSharry & Jones, 2000). However, there is little research into the link between the social and affective features of a drama analogy in relation to students' resultant scientific conceptions (Dorion, 2009). The examples by which attraction was expressed in both the intervention and subsequent interview stages suggested that students chose to portray particular social analogies to convey a sense of the physical effect of different *types of attraction* (to which later lessons might apply the terms H-bonds, covalent bonds and Van der Waals forces), within different contexts (substances, heat energy), and with reference to multiple particle systems (§§12.2c – 12.2i)

12.3a Which are better: BAPs or HAMs?

Multimodal research asserts that there are complex decisions for children who are involved in the design of multimodal texts: such as in deciding what mode to use in order to 'best' represent and communicate a particular meaning (Kress, Jewitt, Ogborn, & Tsatsarelis, 2001). Considering students in the classroom as designers of meaning has implications for learning, leading to questions of what semiotic resources should we make available to them to 'imagine the invisible' (Jewitt, 2006, p.145). This leads to the question of what form of physical simulation may be most useful, BAPs or HAMs?

12.3b Bodies-as-particle simulations may not be a series of simple objectives

Given the evidence from this case, BAPs provided a more limited range of semiotic resources, and entailed briefer tasks than HAMs, which gave less time for student-centred discourse. However, as a teacher, the BAPs proved useful as a means to control the development of initially simple concepts in progression towards the more complex HAMs. Furthermore, BAPs appeared to be quicker to devise within a lesson. However, evidence suggested that students may not have followed their objectives wholly as expected (§12.2c), nor have seen the model as a whole (§12.2c.i). BAPs have generally been seen to focus on presenting rule-based, mechanical interactions between students (McSharry & Jones, 2000; Dorion, 2009). In doing so, the BAPs may be considered to employ students in a somewhat automatic series of actions. However, as the whole class 'dipole organisation' task revealed, this may be an errant perception. Rather than a mechanistic simulation this episode might be better thought of as a site of personal expression. Although it appeared similar to a, 'computer simulation,' according to the teacher (§12.2c.i) in fact, the behaviour of the 'spinning' boy and the 'directing' boy, suggested that in following their aims, some did not stick to the rules. The group behaviour seemed therefore to allow for individual expression to exist within a more holistic system that *aspired* towards rule-based interaction, so that a self-organising system was ultimately simulated despite students' less than ubiquitous focus on playing the 'unit' objectives. In this context, a degree of exuberance or individual response may have been beneficial, by supporting wider affective features such as complicity and comfort within the group, which in turn supported the students' engagement with the task.

12.4 Summary of Case 8

This case focussed upon the teaching of the solubility of solids and gases in water. The lesson progressed from the warm-ups to a demonstration BAPs of a water molecule, a whole class BAPs of dipole molecule behaviour, a group BAPs of sugar dissolving in water, a HAMs of sugar dissolving in 'cold' and 'hot' water, and a whole class BAPs of gas dissolving in 'cold' and 'hot' water. This case focussed upon students' conceptions of attraction between particles, and their expressions of attraction. The case foregrounded the scope for multiple perspectives of the models.

Attraction was observed to be portrayed with reference to affect, such as in comparisons of love or collegiate friendship with different levels of strengths of bonds. Two interviewees were interpreted to employ different models, including the memory of simulations, to support their learning of solubility over the medium term. The three interviewees were interpreted to develop richer visualisations of solvation at the sub-micro level.

13.0

Multiple Case Findings

This chapter presents findings of the multiple case analysis of the eight cases in the study. Sections §§13.2 – 13.4 relate findings to the research questions (§4.1), with thematically similar findings grouped together in sections, and referenced to examples within the case reports. First, however, the chapter reports upon findings for the RQ2 subsidiary question. These findings that may otherwise have appeared in small sections within the case reports have been brought together in one section for the sake of coherence and clarity.

13.1 Alternative conceptions: Anthropomorphism

The following section reports on the research question: Do anthropomorphic analogies in the interventions promote alternative conceptions? The section focuses upon an analysis of anthropomorphic utterances recorded across the interview stages.

The following table (Table 13.1) is not the result of a statistical analysis, and therefore there is no indication of a correlation between the intervention and the resultant conceptions. However, one can see that anthropomorphisms occurred throughout all interview stages, and that they tended to decrease in number after the pre-interviews. The lack of an increase in utterances suggested that the interventions did not significantly promote anthropomorphic conceptions. The evidence and the examples below supported an interpretation that students tended to use anthropomorphisms with different degrees of metacognitive awareness. The implications of this are to be found in the discussion chapter (§12.0).

13.2 Anthropomorphic utterances in pre, post and delayed interviews

Anthropomorphic utterances were recorded in twenty of the twenty-four student interviews, across all interview stages, in all cases, and from both younger and older boys (i.e. C4:S3 (11 years old); (i.e. C8:S1 (14 years old)), and girls (i.e. C4:S2 (11 years old); C1:S3 (13 years old)). Of the seventy anthropomorphic utterances from twenty-four interviewees, thirty utterances occurred in the pre-intervention interviews while nineteen occurred in the post intervention interviews, and twenty-one in the delayed interviews. Of these, twenty-seven utterances were made by four students across three cases.

Table 13.1

Anthropomorphic utterances in interviews

Key: *Italics*: weak anthropomorphism
Regular Calibri font: strong anthropomorphism
Case number and student number are included: i.e. C5:S2
N.B. Ambiguous examples such as 'floating' and 'bouncing' which could be construed as machine analogies were omitted from the table. At times, utterances were shortened for ease of representation, and are marked with an asterisk.

Pre Intervention	*Post intervention*	*Delayed Interviews*
Particles		
Liquid particles are like dancing. C4:S3 They are living; with heat they will die – disappear. C4:S3 Microorganisms*. C2:S3 Particles want to move around*. C2:S3 *Particles are squashed together.* C3:S2 Tiny little things that live in different things. C3:S2 They are trying to push away from each other because there are so many they are all like crashing. C8:S3 They have got more energy to move around so they like need more space. C8:S3	*Solid particles are strong in a line.* C4:S1 Alive because they are moving*. C2:S3 Alive because they are moving*. C4:S2 Gas is where the particles are allowed to move randomly. C1:S2 They are not allowed [to move], and it is just like nature. C1:S2	*Pretend that particles are like little men… they like grab the [heat].* C3:S3 *A solid goes crazy with heat.* C4:S1 [Particles] and microbes are both living things. C4:S2 *Well the [halogen] is like gas jumping around all the time, and in a liquid they are more like more relaxed.* C6:S1 *One particle is more hyperactive.* C5:S3 [Solid particles] want to get away but they can`t. C1:S1 A particle, the hotter it gets, the more excited it gets, and so it moves. C1:S1

Dissolving		
Sugar will come to little pieces because they will struggle at the force of water which is trying to get rid of tiny bits of sugar. C4:S3 *[Water particles] kind of intercept [sugar particles] and make them spread apart.* C1:S2 *…it has mixed and diffused within the, diffuse isn't the right word but you know, spread itself out with him the water and water has managed to hold it in it.* C8:S1 *However, some of [the gas particles] still manages to go right to the top. C8:S1* Because the hotter it gets, like the more lively the atoms get and try and break out. C8:S2 The coke with go lively, like they will try and get away as well. C8:S2	The gas is like, it needs more energy than them, if you know what I mean. C8:S3 The water is warm the gas can't get out of the way. If you see what I mean. C8:S3	*And it would try to break the bonds... No but trying, it isn`t a human thing.*C8:S1
Diffusion		
Gas wants to escape a bottle*. C4:S2 Particles kind of, like, want to breathe. C4:S2 And they try to move and all they do is vibrate. C6:S3 [Particles] get more excited and they move around, and then they just kind of break free. C1:S3 They would try and equal, and balance themselves out. C1:S2	Particles are trying to get out [of a bottle]. C4:S2 They will die with too much heat. C4:S3 *Maybe to the particles, it might be, like, fast.* C4:S3 Yes, so they kind of run and kind of bump into each other and release the smell. C1:S3	*Gas particles splurt out… they are all waiting, smashing against the lid.* C2:S3 In a couple of hours they will start to die. C2:S3 Gas particles try to go as fast as they can*. C1:S1 Gas particles always want to make things balanced*. C1:S1
Atoms		
Nucleus is the heart and brain of the atom. C5:S1 There's a brain inside the nucleus. C5:S3 Nucleus has organisms inside which make it work, or just do its job properly. C5:S3	Nucleus is the brain. C5:S1 Nucleus is kind of like the brain. C5:S3 *The tiny time things, that like, sit on the end of a, sit on the end of a pin.* C7:S3 Atoms, atoms of gas, I guess. Just, like, dancing about. C7:S1	*That they travel around in pairs, the atoms are in pairs.* C6:S3 *Nucleus is sort of the brain of the atom… it is not a living thing but it decides…* C5:S1
Ions		
Starting to fill the fourth shell, and then deciding that it could actually have another ten. C6:S3 And the Chlorine has kind of like given [the electron] up in the chemical reaction. C5:S3 *[Two types of] elements grabbed each other to make a bond.* C5:S1 An atom wants to gain an electron, to become stable, like the noble gases, which is when it has a full outer shell.	*Before I pictured dots on paper and now I picture people.* C5:S3 *It takes the electrons, to make the full shell.* C5:S2 They sort of try to have a full shell. C5:S2 One electron is sent off to complete the shell, which makes them stay in a fixed place. C5:S1	It needs to attract one more, needs to obtain one more electron. C6:S1 Because this one needs to lose electrons to gain a full outer Shell, that's what they are all trying to achieve. C6:S3 …so they need one more electron to become, to obtain a full outer shell.

C6:S1 *Gaining an electron is negative because if you gained weight you wouldn't be too happy about it.* C5:S2		C6:S1 It wants to make it neutral so it causes a loss of an electron. C5:S2 One atom loses its electron to give it to another so they can complete their outer shell. C5:S3 It would prefer to be; yes; like a person, because like then it could have a full shell of electrons. C8:S3
Displacement Reactions		
War between two halogens for an alkali ion. C5:S1 Like planets that feel weaker. C5:S1 *They kind of like the battle with the other elements, and will displace that element out and make a compound.* C6:S1		*I think it should be nearer to the fluorine, so that it can steal the electron away.* C6:S1
Utterances: 30	**19**	**21**

13.2a Patterns and commonalities across utterances

Anthropomorphisms spanned a breadth of topics and focussed on concept features related to movement (C4:S3), shape (C5:S3), inter molecular (C1:S1), and intra molecular forces (C6:S1).

Of the total, twenty-two appeared to reflect 'weak' anthropomorphisms in which the students aimed to describe, rather than explain, a phenomenon. Examples included particles 'dancing' (C4:S3); 'jumping' (C6:S1); 'go[ing] crazy' (C4:S1); 'battl[ing]' (C6:S1); 'grab[bing]' (C3:S3); and 'pulling' (C4:S3). These descriptive anthropomorphisms tended to be used once, and did not recur across interview stages.

'Strong', teleological anthropomorphisms were interpreted in thirty-eight utterances. There were two predominant situations in which these occurred: in explanations of particle movement in states of matter, and in explanations relating to mechanisms for interaction between ions. The states of matter examples emphasised ‘intentions’ as an aspect of why particles move (or do not move) such as in a description of gas particles, in a container, when the top is opened, where, ‘Particles kind of, like, *want* to breathe [and therefore escape]’ (C4:S2). Utterances also suggested *competing* intentions between phenomena: for example, in the line, ‘[The solid particles] are not *allowed* to move, and it is just like nature’ (C1:S2). This utterance suggested that there is an opposition between the intention of a particle ‘to move’, which must compete against the intention of ‘nature’ which aims to keep it from moving.

The ‘strong’ anthropomorphisms that related to ionisation and displacement reactions (C2:S3; C6:S1) were indicative of an octet heuristic (Taber, 1995) in which atoms are imbued with a need to develop a noble gas electronic configuration. Again, the language tended to focus on intention, such as to ‘want’ as in, ‘An atom *wants* to gain an electron, to become stable, like the noble gases, which is when it has a full outer shell’ (C6:S1). These might also indicate particle *choice* as in, ‘It would *prefer* to be; yes; like a person, because like then it could have a full shell of electrons (C8:S3).

A final set of strong anthropomorphisms were uttered in responses about the relationship between heat energy and kinetic energy, for example, ‘A particle, the hotter it gets, the more excited it gets, and so it moves’ (C1:S1). These tended to reflect a view that particles are living (C4:S2; C4:S3; C2:S3).

13.2b Self reflexivity and metacognitive awareness in using anthropomorphisms in interview

Responses across different contexts suggested that the interviewees employed a range of anthropomorphic ‘tactics’ with a corresponding range of self-reflexivity and metacognitive awareness, from lacking awareness that they were employing metaphors, to seemingly thoughtful attempts to use anthropomorphic terms as placeholders for unknown concepts. The degree of self-reflexivity was interpreted according to the degree by which the learner made explicit that his or her anthropomorphism should be considered as a figure of speech. Three examples are provided in order to suggest the scope of awareness in their use. First, the fifteen year old, John (§12.0) was asked to justify his statement that a solvent atom ‘tries’ to break solute bonds. The third line and final line suggested that John was unaware of the anthropomorphic nature of his reasoning.

> And it would try to break the bonds.
>
> Okay, *it tries to break* the bonds.
>
> Oh, I am sorry, it would succeed actually.
>
> *No but - ‘trying’. Is it a human thing? Like is it actually going like, ‘C,mon guys?’*
>
> Alright, yes.
>
> *Is it doing that? Does it want to do this [break the bonds]?*
>
> I think it *wants* to.
>
> (C8:S1del)

Although the prompts could be seen as leading questions, the interest in John’s response was not that he accepted the term ‘wants’, but that his behaviour supported an interpretation of his confusion. John vacillated and became more tentative in his responses, as if trying to re-orient himself to the initial prompt. His mimicking of the term ‘want’ in his final response, his behaviour in the acceptance of the leading question, and his initial bewilderment suggested that his level of awareness of the figurative nature of his explanation appeared ambiguous at best. By contrast, the passage below suggested the use of anthropomorphic language within a more explicitly metaphorical context. This thirteen year old, Maddy (§9.0) corrected me for using her analogy as a literal statement. This occurred while defining the show card term, ‘particle’. Maddy said,

> I'm not quite sure what [particles] are but they are like quite tiny little things that live in other things.
>
> *Tiny little things that live in different things.*
>
> Yes.
>
> *So when we talk about particles in solids and in the air, they are, you say that they are tiny little things that live in other things. Do you mean-*
>
> They don't actually live.
>
> *Oh. Don't live.*
>
> No. They are just there. (C6:S1pre)

Maddy began her explanation tentatively. Her response was hedging, as espoused by her use of the vague words, ‘quite’, ‘tiny little’, and ‘other things’. This contrasted with the authoritative tone of her final two sentences. Given her clarification of the metaphor ‘live in’, it was plausible that she had expected the metaphor to be understood by the interviewer. To this extent, she appeared to have a metacognitive awareness of 'live in' as an analogy for the concept of 'existing within.' She argued that she had limited knowledge of particles; the anthropomorphism, in this context, was interpreted to have been used in an attempt to 'talk around' the concept.

This tactic of talking-around was suggested in a response by Morley in regard to ionic bonding (§7.0). This fourteen year old appeared to describe the difference in attractive force between two nuclei by comparing it with the human trait of 'deciding' which atom gets an electron. In this dialogue, self-reflexivity was suggested in the use of similes rather than metaphors, and the shift between social (i.e. 'deciding') and science domain ('gravity') metaphors:

> *So what is giving [the ion] that strength?*
>
> That's what I'm confused with -- it is basically more strong because there are more exes [electrons] around it [the nucleus].
>
> *Okay,*
>
> And it is just deciding, oh you know --
>
> *Deciding.*
>
> Well not deciding, but like, thinking, I don't know. Maybe it is like a sort of war between the two [atoms] just pulling one another, and that one wins and [that one] loses.
>
> *A war, pulling.*
>
> Yes sort of pulling...
>
> *What is pulling? Hands coming out of the atom, harpoons?*
>
> I think of it as like, gravity, and things get drawn in towards it a bit, and

> the stronger the gravity, more like… like a tug of war.
>
> (C5:S3 post)

The term ‘deciding’ was one of five possible descriptions that the student entertained, including ‘thinking’, ‘war’ ‘gravity’ and ‘tug of war’. Morley indicated that these were explicit analogies through the use of similes, ‘like’ and ‘sort of’. He also shifted his focus from a human analogy to the science analogy of ‘gravity’, which was made explicit by the use of ‘like’. Morley seemed to be unable to directly identify the cause of particle interaction by this approach. Nonetheless, he closed in on a more specific meaning by juxtaposing the synonyms of ‘war’, ‘pulling’, gravity, and ‘tug of war’. The example suggested an attempt by Morley to employ the anthropomorphic analogy ‘deciding’ as one of several analogies in order to ‘talk around’ his gaps in understanding.

13.2c No clear connection between intervention analogies and anthropomorphisms in interviews

The prevalence of anthropomorphisms before and after the intervention suggested that they had not been wholly introduced within the intervention. The range of weak and strong anthropomorphisms suggested that students held some malleable, and other more tenacious, alternative conceptions. However, they also revealed an ability to use anthropomorphic simulations across a range of contexts, and at times with a degree of self-reflexivity that suggested a comfort with, and, at times, an ability to use these analogies as a learning tactic, in a similar way to how I employed some actional analogies, such as the barn dance (§5.2) to help overcome gaps in students’ understanding.

13.3 Research Question 1: Findings

The following sections (§§13.3a-13.2n) describe findings in relation to the first research question, which asks: What are the features of physical simulations that may support conceptual development?

13.3a Interest and motivation

All twenty-four interviewees in post interviews tended to perceive the lessons as enjoyable, as interpreted from interviewees' synonymous descriptions such as, 'fun' (§7.2f; §8.0; §10.0). Teacher perceptions corroborated these comments, for example, 'I was impressed with how much they got out of it as well' (§9.2h), and 'they were so keen' (§11.2d). Although students had been told prior to the lessons that they could refuse to take part, none of the 163 students refused any of the activities. As a further suggestion of students' interest and attention, teachers tended to perceive that the classes were highly focussed throughout the interventions (§5.2g; §7.2f; §9.2h; §11.2f). Student interest during the interventions was assessed in part through their perception of the utility of the pedagogy. For example, interviewees tended to agree that they would use physical simulations if they were teachers (§10.0; §12.2n). They and other interviewees perceived that some activities were useful because they enabled greater visualisation (§7.0; §9.0; §12.2n).

13.3b There was no clear evidence that gender or age was a factor in the students' motivation

Teachers tended to highlight the engagement of all students (§5.2; §7.2f; §9.2h; §11.2f). However, they also foregrounded the engagement of otherwise quiet students. These students included those who were considered to be weak academically (§7.2f; §8.2h; §10.2g) or higher achieving (§10.2g), but both types were observed by their teachers to be atypically engaged in the lessons. Some teachers also commented upon the positive behaviour of boys who they had expected to prove challenging (§9.2h; §10.2g; §11.2f).

13.3c Complicity and autonomy

Complicity and autonomy were evidenced in students' support of group work and in their expressions that suggested a positive affective learning environment[9]. Student interaction and discourse was at times interpreted to be atypical for science lessons (§8.2h; §10.2g; §5.2g; §6.2d). Whole class improvisations and preparation for performance were observed to feature laughter (6.2d; 10.2g, 12.2c.i), exuberance (§5.2g; §8.2h; §12.2c.iii), humour (§5.2g; §6.2d; §10.2g; §12.2c.iii), playful noise (§3.2f; §10.2g) and touch (§10.2g; §12.2c.i. In one case this behaviour was compared to 'student play' (§10.2g).

Despite this atypical behaviour, students were interpreted to regulate their behaviour (§7.2c.i; §10.2g; §11.2f). Group-regulation was perceived to occur in the successful completion of the tasks (§5.1b; §6.1b; §12.3). It was also evidenced in teachers' positive descriptions of class behaviour (§7.2f; §9.2h; §11.2f) and comments such as, 'Your style of classroom management worked perfectly. They, they were perfect.' (§5.3d). Group-regulation was also supported by instances of *exuberance* in which some individual students were observed to briefly engage in self expression that was not supported by the rest of a group, whose combined reactions, such as a lack of attention towards the individual, supported the students' modulation of their

[9] i.e. a classroom situation in which examples of positive affect was interpreted. Linnenbrink and Pintrich (2004) have described *positive affect* as composed of *emotions*, feelings that occur in the moment that a task is undertaken, and *moods*, which occur over the longer term. Examples of positive affect include 'joy which is associated with an urge to play' (p65).

behaviour (§5.2g; §9.2g). Group-regulation was suggested in interpretations of complicity based on observations of group work (§10.2g; §11.2b; §12.3b).

13.3d Student creativity

Students' creativity was evidenced in examples of action-based self-expression during improvised BAPs (§5.2g; §8.2h; §12.2c.iii). Creative expression was also interpreted to occur within the humour that students employed in the interventions, with examples including physical humour (§6.2d, §10.2g, §11.2b), black humour (§7.2e; §10.2g), and character-based humour (§11.2a; §12.2.d). Creativity was interpreted in relation to novel analogies such as the ice cream vendor, Stockholm syndrome (§7.2e), and soap opera analogies (§5.2e) for displacement reaction HAMs. Creativity was also suggested in relation to one group's novel superimposition of a BAPs and GTM to express gas particles – an idea that was initially perceived to imply an alternative conception until justified by a group member during interview (§9.2h).

13.3e Affordances of student expressions

Students observed or engaged in representations of concepts across a range of external and internal modalities. The expressions that they employed extended across the range of those identified by Kress and Leeuwen's modes (§3.3a) (Table 13.2). The students' use of these modes was interpreted to be inspired strongly by their observations of multimodal teacher demonstrations, both in the warm-ups and initial topic tasks (§7.2c.i; §11.2c; §12.2c.i)

Table 13.2
Case reports in which Kress and Leeuwen's modes are referred to with respect to the expression of a topic concept

	Sight	Sound	Touch	Spatial (embodied)	Affective	Imagination	Social Interaction
Case	1-8	1,3,8	7,8	1-8	1-8	1-8	1,3,6,7,8

13.3f Scope for a variety of points of view

Students' positioning within the simulations suggested the potential to perceive their classroom representations through different and unique points of view. These perspectives included the point of view of a particle in a simple system (§5.2; §8.2; §10.2), a dynamic multiparticle system (§7.2c.i; §11.2b; §12.2e), a symbolic system (§11.2c), a human analogy of the system (§5.2e; §7.2; §12.2f), and as observers outside the system (§9.2g; §11.2b; §12.2.i). Different points of view were perceived to foreground concept features such as relative particle speed (§6.2d; §8.2f; §9.2h), proximity (§5.2f; §9.2h; §12.2d), particle orientation (§5.2f; §7.2c.i; §12.2c) and the random, chaotic nature of particles within a sugar and water multiparticle system (§12.2c.i).

13.3g Working with pretend objects

During some simulations, students were observed to interact with *pretend objects*. Students were observed to convey pretend objects through the use of mime and action, for example, in modelling pretend gas particles by acting out collisions (§9.2h), or by translating a one-teacher demonstration to three-person student simulation (§7.2; §11.3a). Students in the ionic bonding cases engaged with imagined objects proposed by the teacher, and applied these in their own subsequent simulations during the lesson (§5.1b; §7.2d).

13.3h Promoting visualisation across multiple representational levels

Students devised, enacted, and evaluated simulations across macro (§5.1b; §8.1b; §9.1b) symbolic (§11.1b; §12.2c) and sub-micro (§6.2d; §10.2g; §11.2b) levels. In 'The Spy's Perfume', KS3 students superimposed macro and sub-micro level signifiers (§8.2f; §10.2g; §11.2b). In the HAMs, students expressed social analogies for sub-micro level concepts (§5.2d; §7.2e; §12.2f). In BAPs such as 'The Spy's Perfume' students expressed superimpositions of macro level characters and sub-micro level particles in the same representational space (§8.2f, §9.2h; §10.2g). Some physical simulations were interpreted to produce narratives of physical processes which appeared to support students' visualisation (§5.2d; §9.3a; §12.2h), with one episode that suggested that the pedagogy supported students' identification of gaps in their understanding of displacement reactions in solution (§5.2d).

13.3i Affordances for student assessment of peers

The simulations were interpreted to promote environments in which students' expressions were informed by their observations of other students' expressions (§5.2f; §6.2d; §12.2c.i). Within the GTMs, some students' observations of others were seen to precede the observers' mimicry of the observed actions (§6.2d; §11.2b). Within the BAPs, some students watched other individuals, and groups, in action, and incorporated those actions into their own simulations, as evidenced in examples of the ripple effect (§5.2f, §7.2c.i §12.2ci). In all cases, some students assessed others' performances in forum evaluation, commenting upon, for example particle type (§7.2e), three-dimensional movement in space (§9.2f), multiple particle systems (§9.2f) and the interaction of solute and solvent particles (§12.2i).

13.3j Affordances for assessment: incongruous actions

The pedagogy was interpreted to afford scope for the teacher's formative assessment of students' topic understanding through observing body language, proximity, and movement during performance (§5.2f; §6.4b; §7.2f). Noise in the room was not perceived to obscure the clarity of visual assessment (§5.2f). Incongruous actions during multi-group performances were employed by the teacher to stimulate discussion of particular conceptual features with the class (§5.2f; §9.3c). Mimicry of students' gestural metaphors provided a real-time illustration which facilitated discussion between myself and the student, and between students (§9.2f). The ripple effect was interpreted to allow the teacher to perceive examples of rapid agreement amongst some pupils within a whole class (§5.2f, §7.2c.i; §12.2ci).

13.3k Discourse: simulations did not engender meaningful science-oriented talk within student groups in Year 7

Year 7s did not engage in extended science-oriented talk during preparation and performance activities that included BAPs, but rather engaged in non-verbal interaction during improvisations. The preparation tasks promoted increasing levels of science-oriented talk amongst the Year 9 students (§9.2h; §10.2g) and in Year 10, where discourse appeared to be most rich in HAMs preparations (§11.2a; §12.2g).

13.3l Science discourse through shared metaphors

In discussion between the teacher and the students, GTMs were observed to be used simultaneously in real-time to illustrate science-oriented talk (§6.2c; §10.2e; §9.2h) and in one example, revealed the potential for clarification of ideas in the intervention such as through mirroring another's gestures (§9.2h). Previous HAMs and BAPs observed during the lesson provided shared models to support science-oriented talk during forum evaluations, using images and analogies of human interaction (§5.1b; §11.1b; §12.1b), which afforded the potential to support student discourse when science-oriented talk was difficult (§10.2e).

13.3m Students were interpreted to engage in group thought experiments across the age-range

Students were observed to have co-constructed *group thought experiment*s (§7.2c.i; §11.2b; §12.2h). Topics included questions that asked students to explain what happens when a new halogen element is introduced to an alkali-halide solution (§5.2; §7.2e); how one might imagine the structure of fluorine (§7.2c.i) and how two hydrogen atoms may be combined as a diatomic molecule (§11.2b). Students were also asked to visualise the interaction of a dipole solvent with a polar solute at different temperatures (§12.2f), to work within a particle visualisation of a balancing equations task, to explain what happens when an evil spy sprays poison perfume at the far end of a room towards a King (§8.2; §9.2), and to explain what happens during the combustion of magnesium (§6.2).

13.3n A classroom resource

Interpretations of students' development of drama-based techniques such as gesture (§6.2d; §11.2b; §12.2e), use of space (§12.2e), levels (§5.2f; §7.2.c.i; §9.2f), facial expression (§5.2f; §9.2f; §12.2g), body language (§7.2c.i; §9.2f; §12.2f), collaborative discourse (§5.2e; §9.2h; §12.2g) and an increased sense of metavisual skill (§5.3; §9.2h; §12.2i) in relation to the topic over the course of the interventions, suggested that they had developed a core of skills as a classroom resource, to which they could return with future physical simulations.

13.4 Research questions 2 and 3

The following sections (§§13.4a-13.40) report on Research Questions 2 and 3. These sections describe the characteristics of students' resultant conceptions and whether the pedagogy develops conceptions which promote or enable further development.

13.4a Consistent delineation of sub-micro and macro level features in delayed and post interviews

A consistent finding was that in relation to pre-interviews, students increasingly delineated sub-micro and macro level features in their post intervention descriptions and explanations of topic concepts (§6.2b; §9.2e; §10.2b). Students who had conferred macro properties to particles in the pre-interviews tended to describe particles at the sub-microscopic level according to particle theory properties in the post interviews (§9.2d). Some exceptions to this tendency were in TE-type responses to diffusion, in which students revealed animistic thinking (§6.2b.ii; §8.2g) or described gas particles as slow and floating (§6.2d; §8.2f).

13.4b Multiple-particle systems

In post and delayed interviews, Year 7 and 9 students increasingly tended to emphasise the multiple particle nature of substances (§8.2a; §9.2c; §10.2a). For some students, this was revealed in 'richer' descriptions of the topic concepts, in which multiple particles and different types were suggested in drawings through the use of colour or shape (§6.2b.i; §10.2b) and the use of 'magnifying lenses' (§9.2e).

13.4c Extensive and various expressions of attraction

Attraction was rarely described in pre-interviews across all year groups. However, it consistently featured in post and delayed interviews, in which students either initiated the term (§6.2b; §7.2b; §10.2f; §11.2a; §12.2b), or responded to prompts to use or define the term (§9.2b). In lessons in which states of matter featured as a teaching objective, students' descriptions of attraction foregrounded its relationship with heat and energy (§6.2b; §8.2b; §9.2b; §10.2f). Post interview descriptions of attraction were expressed in relation to subatomic particles (§11.2a), inter molecular attraction (§6.2b; §10.2f; §12.2b), and intra molecular attraction (§7.2b; §11.2a).

13.4d Movement

KS3 students revealed a tendency to describe solid particles 'vibrating' in post and delayed interviews (§9.2d; §10.2a; §6.2b). KS3 students tended to increasingly describe gas particles more in post and delayed interviews in relation to movement, rather than, for example, spacing or macro descriptions, (§6.2b; §8.2b; §9.2c). Post and delayed interview concept maps suggested an increased association between heat energy and particle movement than in pre-interviews (§8.2b; §9.2b; §10.2f).

13.4e Embodied knowledge

Embodied knowledge was interpreted to be a factor in some Year 7 and 9 students' tendencies to express gas particle movement as slow when defining diffusion in the post interviews (§6.2d; §8.2f). Some KS3 and KS4 students' descriptions of particle movement suggested an association between descriptions of fast particle movement and intervention expressions in which a sense of intensity was perceived to be developed (§6.2d; §12.2h). The use of gaze to describe attraction was interpreted to convey an embodied/affective understanding (§7.2c; §11.2b).

13.4f Spatial awareness

KS4 drawings suggested a greater understanding of the proximity and orientation of particles during displacement reactions (§5.3; §7.2c) and dissolving (§12.2l). KS3 examples of drawings between pre and post interviews suggested more consensus descriptions of particle proximity in dissolving (§8.2b; §9.2b) and diffusion (§8.2b; §9.2c; §10.2b).

13.4g Memory

Post and delayed interviews suggested that the activities aided memory of the interventions, and of key conceptual features, (§8.2a; §12.2n) and that some students developed ‘richer’ conceptions as time progressed without further teaching of the topic concept (§6.2b; §9.2e; §10.2b) up to four months after the interventions. Recall at times was interpreted to be supported by striking imagery (§7.3b; §12.2n) informed by affect (§11.2e; §12.2n).

13.4h Anchor metaphors

In all interview stages, when students attempted to describe concepts of which they had gaps in their knowledge, they could rely upon a range of images and explanations including anthropomorphic, machine, gestural, action-based, and social. These were drawn from range of experiences, from previous lessons (§9.3a; §7.2c; §8.2d), to television (C6:S3pre), to lessons in different subjects (§7.2a; §8.2g; §11.2b). A recurrent theme amongst these responses was that they were centred upon what I interpreted as striking images (§7.3b). Intervention explanations which challenged or replaced pre-interview explanations appeared to be associated with strong imagery or a strong visual narrative during the intervention (§5.3; §7.3b; §9.2c).

13.4i Reconceptualisations of image and context

Imagery and explanations in the intervention had the potential to be detached from each other, such that an image employed in a students' discourse in post or delayed interviews was interpreted to be decontextualised from its original association. In support of this interpretation, GTMs of the states of matter were perceived to cause conflict between the students' gestural and mental models in post and delayed interviews (§6.2c; §10.2e). Further support for an interpretation of detached image and explanation was in some interviewees' drawings in which images remained similar across all three stages of interview but were re-labelled to signify new conceptual features (§10.2b), and an interviewee who appeared to disassociate a strong image of polar molecule orientation from the explanation of charged particles (§12.2.m).

13.4j Pretend objects

Students appeared to be unable to remember potassium atoms that they had been asked to imagine in class (§5.1b; §7.2c). Although they appeared to work with the imagined object in mind in the lesson, none offered the memory of the potassium atoms in post and delayed interviews. This was perceived to hinder their visualisation of ionisation (§7.2c). Elsewhere, post-interviews related to ideal atoms and molecule simulations (§11.3a) suggested that if imagined objects were made concrete by being made manifest within students' own models, then they would be recalled in interview.

13.4k Metacognition/ metavisual skills

Students tended to display a greater metacognitive understanding of particles as models of atoms and molecules in the post-interviews than in pre-interviews, as expressed in show card definitions (§8.2a; §11.2b; 13.2a.i), in increasingly metavisual devices in drawings (§6.2b; §9.2e; §10.2b), and in their TE-responses in interview (§6.3a; §10.2e; §12.2n).

13.4l Shared metaphors

BAPs and HAMs and GTMs were interpreted to provide shared metaphors which supported conceptual discourse in the post and delayed interviews. These simulations could be remembered by the interviewee and myself, which allowed me to reassert or draw students towards key features in the simulations in order to elicit new understanding or application of the models (§6.2d; §9.2c; §10.2e; §11.2a). Shared memory of enacted HAMs and BAPs afforded some weaker students a means of expressing chemical phenomena through non science language (§7.2e; §10.2c; §11.2a). Students who initially could not recall a concept or feature could be guided towards the visualisation through remembering their peers involved in constructing the BAPs or HAM with which they described the concept initially (§11.2b).

13.4m GTMs: embodied analogies for real-time illustration in discussions

In KS3 cases students were observed to initiate (§6.2d; §8.2e; §9.2d; §10.2e) the GTM in post or delayed interviews. The GTM was observed to provide a real-time modelling resource for use in interview and intervention discussions, and in doing so, supported students with weak terminology by supporting their descriptions of particle interaction (§6.2d; §8.2e; §9.2d). GTMs were also observed to support students engaged in TE-type responses (§10.2e). In one episode, the GTM was interpreted to provide an authoritative teaching model which I could use to affect conceptual challenge to a students' previous belief in the contraction of a heated iron bar (§10.2e).

13.4n Scope for continual formative assessment in future teacher-student discussions

The GTMs appeared to afford scope for formative assessment when, in interview I could highlight features of a student's model which was incongruous with their verbal explanation (§10.2e). These shared metaphors allowed me also to highlight features of students' personal, metaphorical gestures, in an effort to initiate discussion as to why these personal models might be incongruous with an ideal GTM (§8.2e; §9.2d). Highlighting incongruities between different gestural metaphors stimulated further discussions of the topic concept, which I interpreted would aid conceptual development (§8.2e; §9.2d; §10.2e).

13.4o Visualisation and thought experiments

A key interpretation of the cases was of students' increased ability to visualise particle interactions when considering the topic concepts (§5.3; §6.3; §7.3; §8.3; §9.3a; §10.3b; §11.3a; §12.3). This was supported by students' TE-type responses in the post and delayed interviews, such as those related to problems regarding diffusion (§6.2.b.i; §8.2b), combustion (§9.2c), the heating of a metal bar (§10.2e), the visualisation of whether and why displacement reactions may occur with the introduction of a new halogen to an ideal halogen/alkali metal solution (§5.2c), and the sub-micro processes of solvation (§12.2m).

14.0

Discussion

This study was unique within the small body of literature on physical simulations, in that it explored the relationship between students' interaction and the nature of their resultant conceptions over time. The study has suggested that a key attribute of the pedagogical model was its potential to support thought experiment-type visualisations of dynamic, multiple particle systems, in which students could telescope between macro and sub-micro levels of representation, and express these concepts, at times despite an insufficient grasp of the terminology. Within the context of these eight cases, the findings have extended the scope by which we perceive how physical simulations may enable conceptual development. Previous literature has noted the presence of motivation, (§2.2d), dialogic-type discourse (§3.4a), and the communication of particular conceptual features across particular modes and analogies (§3.3). The findings corroborate such claims, but also suggest why these are key attributes, and how they work.

The study suggested that these features must be perceived within the context of intentionally complex learning environments which promoted a potentially huge range of perceptions of enmeshed *image, affect* and *explanation*. Within this context, after the interventions, many of these potential perceptions appeared to be lost to conscious memory, were 're-contextualised', or competed with other explanations and images during post interview recall. In the following sections, I argue that the primary attributes of these physical simulations promoted *active engagement* in *socially mediated expressions* of scientific analogies, which supported a holistic process of concept development. The first few sections describe how the interventions provided a potentially wide range of perceptions of the topic concepts. In this environment, the teacher could highlight particular perceptions but could not be sure how students incorporated such perceptions into their own mental models. Next, this chapter focuses upon the role of social interaction in promoting students' engagement within a cognitively challenging environment: that it promoted choice and conflict within group work, which helped to coalesce personal perceptions of a concept. Next, the chapter describes a theory of learning informed by analogical reasoning theory, which emphasises the importance of an iterative pedagogical model by which students re-apply and reconsider conceptual features in new situations. Finally, I relate the model to Aubusson's questioning of role within physical simulations.

14.1a Scope for foregrounding individual concept features

The findings supported assumptions within Tveita (1999) and Aubusson et al.'s (1997) studies, and suggestions in my preliminary study (2007), that particular modes may provide particular perceptions of concept features. In this, it echoed multimodal research which has asserted that individual modes may foreground particular conceptual meanings (§3.4). Physical simulations appeared to afford a modal palette, primarily across embodied, spatial, gestural, and social modes. In practice, these afforded a range of signifiers with which to convey a single conceptual feature. However, given the range of representations in each intervention (§14.1c), the subsequent potential for the interplay of initially singular modes and signifiers supported a potentially vast range of perceptions among learners. For example, a range of signifiers became associated with attraction: as an *invisible connector* portrayed by students' mutual staring; as a *mutual pull* causing students to move together simultaneously; as a feature to *cause reorientation*, as when students spun into new configurations as dipole molecules, and in *variations of strengths* of attraction suggested by familial, collegiate, or lovers' attractions. At times these signifiers would occur simultaneously, which may or may not have provided complementary or conflicting meanings. In the case of *attraction*, anthropomorphic analogies and embodied signifiers for attraction coincided in the same performances. Interestingly, students themselves adopted or adapted these features, which suggested their comfort with the modelling form and with operating within an environment of multiple meanings.

14.1b Modal conflicts

The potential that my modal choices for conveying concept features may have conflicted with other modes was found, for example, in the use of slow-motion actions with the Year 7 groups, in which some but not all students' post-interview gestural metaphors of 'floating particles', and some slow-motion actions, conflicted with verbal expressions of high-speed gas particles. It was evident that conflicting modes did not necessarily mean that a stronger perception cancelled out a weaker perception, but rather that they may have informed different domains of thought related to the topic concept: students' responses in the post and delayed interviews indicated the potential for them to develop what Bouwma-Gearheart et al. (2009) have described as *dual conceptions* of gas particle movement, so that their perception of relative speed depended on whether they were defining states of matter or describing particle behaviour in diffusion. This dual-conception condition was interpreted to even co-exist within domains, as supported by evidence of two students who had developed conceptions of particle movement in diffusion, while also retaining animistic perceptions that particles moved because they were biological entities.

14.1c The pretend object

One mode that appeared to hinder conceptual development in the long term was the use of 'pretend objects'. In the ionic bonding lessons, after a 'pretend object' demonstration, some group expressions in class suggested that students could work with *pretend* potassium atoms and ions in completing further tasks (§13.3g). However, these imagined images were not recalled by some interviewees (§13.4j), and this in turn appeared to hinder their later visualisations of ionic bonding. Elsewhere it emerged that if students made pretend atoms and molecules into concrete expressions during the lesson, then they appeared to better recall the objects in post and delayed interviews. This would appear to suggest that pretend images did not pass from working memory to long term memory.

14.1d An environment of multiple representations

While physical simulations were interpreted to provide a wider range of signifiers for describing and highlighting key analogical features, the number of potential juxtapositions of sensations presented scope for a wide range of perceptions of concept features. The scope for more perceptions increases in light of the range of analogies with which students engaged. For example, each intervention provided a large number of representations relating to the topic concept: Five to ten modelling events occurred in each intervention. In those, students had the opportunity to be in three to seven simulations, and also to observe between eight and eighteen simulations and models expressed by their peers. For those interventions in which GTMs were used, they added between eighteen and twenty-six extra representations. In total, each class had the opportunity to experience twelve to thirty-eight representations within the lesson. The groups also produced warm-up representations which added another eight representations in which the same modelling resources were used to create meaning. The inclusion of social and affective points of view added further potential perceptions of the topic concepts.

14.1e Scope for multiple points of view

Further evidence of the potential complexity of the learning environment, and also for indicating the potential for focussing attention on particular conceptual features, was drawn from multimodal analysis of students' points of view (POV) during the lesson. Observation of students' POVs highlighted the individualistic nature of their perceptions during simulation performances, but also presented the potential for students to experience various perspectives of visual analogies of chaotic, random, multi-particle systems. Metcalfe et al. (1984) had initially mused that students might gain empathy with a molecule, in effect perceiving the system from the molecules' POV. In support of his conclusion, during group and whole class simulations, students' viewpoints were often framed as from the inside of a system. A similar interpretation can be drawn, for example, in whole class constructions of a fluorine atom (§5.1b; §7.2c), or students in-role as dipole molecules surrounded within a jostling group of other molecules (§9.2d), such that students entertained the POV of the particles that they represented. An aspect of these examples was that, at these times, students did not perceive a global image of the systems but rather a partial view. Their different roles and positions effected individual perspectives different from those of students in other roles. This scope for a range of POVs reinforced the assumption that there would be no shared understanding of a concept in which students would be aware of the exactly the same points of view as other students. Visual understandings from these episodes were likely to be fractured and amorphous.

However, an affordance of *action*-based POVs was the potential for a shared understanding of embodied, affective, and social features: Students in the middle of dynamic groups were interpreted to experience feelings of intensity and chaos within systems developed through the students' physical and social relationships with one another. This finding supported Metcalfe's choice of the word 'empathy', framing it as representative of an embodied, affective, and social sensation.

14.2 Suggestions of how the Complexity of Potential Images and Explanations Supported Conceptual Development during the Interventions

14.2a Thought experiments

The study supported suggestions within the preliminary study that simulations enabled both group and individual thought experiments. Students expressed concepts across progressively more complex modelling forms (i.e. from GTMs to BAPs to HAMs), which suggested that students could increasingly translate conceptual features across different modes, i.e., from gesture to action to anthropomorphic analogies. Some students' drawings, and some students' responses to TE questions suggested that they continued to develop richer visualisations of the topic concepts after the interventions, in that they could more clearly and subtly delineate macro and sub-micro levels of representation (for example through new uses of magnification signs in their drawings). Interestingly, students' visualisation skills did not appear to be hindered by group TE activities in which they *superimposed* macro and micro images within the same scene, such as in 'The Spy's Perfume' in which particle-actors moved around character-actors, or in the HAMs in which particles could be construed simultaneously as sellers and buyers in a store. Such superimposition may have aided students' understanding, as Ault, Charles and Novak have reported that understanding about molecules evolved more rapidly in students with *rich conceptualisations*, even when these included a range of idiosyncratic 'alternative' conceptions (1984).

14.2b Anthropomorphism as a means of navigating an environment of multiple representations

Despite suggestions in the literature that anthropomorphic teaching analogies may lead to anthropomorphic conceptions, the explicitly anthropomorphic HAMs and implicitly anthropomorphic BAPs and GTMs within the interventions did not appear to affect an increase in anthropomorphic utterances in the post and delayed interventions. Rather than 'hinder' learning (Hellden, 2003) anthropomorphic analogies appeared to enable students to express narratives of systems and processes, suggesting that these anthropomorphic analogies were used to support learning by allowing students to initially bridge over gaps in mental models of scientific processes. Such findings did not challenge previous assertions that anthropomorphic analogies could lead to tenacious 'alternative' conceptions (Taber & Watts, 1996), since some conceptions from the pre-interviews appeared to be retained in later interviews. Rather, the evidence suggested a mechanism by which anthropomorphic features could be perceived as supporting some students' learning tactics. In comparison with Kelemen and Rosset's evidence (§3.1), the findings of students' use of anthropomorphism in the interviews, and student responses to my ad hoc use of anthropomorphic analogies such as the 'barn dance' to simulate ions in solution, suggested that anthropomorphisms may have provided working explanations for gaps in students' knowledge. Evidence of students' self-reflexivity and metacognitive use of anthropomorphisms within interviews further suggested that these working explanations allowed scientific conceptions to develop around, or in conjunction with non-scientific anthropomorphic analogies. In this respect, physical simulations provided the potential for an external expression of this learner's strategy, supporting a piecemeal construction of scientific conceptions over time.

14.2c Simulations as a source of shared metaphors during formative assessment in the intervention and in future discussions

A utility of the simulations for developing conceptions was found in the shared metaphors with which I as a teacher, or later as an interviewer (a proxy for later teacher discussions with students) could discuss the topic concepts with the interviewees in the post and delayed interviews. Some episodes suggested that recall of in-class simulations allowed students in interview to actively engage with concepts for which they did not yet have a full working terminology. For example, some interviewees, such as Kate (§11.2b) engaged in extended discussions of physical processes by directing fellow students in hypothetical simulations while solving new problems. The GTMs, furthermore, were initiated by some students in order to illustrate and engage in discourse about the topic concepts. In interventions and interview, this supported formative assessment in that the GTMs allowed me to observe incongruities and patterns, in real-time, between students' verbal descriptions and their modelling of their understanding.

14.2d Affordances for developing metacognitive skills

The literature has suggested that traditional diagrammatic representations may promote tenacious conceptions that may hinder conceptual development (Treagust &

Harrison, 2000). It has been asserted that this is in part to do with a perception on behalf of the students of a 1:1 representation between the analogy and the phenomena (Grosslight, Unger, & Jay, 1991). The degree to which this occurs with human-based analogies was raised in my Masters research. This study provided further supporting evidence that using humans as modelling resources did not promote '1:1' conceptions; in essence, students did not tend to perceive that atoms looked like little people, whereas they may have perceived that atoms looked like little balls. This supported the interpretation that physical simulations promoted a metacognitive perspective. Indeed, some KS3 and KS4 students, in post and delayed interviews, asserted that they used their recall of the BAPs and HAMs within a wider range of models with which they understood a concept. It was suggested by some teachers that the non science warm-ups provided a useful frame in which to discuss model-making and representation, as well as to support the acquisition of modelling resources. Within this context, there may be scope to consider drama-based activities which promote the precursor metavisual perspectives needed in model-making and in developing awareness of representation in Science.

14.2e Affective characteristics of the learning environment

Physical simulations were interpreted to support affective features such as motivation, interest, and self-regulation within the learning environment, echoing attributes which had been cited in previous literature on physical simulations (§§1.4-1.4c) and in Drama in Science (Odegaard, 2003; Dorion, 2009). The physical simulations within this case appeared to promote and reciprocally develop a sense of comfort and confidence within the classroom, despite the potential for vulnerability associated with role-play, with having a novel teacher and a novel lesson, and with participating in groups that tended to be larger than in regular lessons. The suggestion that physical simulations promoted positive social environments was reinforced by the participation of all students, in particular those who were perceived by their teachers to normally disengage with Science discussions. This characteristic supported an emergent theme within the cross-case analysis: the importance of the formation of relationships between peers and teacher. Lemke (1990) has noted that the teaching of Science may alienate some students, and that this is due to an imbalance of power, in that the teacher is the authority and the students are assumed to be ignorant of science. In this study, one way in which the balance of power was perceived to be mediated was in the dialogic environments, which gave students an opportunity to creatively draw from their own experiences. In this sense, they drew upon knowledge that I did not have. Students' growing sense of autonomy was in evidence as the interventions moved towards the final student-centred tasks, which entailed extended group negotiations. Another example was in Case 6 when students took control of the direction of discussions to pursue their own questions, such as whether sugar melts in water, and surprised their teacher with their interest and motivation at this stage in the intervention, and at the end of the school day (§9.2).

14.3 A Model of Learning

Observations of students' use of anchor metaphors, the failure of some pretend objects to be recalled over time, the dynamic nature of anthropomorphic utterances, and evidence of dual-conceptions helped to inform an interpretation that students' understanding was often piecemeal and non-linear in their development across the interview stages. However, some conceptions were also seen to be *consistently anchored* by associations of explanation, image and affect which appeared to successfully compete with other ‘anchor metaphors’ to be the primary explanation for a phenomenon.

This provides a context in which physical simulations pedagogy may be best contextualised, within a theory of learning as a complex, non-linear process by which conceptual development is mediated through the initiation and evolution of individual heuristics, or ‘fuzzy’ analogical units which combine into useful, but still ‘fuzzy’ conceptions. This view is informed by Wilbers and Duit’s (2006) ideas of ‘heuristic analogy’ and elsewhere Heywood’s ‘hermeneutic approach’ (2002), which situates interpretation and meaning within the context of a *journey towards* rather than a *state of being* in the world (p. 244). These theories assert that the learning of Science analogies is a process of students’ progression towards the teacher’s heuristic, rather than progression towards conceptual understanding.

The model of learning that has emerged within this study places emphasis upon the roles of image, affect and memory. The importance of the linking of cognitive, imagistic and affective features to memory has been widely asserted (Kokinov & Petrov, 2001; Dai & Sternberg, 2004). This model of learning synthesises these features with the heuristic analogy theory above. In this view, concepts consist of a series of heuristic units which must be robust enough to pass into long term memory, and must also compete for explanatory value with alternative heuristics. They are subsequently recalled into conscious thought, and then evaluated in juxtaposition with other heuristics. In this model, successful heuristics will include a visual or embodied image, referred to variously as *intuitive schemata* (Clement, 1993), *image schemata* (Sfard, 1994) and *embodied schemata* (Lakoff & Johnson, 1980). These sense-based units, rather than propositional units have been argued by Wilbers and Duit (2006) to be a dominant characteristic in learning through their heuristic analogy. However, this study asserted that within the context of these eight cases, that equal importance should be given to *affect,* since many competitive heuristic units were interpreted to be linked to an emotional or social attribute. While affect has long been considered a potential feature which promotes learning in Science (Watts & Alsop, 1997; Thagard & Shelley, 2001), it has tended to be viewed in respect to motivation and attention, rather than as an integral aspect of concepts themselves**.** Thagard and Shelley have observed that 'Despite the growing appreciation of the relevance of affect to cognition, analogy researchers have paid remarkably little attention to emotion' (2001, p.335).

In this model of learning, affect and image form a heuristic unit (Figure 14.1), which acts as a carrier of *explanations*. However, the explanatory context of the image is not necessarily retrievable at will, as evidenced by 'decontextualised' anchor metaphors in some post and delayed interviews (§6.2c; §10.2e). This theory asserts that *image-affect* and *explanation* can be thought of as two discrete features of a heuristic unit: Around the image-affect core lies the explanatory layer (Figure 14.1, below).

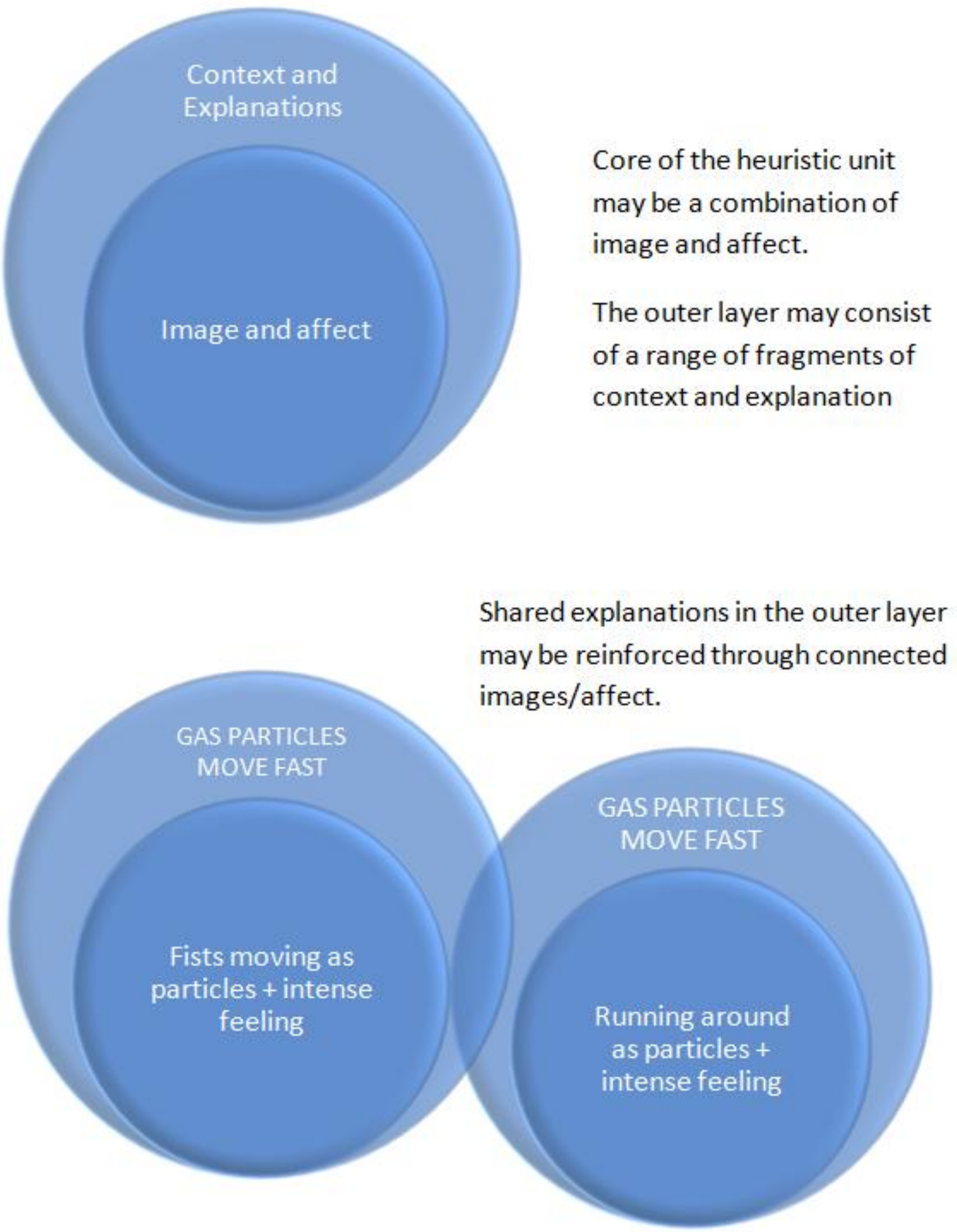

Figure 14.1 An illustration of two heuristic units combining to enhance the conceptual understanding of gas particle movement

This model for learning provides a solution to the debate over whether analogical reasoning, and by extension, visualisation, is reliant on non-propositional or propositional features (Gilbert, 2005). The theory assumes that propositions (explanations) are less memorable than non-propositional affect-images. Within the context of the case studies, these two discrete layers offer different affordances: First, the non-propositional element, the affect-images, may inspire new juxtapositions with other affect-images. Second, after new juxtapositions are made, the proposition-based explanations associated with the cores may be recalled into juxtaposition with other, complementary explanations. These explanation pairings then fuse the two heuristic units (Figure 14.1). In this context, explanations which complement one another may create links between their heuristic units and this linking in turn reinforces their heuristic strength and the likeliness of recall at a later date. As such, the strength of the new explanations ultimately draws more units into a growing conceptual framework. However, as with the example of conceptual challenge related to the heating of the iron bar (§10.2e), connections may also be broken in favour of more explanatorily powerful juxtapositions.

This process can continue indefinitely with the connection of new heuristic units, a process that may occur during recall in teacher lectures, demonstrations, and new group expressions (and also in this study during post and delayed interviews). Figure 14.2 (following page) illustrates a larger grain perspective of this concept, with heuristic units shown to be constructed through students' *motivated engagement* in a dialectic, mediated through social interaction, in which they encounter multiple perceptions. The initial groupings of heuristic units are the *nascent conceptions* that can be recalled in the post interviews, but which then compete with isolated, remembered heuristic units and alternative heuristics. These together inform the students' construction of progressively mature conceptions.

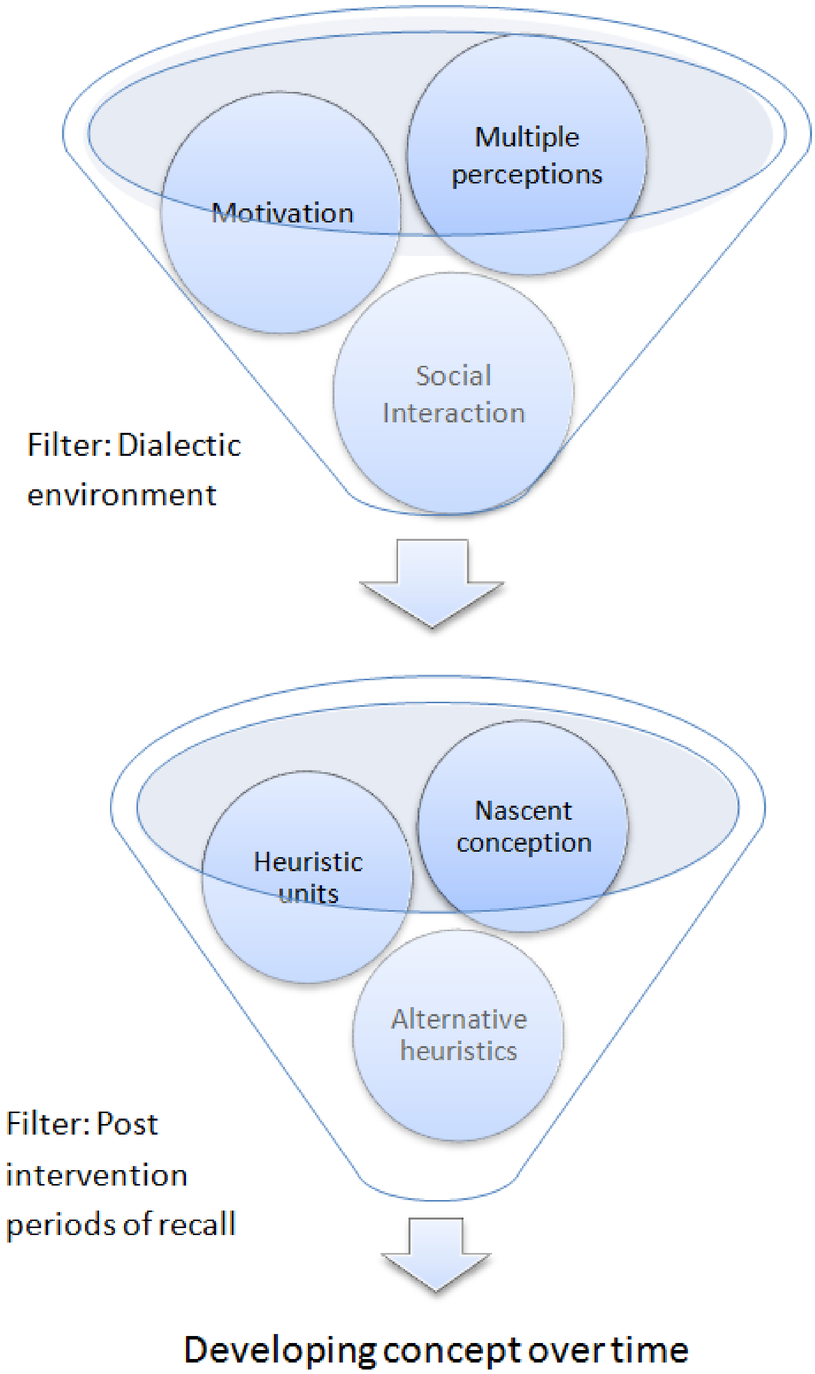

Figure 14.2 The process of concept development. The top illustration represents the key features of the interventions: the motivation to engage with a range of perceptions in discourse with others. The bottom illustration illustrates the interviewees' mental environments afterwards, in which heuristics from the intervention and elsewhere connect with or challenge the units already associated with the nascent conception.

14.3a Implications for the model of learning in relation to evidence of discourse

It is within this learning context that the cross-case analysis of discourse may best be described. My initial assumptions in this respect were challenged by the evidence: As with Aubusson (2006), I perceived that physical simulations would promote a high degree of science-oriented talk. Aubusson, however, worked with 16-17 year olds. In my study, which spanned ages from 11-15, older students' discourse appeared to include a degree of science talk, but younger years included little of this during group work, and instead included some science and some social domain talk and a much higher degree of non verbal discourse. As such, the degree of science-oriented talk appeared to increase with age and general academic ability, so that the GCSE groups engaged in more extended verbal discourse. Hypothesis generation for all but these most thoughtful groups tended to be brief. The principle sites of verbal scientific explanations were to be found in the forum evaluations and teacher-led demonstrations and lectures, which were primarily interactive/authoritative occasions. To this extent, the 'tension' between dialogic and non dialogic discourse (Amettler et al., 2007) was mediated by the variegation of teaching routes (§3.4) of different levels of dialogic and authoritative talk in the research model.

Given this context, while the dialogic discourse tasks entailed some hypothesis generation in relation to the scientific concepts, they may be better perceived as rich environments of expression in which personal choices and group conflicts were negotiated by students in relation to the signifiers that best supported their present understanding of the topic concepts. Refracted through the learning model, conceptual development occurred in part through serendipitous juxtapositions of image-affect and explanations over time.

14.4 The Pedagogical Model Reconsidered

These interventions employed a lengthened version of the pedagogical model (§2.5c; §2.4) in order to maximise observations of students' behaviour and to explore the scope for its use within a classroom environment. In practice, an intervention would be assumed to take place in conjunction with other teaching methods. With these caveats, in light of the findings, the pedagogy appeared to engender some conceptual development.

Key episodes in some lessons suggested that the pedagogical model, as previously described within my Masters study, was too rigid. For example, the circumstances of the 'barn dance' analogy (§5.2e) suggested that I could depart from the initial cycle in order to attend to gaps in students' understanding. Once the iteration was complete, then the class might return to the model (Figure 14.3).

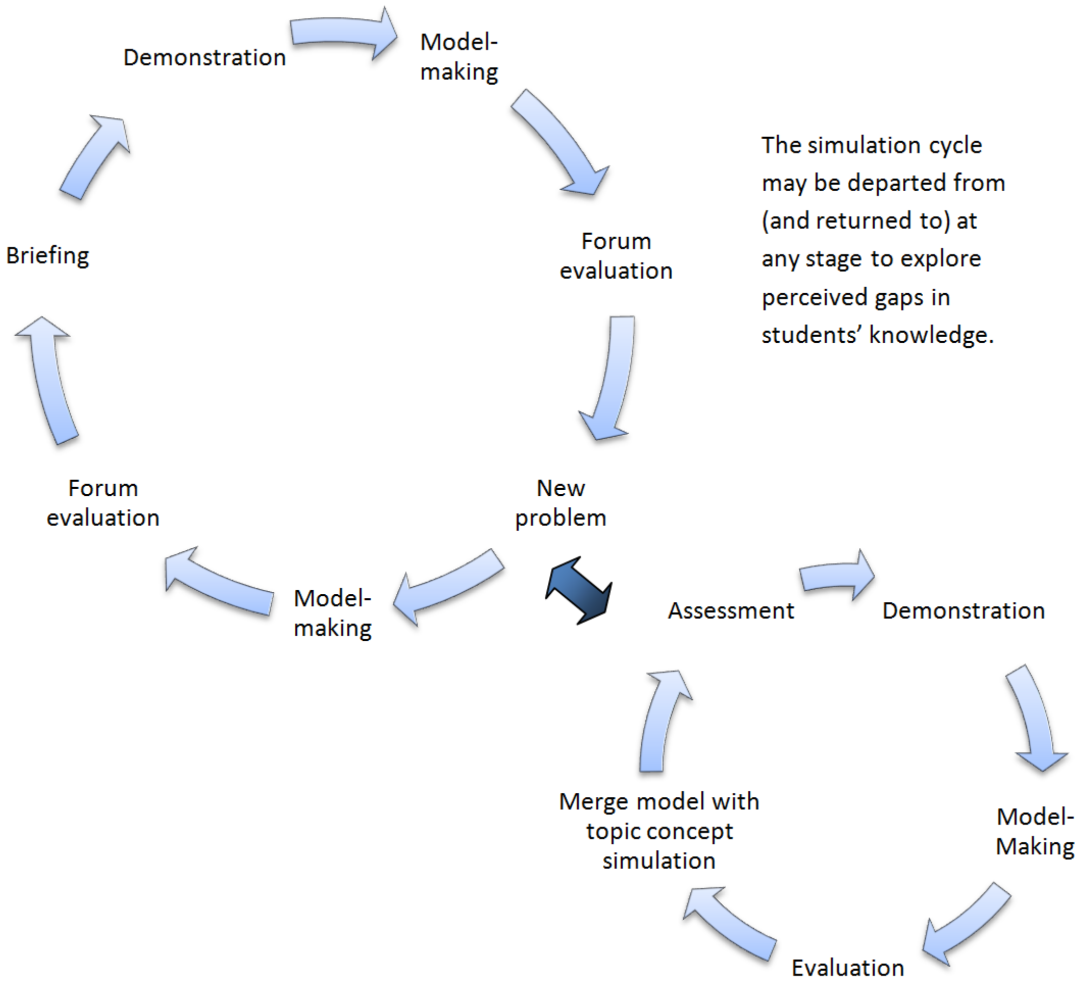

Figure 14.3 The augmented simulation cycle.

The benefit of moving into an additional simulation cycle would be to focus more narrowly upon specific conceptual features within the wider topic concept. As students' visualisation skills developed during the interventions, and the clarity of their narratives of process improved, their lack of understanding of some discrete conceptual features provided obstacles to their further visualisation. These features were sometimes not even part of the teaching objectives (for example, a lack of knowledge of polar molecules in Chapter 3). The additional simulation cycle could engage students in developing 'placeholder' analogies, such as the 'barn dance' and the anthropomorphic analogies that some students were observed to use tactically in interview. The smaller simulations cycle would allow the students to learn and then apply the placeholder analogy and merge it with the topic concept simulation. Upon returning to the larger simulations cycle, the placeholder analogy would inform the continued development of students' models of the topic concept.

14.5 Future Research

While Metcalfe (1984) and Tveita's studies (1993; 1999) have suggested that physical simulations promoted learning, the former was a small study (§2.1) and the latter studies included other modelling approaches (§2.4a). One of the key research aims for this study has been to provide theoretical and empirical support from which to evaluate the pedagogical model within a wider-scale, quantitative study, in order to corroborate or challenge Metcalfe and Tveita's quasi-experimental findings. Over the course of the study, a range of other issues for further research have arisen. Related to the initial and emergent themes of the study, these issues have been described in the discussion sections within the case reports:

- The utility of anthropomorphic analogies (§5.3)
- The question of BAPs versus HAMs as a focus for the question of to what degree learning relies upon the abstract or simplified nature of the models (§12.3a)
- The utility of GTMs (§6.3; §10.3b)
- How best to describe gas particle speed to students of different metacognitive abilities (§6.3a)
- The promotion of a metacognitive perspective (§11.3)
- The utility of shared physical simulation metaphors in later lessons (§5.3; §10.3b)

- Memory and how it mediates a physical simulations pedagogy (§7.3b)
- The importance of affect as a feature of physical simulation analogies (§12.3)
- The scope for increasing the duration of dialogic tasks (§11.3)
- The importance of affect as an analogical feature (§7.3b; §12.3)
- The degree to which an adult modelling bias hinders learning (§9.3c)

These issues suggested new research questions and directions of focus, some of which have been described in detail within the case reports. The reader is directed to these sections for greater explication, but below, three key issues are summarised and relevant research questions are noted.

Anthropomorphic analogies were ubiquitous within the interventions, but analysis of students' utterances did not suggest that they hindered conceptual development. Rather, the students appeared to use anthropomorphisms of their own as a learning tactic. This suggested that the analogies within the intervention might have provided affordances such as the bridging of gaps in students' understanding (§5.3). While the wider literature on analogy supported a perspective by which anthropomorphic analogies could be perceived as potentially useful (§3.1), and literature in Science Education suggested that anthropomorphic analogies may support some learning (§3.1), this study has suggested that its utility may be found in its support of a range of metacognitive or self-reflexive learning tactics that students used (§13.2b). The study also suggested that students' utterances may have revealed the boundaries of their scientific understanding of a topic concept (§5.3a). Research into the validity of this hypothesis would support formative assessment of verbal expressions in Science, and may also inform the assessment of students' actional or gestural expressions within physical simulations.

Memory and the filtering effect between working memory and long term memory was found to be a key issue, as highlighted by pretend objects (§7.3a), anchor metaphors (§7.3b), and the decontextualisation of images such as GTMs which were easily recalled but seemed to be read anew in the delayed interviews (§6.2c; §10.3b). Taber (2003) has noted that little research has been done with memory in relation to Science Education. Two central questions arising out of this study which relate to the model of learning (§14.6) are how to best promote scientific explanations as physical simulations analogies so that they may be recalled over time, and how we might use physical simulations techniques to recall and re-conceptualise shared metaphors in later lessons to support conceptual development in the long term.

Gestural Teaching Models emerged as a key analogical tool with the KS3 students. These were interpreted to be potentially useful in promoting visualisations and engendering discourse in relation to particle theory concepts. The evidence echoed suggestions elsewhere into the use of gesture in Science Education, in that it can support discourse (Roth & Lawless, 2002), and does so in part by allowing students to discuss concepts despite being unable to clearly verbalise individual conceptual features (Lozano & Tversky, 2006). The GTMs provided the first example that I know of in which gestural metaphors were employed specifically as a teaching tool. The consistency with which students could describe states of matter and engage in TE responses using the GTM in real-time with talk (§13.3l) suggested the potential for this approach to be explored through gesture research as well as physical simulations research, and provides a reply to Roth's call for more research into teaching which supports students' use of gestures for conceptual development (Roth, 2000).

The distancing effect, by which students tended to avoid being drawn into a perception of these models as representations of reality (§13.4k), was in evidence, and seemed to reinforce a metavisual approach to science modelling. Jungwirth has asserted that teachers and students may not be aware of the metaphors that they are using in class (1974). A research focus on greater metavisual awareness through physical simulations might inform interest in a wider range of modelling forms. Theile and Treagust (1994) and Heywood (2002) have argued that there is a limited range of representation in traditional teaching, which they describe as pictorial and monomodal respectively. This study suggested that the construction of new modelling forms in Science may provide visualisations that focus on different concept features, and support further creativity and engagement in lessons.

Thought Experiment responses in interventions, and in the interviews, revealed potential for what Osborne (2002) and Gilbert (2008) have described as a neglected but integral issue in research: finding new ways for students to explore and understand scientific reasoning. This study argued that some students increased their range of expression and engagement in discourse about their topic concepts in the post and delayed interviews (§13.3m; §13.4o). Osborne argued that we must offer students the opportunity to explore the language of scientific reasoning and the rhetoric of science thought (2002). The physical simulations suggested a site of immersion into thinking about multiple representations of matter, and that such thinking can be supported, in the Brunerian sense of 'playing' with concepts before engaging in formal expression (1974). While the tension between dialogic and authoritative discourse was evident in the lesson structure, the TE tasks suggested the potential (as a classroom resource) for students to be highly autonomous in choosing how to explain phenomena. Odegaard (2003) noted that there is a, ‘paradox that science relies heavily on creativity and imagination’, but that in Science, the main teaching language can be, ‘merely a descriptive labelling system (Lemke, 1990; Sutton, 1996)’. Given this context of a versatile medium that affords a high degree of control to students over their learning, this pedagogy provides scope for exploring the degree to which students may be able to construct highly abstract science simulations (§9.3; §12.3) in order to support scientific reasoning and visualisation across a range of abilities and ages.

15.0

Conclusion

A pedagogical tool which has proved useful in informing this research into physical simulations has been that of computer simulations (Ihde, 2002; Reiner, 2008). This field has shared an interest in the 'qualia' (p.76) of different sensations, whether they inform particular conceptual features, and to what extent they can support different forms of discourse (Snyder, 2002; Jewitt, 2008). The opportunities to experience and interact with particle-based simulations leads one to speculate that students may someday don the technological equivalent of Magic Goggles and move through and manipulate virtual environments in 'everyday lessons'. What then, is the purpose of physical simulations?

I asked my wife, a languages teacher, this question. Aware of my findings, she said, 'You can't have a relationship with a diagram'. This seemed to capture the unique nature of dialect, engagement, and affect in physical simulations: To use this modelling resource required the complicity and trust of the modelling resource. In group work this resource reacted to, supported, and challenged individual model-makers' decisions, and then regulated their actions in accordance with groups' emergent expressions. The model-maker was part of the model, and the modelling itself could resemble 'playground behaviour' (§11.0) with large groups engaged in pretend play. Such features may continue to suggest the holistic and child-centred uniqueness and utility of the pedagogy, and may inform research into the complex but impactful relationships between cognitive, affective and social domains of thought during conceptual development (Zemyblas, 2005; Alsop & Watts, 2000).

On a more practical level, despite the proliferation of virtual learning software, physical simulations may provide a complementary pedagogy that offers an *inexpensive* means of experiencing abstract phenomena. This may be of particular benefit to resource-poor Science departments, both in the UK and the wider world. Beyond schools, drama-based analogies may also provide potential support to public health initiatives in developing nations (Choto, 1989). In informing these domains, this study and those that follow from it could ultimately provide a small but worthwhile contribution to the quality of international science education.

Ultimately, this study aimed to provide practical benefits to teachers, teacher trainers, and educators within the wider society (§1.4a). Although physical simulations and Drama in Science have been strongly informed by Drama in Education in UK schools over the past century, the physical simulations literature now draws from an international forum, from Australia (Aubusson and Fogwill, 2006) and the US (Edmiston, 1998), to India (Venkateswaran, 2006), Norway (Odegaard, 2003), and Germany (Sturm, 2009). This widening of the field suggests the potential for greater international interest from teachers. It is hoped that this leads to further descriptive research into 'everyday' Science teachers' use of drama-based activities in a variety of subjects and contexts. To date, there remains little descriptive research related to typical Science teachers' use of these techniques, but the progress of discovery in the nascent literature suggests scope for more. And, if resultant pedagogies are successfully evaluated as techniques to support learning at secondary level, this strategy may support the status of the Chemistry teacher as an Analogy Engineer, with the skills of a science poet (Claxton, 1997) and one day the National Curriculum may give guidance for Humanities teachers to seek advice in using Drama techniques from their colleagues in the Science Department.

15.1 Final Reflections

Before I began my Masters study that preceded this doctoral work, I sat at a table in the Faculty of Education with two potential supervisors, one Science Education specialist and one Creative Arts specialist. I had to make a decision as to whether I was looking at Science through drama or at Drama in Science. My preference was to situate myself within Science Education, and to focus on drama as a Science-specialist pedagogy. Although I made a choice, it was perhaps to be expected that my subsequent assumptions of learning, my research questions and study designs would continue to be influenced by my drama experience. For example, my sensitivity to the importance of non-verbal communication and complex social negotiations in lessons probably predisposed me towards Semiotics-based and dialogic theories of learning.

My drama background influenced me in another respect: as a sort of cross-curricular stigma. At the beginning, I feared having my research dismissed within Science Education unless I made an effort to 'fit in' to the mainstream research programme. I had been influenced, during my Masters course, by discussions and reviews on the 'mixed methods' debate, that suggested to me that there was still a strong view held by many in Science Education that evidence should have a quantitative, preferably experimental basis (Taber, 2009). Yet here I was, doing exploratory, ethnographic, work with drama activities and anthropomorphic analogies. Much of the Drama in Education research that I had read tended towards qualitative, case study approaches.

Neither it, nor my own work resembled the more experimental-based Science Education research that I had studied.

I attempted to situate my work within what I perceived as a mainstream Science Education perspective by moving towards a more reductionist, cognitive-focussed perspective of conceptual development. This drew me to focus upon an assumption that the interaction of a few key multimodal signifiers in class could create a corresponding conception in the student: Following this assumption, I assumed that I might find and categorise and classify patterns of signifiers and their resultant conceptions. This, I remember thinking initially, would help to provide a bit more of a *quantitative impression* to readers of my work.

At the same time, while I acknowledged that social interaction and discourse were important features of conceptual development, I was less interested in understanding the dynamics of these features – because they were just too complex. The Science Education research that I had read at the time suggested that I might end up with evidence of how physical simulations promoted ‘interest’ and ‘attention’. This would hardly be a unique finding, and so it was difficult initially to see how I might gain new insight here.

What fascinates me now is how my methodology prompted me to overcome my initial biases. Following Stake’s ethnographic approach (§4.1a), I found that I quickly ended up following the data rather than channelling it into my own perspectives. I recall being confronted by evidence in the post and delayed interviews of different cases, which emphasised affect and social interaction (such as in interviewees’ easy recall of gaze as a signifier for electron-proton attraction). I could not comfortably incorporate this evidence into the study's initial themes. This prompted me to engage in further literature reviews and reflection, from which new theories informed analysis; for example, theories which viewed analogies as non-propositional and heuristic.

Ironically, I believe that my initial biases may have provided an alternative critical perspective during cross-curricular analysis. One result of this was that, while it would have been easier to support Wilber's and Duit's unadulterated heuristic analogy when I developed my model of learning (§14.3), my past *reductionist* bias strengthened my interpretation that affect should be included as a discrete feature within each 'heuristic unit'. In retrospect, I think that this aspect improved my model.
A second characteristic of this study through which I developed as a researcher, began with my decision, justified in section 4.3b, to teach the interventions. I did not initially want to teach, primarily due to issues of ecological validity. From a personal point of view, I also realised that I would be increasing the stress of organising and running the interventions, and increasing my responsibility for the potential failure of the interventions, rather than being able to deflect criticisms, for example, by arguing that the classroom teacher somehow failed to implement the lesson properly. Such responsibility caused me stress, but at the end of the cases, and now of the study, I believe that this researcher-as-teacher approach provided a range of perspectives which would have been wholly excluded, or would have been gained second-hand from the teacher in interview. One practical example was that, juxtaposing the video and my own participant observations, for example, helped me to consider the contrast between what the teacher sees, and what the students see. This in turn emphasised to

me the importance of shared interaction, and the potential emotional and multimodal features that may inform subsequent student conceptions.

These two issues emphasise what I think to be an important aspect of my development as a researcher – aside from learning to be pedantically organised with interview data, to have extra tapes for camcorders, to allow twice as much time for writing up as expected, and to be doubly sure to avoid locking your keys in your car – the importance of trusting and being consistent with your trialled methodology.

My final observation is that I feel lucky that I had the opportunity to engage in research with such opportunities for positive emotional reward. In lessons, I developed a rapport with many students, and together we created learning environments which were often creative and humorous, and in which I assessed (as a teacher) that learning occurred. While I had that feeling of being both a coach and a fan of the students, I also felt the pleasure of hearing the teachers enthuse in their observations of particular students who had excelled, or had shown new confidence. The students inspired me to be creative with my developing lesson plans, and also inspired some of the teachers who observed me to consider ways of using these approaches that I had not initially envisioned.

14.0

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Appendix 1

A Sample Lesson Plan for a Year 9 Particle Theory Lesson for States of Matter, Dissolving and Diffusion

1hr 10minute lesson

Briefing
5- 10 minutes
Script: *not verbatim*.
'Everything around us is made of atoms, often stuck to other atoms and called molecules. Atoms are small. There are more atoms in my mug of coffee than there are mugs of water in all the world's oceans.'

'What do they look like? We don't know. You can't imagine them. You can't take a picture of them. So we often say is that they are kind of like this and kind of like that; we use different ways of describing them. One scientist believed that you could only describe them with maths. Another physicist found a way to describe them without maths. He said that atoms and molecules act as if they were a bunch of particles, little balls that tend to stick to each other.'
'
'It turned out that you can answer lots of questions about how things work if you think of tiny balls sticking together. This model was called particle theory. For this model to work, we need a couple of rules:

- The balls are attracted to each other; like magnets.
- You can make them break away from the force of their attraction if you add energy by heating the substance up.
- If the particles can't break away because they don't have enough energy, then they form a solid.
- If the particles break away a little bit but still stick close then they make liquid.
- If the particles have plenty of energy, then they can break free and zoom randomly around, and form a gas.'

Briefing for drama
Discuss safety; in particular, the need for students to stop as soon as they hear a clap and 'stop'. This may need some practise.

Warm up:
10-12 minutes
The following activities may require more space than fixed tables will allow. A 'typical' classroom can have the desks moved to the sides, or the class can move to a large space (gym, outside, multi-purpose room).

Invite students to form groups commensurate with the room size, and then form circles. They must attempt the following tasks without talking, or making a noise. If they do talk, they must stand out of the group. When each model is complete, the teacher deconstructs their behaviour, and praises their work, before continuing to the next warm-up

Group task	**Objective**
1/ ‘Create a square’	Group negotiation; Group discussion through non verbal modes
2/ ‘Create a star’	Group negotiation; Creativity; Increasing complexity
3/ ‘Create the most comfortable sofa in the world’	Introduce the explicit use of gesture, level, space, and repetition of patterns, describing how it creates meaning
4/ ‘Create the most uncomfortable sofa in the world’	Repeats above; emphasises creative use of modes; TE type group expression

Teacher-led demonstration
5 minutes

Topic	**Task**	**Discussion**	**Rationale**
Solid	Direct four or more volunteers to stand together and ‘shake’ lightly with their elbows touching.	Relate model to features of a solid.	Simple exercise allows confidence to build. Space/movement
Liquid	Direct four more volunteers to stand together and ‘dance’ around one another. The teacher may find modelling the dance useful.	Relate model to features of a liquid	Humour. Space is only slightly more enlarged
Gas	Direct four more volunteers, on the command of ‘go’ to move in a random fashion. This may be made more safe by indicating that the movement should be in exaggerated slow motion.	Relate model to features of a gas	Increased distance between particles. Random movement. Ask, ‘What is between the particles?’

The Chocolate Bar Story
3-4 minutes

Problem: Use the three groups created above to illustrate a story. Their preparation task is to devise BAPs actions for states of matter. At the end of preparations, groups simultaneously listen to 'The Chocolate Bar Story', and they must decide when to illustrate the story with their actions, and which state they should represent. The story: Once upon a time I bought a chocolate bar and walked to the park with it in my pocket. It was a hot summers day; when I grabbed the chocolate bar again it was just a bag of liquid. At that very moment, aliens came out of the sky and fired at my chocolate bar with a laser, vaporising it before my very eyes.		
Task		
	Discussion	Rationale
	What was good about that?	Open question to elicit personal responses
	What are particles?	Review
	What are their properties?	Review
	What does the model tell us about particles?	Personal response focussing on scientific features
	Do you know what diffusion is?	Diagnostic assessment

The Spy's Perfume
15-20 minutes

Problem: To be done in groups of four or five. Consider the following situation: There is a King or (other high status character) and a guard in his castle hall. At the far end a spy has snuck in, and opened a jar of poison perfume. What will happen? Using your knowledge of states of matter, devise two scenes: In the first: tell the story from our perspective; what we would see. In the second: show what we would see, and also simulate the perfume/gas particles at the same time.		
Task	Discussion	Rationale
5-10 minutes for preparation		Allow for student-centred response to the modelling.
10 minutes for forum: Show and discuss three groups	Praise performances. Mix the discussion with review, modelling, and new questions	Emphasis on 'science community' expressing and discussing
	What is between the	

	particles?	

Thought experiment
10-15 minutes

Same groups		
Task	Discussion	Rationale
Using your understanding of particle theory, show what happens when a cube of sugar is dropped in a glass of water, between the solid and the liquid, using your understanding of particles. Use a 3-D snapshot model of before during and after. You might dramatise it. Could we tell a story (of how the solid particles of sugar decided to mix with the water particles?)	What other ways might you represent this phenomena?	Emphasise metacognitive process; emphasise relational features between base and target analogies. Allow for student-centred response to the modelling.
Forum	Why is this a good model? What are the important features in the concept of dissolving?	Why were these good? What did they tell us about the way particles are in solids, liquids and gases?

Debriefing:
10-15 minutes
Review particles and states of matter. Review original bullet points.

Appendix 2

Show-Card, Concept Map and Corresponding Interview Section

The following show card (Figure 15.2) was cut up and presented to a student, who was asked to remove the terms that he did not know, to define the terms initially, and then link the terms into a semantic net (Figure 15.3). The transcript excerpt picks up at the point when he explains the links that he drew.

Solid	**Energy**	**Heat**
Liquid	**Dissolve**	**Diffusion**
Gas	**Particle**	**Atoms**

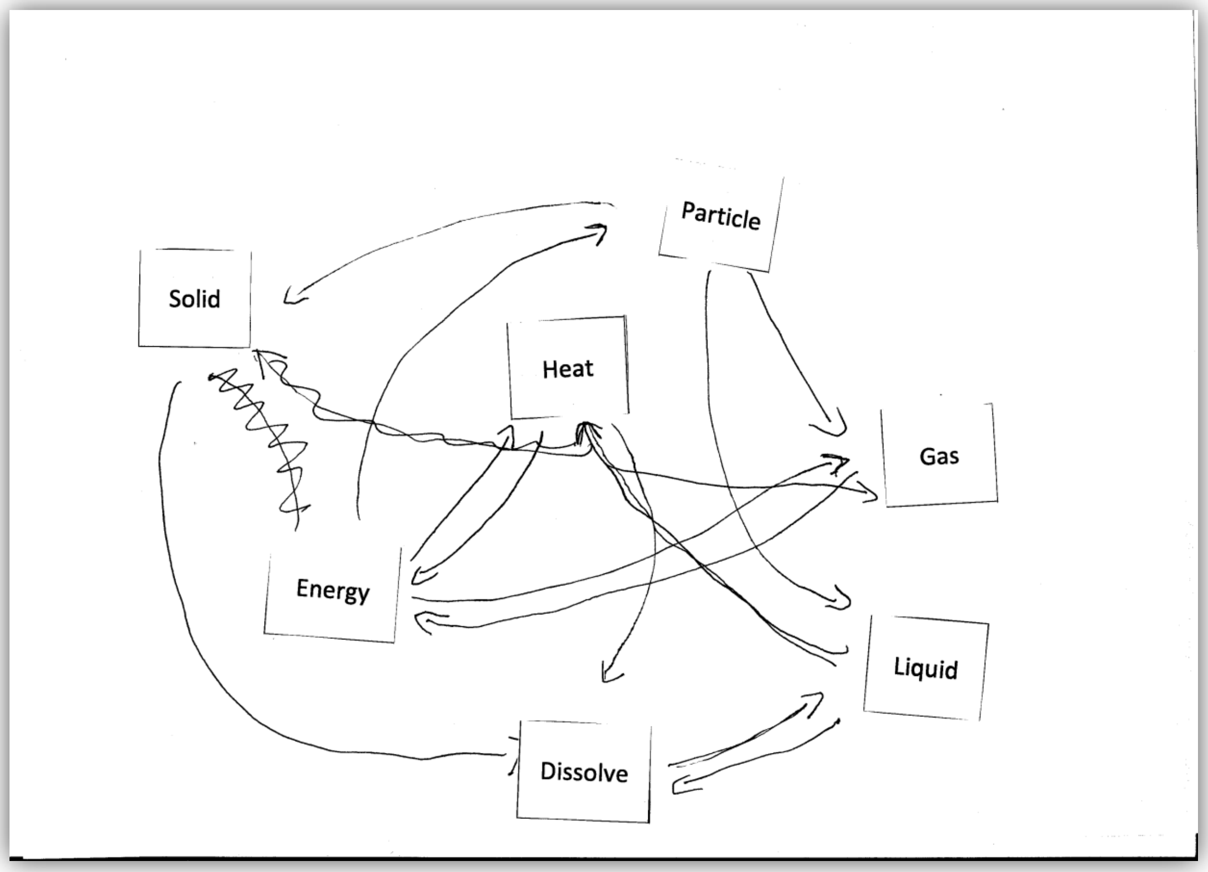

Figure 15.3: Showcard and concept map activity artefact and interview script

1. *Okay. I'm going to now give you some terms and you may or may not know any of these terms. If you don't know any of them at all just push them to the side. Please.*

2. Okay. I'm not sure with this.

3. *Okay, diffusion we moved off.*

4. I kind of know what atoms, but...

5. *Okay. Anything else?*

6. No.

7. *Okay. Well now I am going to ask you to take a shot, and say what you think they are.*

8. Dissolve, I think is where something is like, like say salt in water. It just like, goes away. It kind of melts into it.

9. *So it kind of melts into the water. Is that what you are saying?*

10. Yes. It kind of like, all the particles spread around in the water.

11. *Okay they spread it around in the water. So are their sort of particles in the liqui*d? *What would that look like with my magic goggles?*

12. Well there would be particles around in the liquid and there would be particles in the salt but then they like, mixed together to make one.

13. *So, like, what is, it's not particle in liquid. It is particles in particles?*

14. Yes.

15. *Okay. Choose another one.*

16. Solid.

17. *Go for it.*

18. It is normally hard and it can't change shape and it is normally coloured or opaque. And the particles are squashed together and it can’t. Like, the particles can't move very well.

19. *You said particles squashed together, pushing your fingers together like that (half open hands pushing together) so is that like squashed balloons?*

20. Kind of.

21. *How squashed together?*

22. Well they are just like next to each other. Like one is there and one is there.

23. *Okay.*

24. And if they are like, in rows, and stuff.

25. *Okay. So nice rows and so when you said squashed you meant just beside each other. Gas.*

26. Well gas, like, you can't really see it but you can touch it but you can't really feel anything there. And it is all around us and the particles are spread out and they then go everywhere.

27. *Okay. Have we done particles?*

28. No.

29. *Let's do particles.*

30. I'm not quite sure what they are but they are like quite tiny little things that believes in different.

31. *Tiny little things that live in different things.*

32. Yes.

33. *So when we talk about particles in solids and in the air, they are, you say that tiny little things that live in other things. Do you mean…*

34. They don't actually live.

35. *Oh, don't live.*

36. No they just there.

37. *Okay. Okay don't exist. Is this what you're saying, right? Heat?*

38. It is when things get hotter. Or something.

39. *And what does that do?*

40. It can make things change form, like from a solid two a liquid and then the liquid to a gas.

41. *Does it do anything to particles?*

42. Yeah, it gives them more energy and makes them spread around.

43. *Okay, and you segued nicely into energy. Describe the energy to me.*

44. Well, it is like, I am not quite sure. But it makes things move or something. It gives it heat or sound or light or something.

45. *Okay, well done. Very, very, good. Now I am going to ask you to do a concept map. Do you know what a concept map is? Have you ever heard of a spider diagram or a mind map?*

46. Kind of yes.

47. *Okay. Well it is that sort of thing, I will quickly do another one; I have got some terms, you have got these terms. And you don't need to use the terms you don't know. You might want to throw them in if you can sort of remember them, it is up to you. But (interruption) Okay, the sun, leaves, roots, and bark -- So these are terms that somebody just put down on the table for me. And I just plonk them down on the page and what I want to do is, I want to make connections, so then the sun gives energy to the leaves; this is a connection that I have to remember. The leaves provide food for the roots, but the roots provide water for the leaves, so I have to draw another arrow. Bark, how am I going to fit bark into here? The leaves provide food for the bark there's one. We might - If it was very complex and I needed to go around, I could draw an arrow around like that as well, yeah? Okay. For you, let's throw these on the paper in any way at all. Really, this is like closing one's eyes when putting them on paper. And you can draw arrows anywhere you want. Now do you want those [terms atom and diffusion] on? Go for it. You have got a minute and a half to try and link them up. And think of why you were a linking them because I will ask.*

48. [Long pause, then student completes the task]

49. *Okay let's do it.*

50. I have kind have drawn that like a joined arrow.

51. *A joined arrow from liquid to heat to a solid. Oh I see, okay so it links up again to solid. Excellent way would you like to start?*

52. The liquid, heat and solid, because then liquid gets heated and then; or no, the other way around;

53. *I see, okay, so when a liquid gets heated it…*

54. Can turn into a gas.

55. *Can turn into a gas. Gotcha. Now what?*

56. And then, energy is in particles and it's in heat too, and in gas.

57. *Now what?*

58. And then the particles in solids, gases, and liquids, and solids can dissolve.

59. *How?*

60. In liquid.

61. *How?*

62. Not all solids can. But, some.

63. *Okay. How?*

64. I am not quite sure about this.

65. *Okay.*

66. And then energy, heat and energy.

67. *You talked about energy and heat. From liquid to a gas. What are you going to say about energy?*

68. I was going to say energy has heat and heat has energy.

69. *Okay. They seem to be one and the same to you or one slightly different than the other?*

70. They are kind of the same.

End of section

Appendix 3

Magic Goggles

An episode from a pre-interview transcript for Jenny, chapter 8.0

1. *Okay, I am going to leap into the science bit key, I want you to pretend that we have magic goggles and we put them on, and these magic goggles when we turn them on, can allow us to see better than any microscope could ever allow us. And we have perfect vision to go to the tiniest little things. Now I would like you to tell me what we might see if we looked here (knocks on desk) with your magic goggles.*

2. I don't know, thousands of bacteria.

3. *And can you see anything deeper than that?*

4. I don't know really.

5. *There is no wrong answer, so. Let's look at those bacteria.*

6. All right.

7. *What do you see when you look at the bacteria? Or are they the smallest things that you could possibly see?*

8. Yeah.

9. *Excellent. And if I were to get a glass and put the liquid in it, and am going to look at that liquid. Would you see anything? Or? With magic goggles.*

10. Yeah, I think that you might because water is made up of oxygen hydrogen, so you can obviously see the particles.

11. *You would see the particles? So what would those particles look like, be doing?*

12. I don't know, because it's a liquid they will be spreading out and moving around so.

13. *Okay, spread out and moving around. I am trying to get* --

14. Diffusing.

15. *Diffusing, but I am trying to get a mental image. Is there, I mean if we use our, hands*

16. Yeah.

17. *And fists as particles.*

18. Yeah.

19. *What would they be doing? Can you show me with your fists?*

20. I think they would probably be banging into each other.

21. *Banging into each other.*

22. And then going (just use hands moving apart) --

23. *Yeah.*

24. A long way away

25. *Yeah.*

26. *Going away and coming back.*

27. Excellent. Then, I have got my goggles, and I look at this. Here to this sort of space here [gestured sphere] right inside it what might I see if I see anything?

28. I don't know because there is gas so I think that it is made up of oxygen so I think I'll see various particles from different oxygen, you know, different gases.

29. *And what does a particle look like, can you see particles? How does that work?*

30. I don't know with your magic goggles probably, but --

31. *Okay, so if we had these special magic goggles what would they look like in your mind's eye?*

32. Round, quite round.

33. *They have colour? No colour?*

34. Yeah I think they probably would have some colour like to define them, and make them look different.

Appendix 4

A pre-interview transcript with Aisha, from Case 4

1. *Okay, so what science have you done this year? Can you remember?*

2. We have done acids, we finished reproduction. Um.

3. *Did you do anything right at the beginning of the year? That you can remember?*

4. We've done forces as well.

5. *Okay. Do you remember something the teacher did with forces, with the homework when he was pushing a pram at one point?*

6. Yes, I think so.

7. *Can you tell me about it? What do you remember?*

8. Well, I can't remember.

9. *It was just something we were talking about right at the end and I thought oh I'll just ask you. Have you, let me start this, let me switch on my magic goggles. Magic goggles are my imaginary goggles; I can switch them on. You have got some too. Let's pretend that you have some on as well and there is a switch on the side, and I can see more microscopically then any microscope possibly can in the real world. I can see to the tiniest thing. Now, if I turn and look at this desk, what do I see, do you think? If I have it to the maximum setting. What is this desk made of?*

10. Trees?

11. *Trees. What am I looking at then?*

12. Wood.

13. *Wood. How, what does that would look like?*

14. Like bark.

15. *Okay. And what does that bark look like if I look closely at it what would I see?*

16. ...

17. Okay, and now I'm going to return from the desk and look up here,

and look about here (shaping a ball of air with my gestures) in this space that I'm making in my hands, what do I see?

18. *Concrete?*

19. No, here (reshapes the ball of air). In this little space here. Not up there, here. Right in front of your eyes, right between us. What is here?

20. *Air and oxygen.*

21. Air and oxygen. Can I see air and oxygen if I turn up the magnification of these googles?

22. *No you can't.*

23. So it's invisible even at high magnification?

24. *Yes.*

25. *Excellent. Now a glass of water, or the formaldehyde. Like those little guys are in the jar there. If I were to look, not at the little guys in the jars but at the liquid itself, could I, what would I see?*

26. Chemicals.

27. *Okay. How, how magnified am I looking to see chemicals? Can I see chemicals?*

28. While if you mic-, if you had a microscope, you'll see it really, you might be able to see it.

29. *Okay I'm trying to think of whether I should actually give some terms out yet, more just to set out a bit more, I think I'll put the terms out, and do you know what atoms and molecules are? Have you ever heard of atoms and molecules?*

30. I have heard of atoms.

31. *Okay. What are they?*

32. Ah, are they like tennis balls? Um.

33. *Interesting. Big or little?*

34. They are little.

35. *How little?*

36. Very small.

37. *So I could put an atom here? (Points to a 12 font printed b on a piece of paper).*

38. Yeah.

39. *So it's the size of a 'B'?*

40. It's smaller than that.

41. *Okay, so where would I see one? Or do I see those?*

42. In metal.

43. *Okay, so metal is an atom.*

44. I think so.

45. *Okay have you seen or heard of the word particles, or particle theory?*

46. Yes, I have heard of particles.

47. *Okay, so what would a particle be?*

48. It is a part of the chemical or, it can be in water as well.

49. *Okay and how small are particles then?*

50. Very, very, very small.

51. *Do I, can I see them. Do I need magnification?*

52. I don't think you can see them.

53. *You don't think I can see them. Can I, so I can't see them with magnification either?*

54. With a microscope you might be able to see them.

55. *What would they look like if I might see them?*

56. Well, there are different kinds of particles, there are some that are stuck together --

57. *Okay. Do you know what they are called?*

58. Solid.

59. *Okay, that was good. Go on.*

60. Some go everywhere in the bottle.

61. *Right.*

62. And, um-

63. *What bottle?*

64. Like, different jars or-

65. *So that's where we hold atoms?*

66. Yes.

67. *Okay.*

68. And so for example, water, it's got particles in the jar.

69. *It's got particles in water.*

70. It's a liquid it can mould in any shape.

71. *In any shape. It, does a solid have particles?*

72. Silence, yeah.

73. *So wood (knocks desk). Does that have particles?*

74. I'm not sure.

75. *Well, what are you thinking of when you were thinking of a solid?*

76. Rock.

77. *Rock, okay.*

78. Juice and gas.

79. *Gas has particles? Does it?*

80. Yeah.

81. *I think that's a good time to segue into our next task. Well done by the way. Now the sort of things that you were talking about just now, did you study those in school this year?*

82. Yeah.

83. *Or a last year? When did you do that?*

84. I think it was January or last year.

85. *Okay. These are terms that you may or may not know. You may know all of them or you may know none of them and that's okay either way. But what I'm going to ask you to do, with the ones that you know, can you please tell me what they are.*

86. Okay,

87. *Gas.*

88. If, like, I am, well sometimes with gas you can see them.

89. *Okay.*

90. Sometimes you can't.

91. *Okay, is it made of anything?*

92. Well, like I said, I think it is made out of water.

93. *Okay.*

94. Really, really, hot.

95. *Okay.*

96. And.

97. *You said there were particles in gas.*

98. Yes. There are.

99. *Can you see these particles?*

100. I'm not sure if you can.

101. *Let's move to heat.*

102. Heat, heat is very hot and there are radiators and like fire, temperature, Celsius.

103. *Okay, liquid?*

104. Liquid; there are particles in liquid all jumbled up not in one place.

105. *Okay, you are saying it's all jumbled up and not in one place. That implies that there is something between them?*

106. No, they are like, like well for example you have a glass of water, they are like everywhere in the glass of water not just one place.

107. *Okay, so they're everywhere in the water in the glass of water?*

108. Yes.

109. *Energy?*

110. Energy electronic and energy that is in a computer. There is like energy and batteries and wires.

111. *Its heat, energy? Can energy give you heat?*

112. Yes. I think energy can be turned into heat because the water was something that can get very hot.

113. *Right, diffusion?*

114. I don't know.

115. *Leave it. Particles?*

116. Well I said that already, it's like --

117. *Quickly tell me.*

118. It's like a gas liquid and solid.

119. *Okay, but not all solids? Or all solids? Because you have a question about it.*

120. I'm not sure that it is in all solids.

121. *Okay, dissolve?*

122. Dissolve, like I've done experiments with sugar and salt. And you get the water, a glass of water halfway and you, once you've finished you put it on, and it's not like really gone it's still there but in little particles.

123. *Okay. So particles again.*

124. Yes.

125. *Are these the same particles that are in air? In gas you said.*

126. I think so.

127. *Okay, not sure? Think so?*

128. Not sure.

129. *Not sure. Mixture.*

130. Mixture. Like for example like a cake. Yeah. It's like, you put the ingredients in, you mix it then you have to bake it. It's a mixture, in another way it's like, I can't remember

131. *What other way then? Maybe I can help you. You said the other way.*

132. You'll make, like you are mixing ph with like vinegar.

133. *Okay. And solid?*

134. Solid is like, it also has particles inside. It's really rock hard. It's really hard.

135. *A solid.*

136. Yes.

137. *Okay, so that's a solid, this glue stick.*

138. Yes. But water is a solid and liquid because when you melt ice it turns into a liquid if you freeze on its solid.

139. *So do some solids not turn into liquids?*

140. Yes.

141. *Okay, I'm trying to think. Can gases turn into liquids?*

142. Gas I think so.

143. *So if they can turns into liquids can they turn into solids?*

144. I don't think so.

145. *Can solids turn into gas?*

146. I'm not sure.

147. *Okay, good answer. Now what I'm going to ask you to do is I would like to spend two minutes putting those onto here, the ones that you know, and drawing lines where you think they are connected somehow, so I will quickly discuss this in terms of trees, and leaves of the Sun and roots. And of course I do have lots of other terms as well, park, woodland animals, anything to do with trees and the first line might try is from the Sun to the leaves. And I would, would then need*

to say why that line was drawn there, so I would say it gives energy to the leaves, and then I could draw one from the leads to the roots, and I could say the roots give water to the leaves. But I can also say the leaves create food for the roots to grow. So I, link to them up. Now if I had other things around, these are other terms, I could actually draw lines flaking off like that, or going all the way around, if I felt I needed to so you don't need to be constrained just to draw one line here and one-liner. Do you have an idea of what it is I'd like you to do?

148. Yes.

149. *Just like the terms that you think have something to do with each other. And you've got a minute and a half to do that. (Long pause) Okay, let's take a look at this you've linked up particle to solid. Why?*

150. Well particle is solid.

151. *Okay.*

152. And then particles like air and other things, but in a solid they are stuck together.

153. *Okay, particles are stuck together. What is, do they, do they look like something? Could you describe what they might look like?*

154. Well, they look small circles stuck together.

155. *Okay, small circles stuck together. So if I used my fists, and so with small circles do you mean like that?*

156. Yes.

157. Do they move or are they still?

158. They are still.

159. *Okay. So they are stuck together like that, but there are just a couple of them? Or are there many?*

160. There are loads of them.

161. *Okay. Solid to liquid you have?*

162. Well, like, it starts as a solid but when you melt it it's a liquid.

163. *Okay. Does it have particles in it?*

164. Yes.

165. *Do they, and are they stuck together?*

166. Yes they are stuck together but then as a liquid, when it goes over to liquid it starts spreading out and they are not together any more.

167. *They are not together any more. Interesting. And you had your fists sort of spreading out from being next to each other.*

168. Yes, and you need heat, because when you like boil a liquid it turns into a gas.

169. *You have gas attached to the heat. Okay.*

170. Yes.

171. *And if we could look at these particles which are our fists again, this model. What happens to the particles on a liquid?*

172. Well from the liquid, it goes like that all jumbled up --

173. *Jumbled up apart again* --

174. And boil it. It starts going up and then in the air.

175. *So you've opened your hands and floated them upwards.*

176. Yes.

177. *So they sort of turn into something else when they float up? Are they still little circles or aren't they?*

178. I am not sure.

179. *Okay. That's interesting. So there is, there is a difference between them. Like in a solid and a gas though.*

180. Yes.

181. *That is really interesting. Okay. Now I am going to ask you to do a drawing for me if you do not mind. This drawing is before, middle and after a sugar cube dissolving in water so if you could draw, you don't need to draw a glass or stir stick or anything; we just need to know that there is a line for the water. But what happens? At the very beginning they haven't touched. It's a sugar cube and it's just about to be put in. In the second one it has been put to him. In the third, it's after it's been sitting there for quite a while, after it's been stirred. Okay? (Long pause) okay, tell me.*

182. Well, first you put the sugar and ice cube in the water.

183. *Okay,*

184. And then when you, it’s at the bottom, then you start to mix it.

185. *Okay, did you say sugar and an ice cube?*

186. I meant sugar.

187. *Okay. I just wanted to make sure. And you had three chunks; so was that three sugar cubes?*

188. Yes.

189. *Okay. Oh and you have little dots on the sugar what is that to symbolise?*

190. It's sugar.

191. *Okay, bits of sugar?*

192. Yes bits of sugar.

193. *Okay brilliant.*

194. And then when you mix it together slowly it will start to dissolve.

195. *All right. And you even have little circles on the bottom of the water.*

196. Yes.

197. *Have they mixed, sitting, it looks like it's sitting on the bottom of the water.*

198. Well, they mixed it and it's like you can't really see it but if you look closely through a microscope you will see the particles but in between the sugar cubes in the sugar.

199. *The particles in between the sugar cube and the sugar.*

200. In between the sugar.

201. *In between the sugar.*

202. Yes.

203. *The particles? Are they little bits?*

204. The particles are in between the sugar. Teeny bits of sugar.

205. *Okay. Teeny bits of sugar.*

206. And so you won't actually see it from, like pretend this is the cup with sugar in, you can't really see it because it has-

207. *So this is a model is it?*

208. Yes.

209. *It's not real life. That's fine that's cool. So you, so you can say that what I have is correct, so water particles between the sugar bits.*

210. Yes.

211. *Okay. And the sugar; how big are the sugar bits?*

212. Like, really, really small.

213. *Okay. Are they as small as the particles, or are the particles smaller or bigger?*

214. I think the particles are smaller than them.

215. *Okay. Can I ask you a question about what would happen if you had a bottle of gas or perfume, in a class, and you lifted the lid, what would happen?*

216. In --

217. *With a bottle of perfume, and you lift the lid in the classroom, and it's very pungent very smelly. What would happen in that classroom?*

218. Well, if it's very strong, a strong scent, it will spread into the air and a lot of people will smell it.

219. *Okay. And why does it go through the air?*

220. Well, like there are particles in perfume.

221. *Okay.*

222. And I think everywhere there is scent the smell goes up.

223. *Why?*

224. I'm not sure.

225. *Okay, but you are saying it does move out, does go to every corner in the classroom or does it stay in a particular place?*

226. Well goes into the corners and well and everywhere.

227. *And everywhere.*

228. Yes.

229. *Okay. (Interruption) Have you used role-play or drama in your lessons before?*

230. *Yes.*

231. *In science?*

232. Yes.

233. *Go for it.*

234. Well, we'd done this pram one. When this girl called Lexie, she was pushing a pram slowly, and the teacher explained a force, like upthrust and friction,

235. *Okay, and who was in role as the person pushing the pram?*

236. Well she was a mum.

237. *Okay, so you were talking about this person, were they drawn on the board?*

238. Yes.

239. *Okay, and do you usually work in groups or pairs or alone in your class?*

240. Well sometimes we do experiments we get into groups or pairs of three or four.

241. *Groups of four. Great, brilliant. Excellent, well we are finished, thank you very much.*

Appendix 5

A post interview including stimulated recall with John, from chapter 10.0

1. *A very simple question at the beginning: what did you think of the lesson yesterday?*

2. Yesterday, yesterday was different.

3. *Yes.*

4. I don't think I have had an experience like that before.

5. *Different, was it painful to get through, was it easy to get through?*

6. At the start, I looked at my watch, and you know, it went, you know how lessons, they either go quickly or that they go, really, they drag on a bit.

7. *Yeah.*

8. It was, it was, it went quite quickly.

9. *Right.*

10. Because we spent through, and I looked at my watch and of the first-half, period, had already gone, and then it was, it was good. I thought, you know --

11. *So, last lesson of the day went quickly* --

12. Yeah.

13. *Not too bad.*

14. Yes, I sometimes have French as the last lesson which drags on a long time.

15. *Okay. Now, within that, can you tell me what happened in the lesson?*

16. Okay, do you want me to recall what happened?

17. *Yeah. See if you can.*

18. Well we walked in, and then sat down and you then you talked to us, you asked us what was the structure of an atom, and what a particle was, also what we think a solution is, whatever those things, you asked me: you asked you you you asked the class, you asked questions that were on the, you asked the questions that you asked me the other day.

19. *Yeah.*

20. You asked, but in a different form. And then you had that come you have the role-play of course, what was that about: solutions and how particles are broken up.

21. *Yeah.*

22. And --

23. *Good.*

24. I think that's about it, oh I knew there was something else, but I think that`s about it.

25. What was your most memorable moment? Now, it can be good or bad, just a something that sticks in your mind.

26. Oh something that sticks in my mind most was the sofa one.

27. *Which sofa one?*

28. Well both of them really. It was the abstract, you wouldn't. You walk into a Chemistry lesson then normally you sit down at a desk and you get the handed a piece of paper and then to come into a chemistry lesson and be asked to make a sofa out of, physically out of bodies, you can see what I mean --

29. *Yes, yes.*

30. It is a, new experience.

31. *That is a good way of putting it. Okay, now I am going ask you some things kind of again. The first is with a magic goggles. I put them on crank them up and we'll look here (knocks on desk). What would I see?*

32. You would see particles.

33. *Okay.*

34. Which, while what I said yesterday.

35. *Yes.*

36. Same as what I said, I think what I said last time. Layered, of course, very you know, a solid structure, very little movement.

37. *Okay.*

38. You know, and they are all attracted to each other.

39. *And they are all attracted to each other. Liquid. Look into my cup of tea.*

40. Okay.

41. *And what do you see with your magic goggles?*

42. I see much the same as a solid, however the layers are sliding over each other.

43. *Okay.*

44. There is movement, there is much more movements and it is looser, if you can understand, there is still attraction --

45. *There is still attraction.*

46. But it is is not as solid than solid, tight than solid, it has got a bit more freedom.

47. *Yeah, and I am just going to save the recorder that you have got, that you read in your hands over top of each other sliding, you put your fingers together for --*

48. Attraction.

49. *For attraction so they are, so this is what, like when you do the church and steeple thing, you put your fists together,--*

50. As ever solid. Yeah you know –

51. *Yeah but your fists together sort of a GI Joe grip, um, except together. Gas. Look up here and what do you see?*

52. It is different from liquid and solid.

53. *Okay.*

54. The particles are spread out.

55. *Okay.*

56. There there`s slight attraction. You know, but but they bounce off each other if you see what I mean.

57. *Okay.*

58. But they are very very spread out and of course what I mean by there`s little to no attraction I suppose you could say. And ah, it`s not, it doesn`t

have any structure.

59. *What`s between them?*

60. I don`t know if this is right but would you say a vacuum? I would say a vacuum.

61. *Okay. Um, now I am going to ask you to, no, take that take a look at those and I would like you to define what you can of those particular terms.*

62. I don`t mean to, what, what does that say?

63. *Dipole.*

64. Dipole, okay. So you want me to go through and all the-

65. *If you could define them.*

66. Okay. A dipole molecule, I will start with that one. I think it`s a molecule that has two poles so it has two poles for attraction.

67. *Nice.*

68. So you went over this yesterday with the water molecule.

69. *Okay.*

70. I think this is what applies to it. You said, um, oxygen two hydrogen, the hydrogens of course are oh, the hydroogens are negative.

71. *Okay.*

72. The hydrogens the hydrogens are the positives, the oxygens are negative. So I think yeah has polar attraction. Dipole molecule.

73. *Okay.*

74. A solution is a solute dissolved in a solvent.

75. *Okay.*

76. Insoluble is a substance that cannot be dissolved in a, in a, it's a solute that can`t be dissolved in a solvent. A solute is a substance that can be dissolved in a, no. A solute is something that dissolves in a solvent. Whether it dissolves or not is is you know. A solvent is something that dissolves a solute.

77. *Okay.*

78. For example, water is a solvent or ah, it's the only one I can think of at the

moment. Atom is a building block and its.

79. *Atom is a building block.*

80. Well I suppose it is, it is the simplest form of life.

81. *Like Lego. It is the simplest form of life.*

82. Well

83. *An atom is alive.*

84. Well what I am trying to say is this, the simplest form of, don`t say, I would get confused here but, if you look very closely at an atom there`s not much else that is smaller than it.

85. *Okay.*

86. I mean, I mean I am sure there are things like the stuff that makes up an atom.

87. *Okay.*

88. But it is the basic thing that everything is made out of.

89. *Gotcha.*

90. So you have an element which is made up of atoms. And so on and so forth. Particle is a, Something that can`t be seen by the naked eye, is something that came out of yesterday. That`s what we said isn`t it? It could include atoms, small molecules or compounds.

91. *You can`t see a cell with the naked eye. Could that be a particle?*

92. I don`t think it.

93. *Okay.*

94. Wait actually maybe it can.

95. *Okay.*

96. Your body is made up.

97. Within the context of the class would a cell have been a particle.

98. *Within the context of our class.*

99. That class yesterday. Would the cell have been a particle?

100. *Do you mean the whole class together or-*

101. As in the lesson?

102. *The lesson,*

103. I don`t think it would, I think you were talking about smallness and stuff.

104. *Okay,*

105. Okay, particle theory. Aah,. One I don`t know.. I imagine that particle theory is the way that things are structured. How they fit together.

106. *Okay. What do you mean, like the way a house is structured and it fits together with nails?*

107. Well no I suppose. I suppose you could apply it to a house.

108. *Okay.*

109. If you wanted to you could take, ah, you know, so the human, human, what`s the word you used, a human analogy.

110. *Analogy,*

111. Yes. Human analogy. Well I suppose you could do it with anything.

112. *So particle theory is a human analogy?*

113. No, no, no, no, but you could take particle theory.

114. *right.*

115. And you cold apply it in any form or shape you wanted to.

116. *Okay. So what is particle theory?*

117. Um, ha ha, particle theory is I think. I can`t talk my way out of this one. Particle theory is the way that particles are attracted and how they form solids and different forms of state.

118. *Okay.*

119. Okay.

120. You are telling me that`s fine.

121. *I am not telling you, I am just saying okay.*

122. Okay.

123. But I am going to do that for every single thing you say so don`t read anything into what I am saying.

124. I won't, what's next, saturated is the only thing, that's when a solution can't, when a solvent can't take any more solute. When it has reached its saturation point.

125. *Okay, and does anything happen at that point?*

126. I would imagine the the rest of the solute stays, if it's a solid it just stays a solid, I think, can I give you an example.

127. *Yes sure.*

128. Of what I think. If you take sugar and water like you said yesterday.

129. *Yes.*

130. When you put too much sugar in, the water cannot handle the sugar anymore, cannot dissolve it, the sugar sinks to the bottom.

131. *Okay.*

132. That`s when you know that it has reached the saturation point. When you can't see the sugar dissolving anymore.

133. *Now I am going to ask you to link those up if you could. Do you remember the concept map?*

134. Oh brilliant.

135. *And so if I could give you a minute and a pen (set up and long pause) Talk me through it.*

136. Okay, um, solutes and solvents. Solute goes into a solvent. Solvent dissolves the solute. That`s my…arrow, okay?

137. *Okay.*

138. Solutes can sometimes be insoluble.

139. *Yeah.*

140. Solutes and solvents, solutes and solvents are made up of particles.

141. *Okay.*

142. That`s what I think. Atoms, particles can include atoms. Some. A dipole molecule. Solvents are sometimes made up of dipole molecules such as water. Dipole molecules are made up of different types of atoms, so hydrogen and oxygen.

143. *Okay.*

144. Particle theory, I think it is a theory of the way aa solution is made.

145. *Okay*

146. And solutions can become saturated.

147. *Nice, very good. Okay now I am going to ask you to take a wee look at a video.*

148. Okay.

149. *Now it will be about a minute. And I am going to ask you just to take a look at the behaviour of your classmates. Think about how you felt, think about the sorts of things you were thinking when you were doing this activity. Okay?*

150. (watch video)

151. *Talk me through that. Which group were you in?*

152. The far.

153. *The far-*

154. If you are facing towards the, towards the whiteboard, I am on the right.

155. *So you were on the right hand side, and who did you feel, did you feel there were leaders and supporters or you all led and supported.*

156. It, it was weird, because normally when you when you take an activity, say, this may sound a bit weird, later on today in CCF I found out we are doing things called command tasks.

157. *Right.*

158. Which is where you have someone leading the group, and its you know they have different techniques. I thought, to be honest, I thought it would be anarchy when we went, I thought everyone would try to say, you know, oh do it this way, do it that way. But actually without the voices, it kind of, we kind of fell into a natural. I mean, it was kind of order but in, I think everyone, I think it was in the fact we knew each other that also counts.

159. *Right.*

160. But, in forming the sofa.

161. *Yes.*

162. I think your instructions helped, because you said, use the essence of sofa, I mean we could have done you know some sort of weird object on the floor and we could have passed it off as a sofa, but I think the fact that we took the sofa idea and we tried to imply, I think we saw a good idea, because we watched what everyone else did and then we thought we will do that. There did seem to be leaders in the group. So if you play it back. Can, can, I show you the.

163. *Sure, yes.*

164. Great, if we play it back, there are certain people in the group…Yeah, about, about, yeah about there. Maybe fast forward to a later bit, yeah. There that's fine, okay. (video playing) So if you um, there`s Ben.

165. *Right.*

166. And then there`s Cam, and then me trying to try and organise it.

167. *Yes,*

168. If you see what I mean.

169. *Yes.*

170. But because we can see what he wants to do, and we see the, you know we see the-

171. *Yeah.*

172. You know, because we do that, and then with Ted he has a good idea to try to put spikes in so we try to implicate that idea as well.

173. *Good.*

174. And at the same time we are trying to you know, get this whole thing going, but there did seem to be leaders as such who try to who tried to help us to get where we needed to . Stood back for a bit. Looked at what we did.

175. *Yeah.*

176. But we did take on other, they did take on other people's ideas so I think without voices, natural leaders do emerge.

177. *Okay, that`s interesting so that brings up a question of what does voice*

do?

178. I don`t know because with voice-

179. *For example there was a an actually lets look at the next video because it will bring up just this question. Okay so this, this is an example from a little further on and it is an example of a performance. I would like you to think of the preparation stage as well. That lead to these tasks. Just a moment.*

180. [video playing]

181. Oh there was a camera there as well. Okay, fine.

182. *Okay. So can you think of your group .*

183. Yeah.

184. *First of all in that situation as an audience member, how did it work for you? Were they entertaining or, was there learning in there? Did you find the group worked well with each other, or didn't work well with each other?*

185. I suppose in that group you had people who, ah, are very creative.

186. *Right.*

187. And they could apply science, in terms of the cold water hot water, how things dissolve, to everyday items. I suppose they took; if you compare it to my group I suppose.

188. *Yeah.*

189. My group wasn`t very creative in hindsight, ah we.

190. *Yes they were.*

191. You know, we took everything very, we took everything down to the basics. You know we didn`t add on it, we didn`t, it wasn't 'as entertaining as this was.

192. *Using the language, okay.*

193. Because they, you know they used, they took something that, you know cocoa pops I suppose.

194. *Right.*

195. Its an example, you know, they decided what would hook a child in, whereas we only thought, we thought we would sell it, in in I suppose by

using; what was the question, sorry?

196. *The question is this vague sort; was, did you feel there was learning not learning entertaining not entertaining, how did the group feel, how did the experience feel to you?*

197. I think by making it more entertaining they ah, they got the message across better,

198. *Okay,*

199. If you see what I mean.

200. *Okay.*

201. Cause people are more willing I suppose, to watch something that they find funny.

202. *What did you find, ah, to do with class attention? Do you feel like everybody was focussed on what was going on?*

203. I think people were more focussed on this group, because their, their group was different.

204. *So do you feel that, you seem to be implying that they were less focussed on your group.*

205. No. it wasn`t, what I was trying to say was um. I suppose you could say that. They were still focussed on us but they they were more intent on watching this one because it was original.

206. *Okay.*

207. If you see what I mean.

208. *Okay.Yep.*

209. Because the group after us they had, they pretty much had the same thing as us.

210. *In preparation. In the preparation for your model there, were there leaders and supporters. Was there one person who had the grand narrative, or did everybody help?*

211. We helped but it was more, it was more disorganised than than the sofa for example.

212. Right.

213. With, I don`t know with the voices it seemed everyone it seemed that

everyone wanted to use their voice and say well let`s do it this way. I mean although, we, I suppose we did use one persons idea.

214. *Right.*

215. We didn't really talk about…it was more of a, we took this persons idea then we thought (interruption).

216. *In your group another question I wanted to ask did you discuss, or did you use the human analogy or did you discuss the human analogy and a bit of the science that you were learning or a mix.*

217. It was a mix. Actually to be honest it was mainly scientific because I suppose in this group they had more of a human take on it.

218. *Right.*

219. Whereas our group, I think in making it more basic, I think this may be wrong but I think in making it more basic we were tending to look more at the science side.

220. *Yes, yes.*

221. Because by looking more at the science of it, we it doesn't, we weren't relating it, we weren't it's not that we weren't relating it enough to the human, you know the human way of thinking.

222. *Yeah.*

223. We were, um-

224. *But was there a key feature or two key features or-*

225. The first key feature was how to separate the two, what were the two brothers in this case.

226. *Yeah.*

227. And why, you know, we just, we ripped them apart, you know, how we thought, that would happen, you know how we thought water would rip sugar apart, break the bonds, but, whereas in the you know in the video, they didn't you know they let the water break apart by themselves.

228. *Did you notice that, or not.*

229. I think, you um, you asked them to redo it. Well you didn't, I suppose you asked them to say what would happen in cold water what would happen in hot water. And only then did you, did they go and they took the water.

230. *Right. Right. So was that a useful addition or not a useful addition?*

231. That was definitely a useful addition.

232. *Okay.*

233. But when you looked at. When you took them and you asked them to display what was the difference between cold and hot water were I think it really sunk into the class as to what the difference were,

234. *Right.*

235. Because I suppose before when you asked them about cold and hot water I don’t think. I mean I personally, I didn’t know how. How sugar was dissolved. I didn’t know was there attraction or anything. By by using, by giving the water more energy it helped show the class what was really going on.

236. *Right, good stuff, good answers. Now I am going to ask you to do a drawing. And I am going to ask you to draw a before middle and after of what happens when gas in a water solution is heated up. So we have the gas in solution.*

237. Okay (long pause)

238. *Okay talk me through it.*

239. Okay, fine. Of course you got your cold water, yeah. And your gas in solution.

240. *So we, explain the dots, you have got two different sizes of things.*

241. I have got two different sizes to explain the ah, you know, to to highlight the difference between the molecules.

242. *Excellent yeah.*

243. So you got one which is ah, which is a circles.

244. *Right.*

245. With ah, with lines in them.

246. *Okay*

247. And then you have got the water which is just plain dots.

248. *Brilliant*

249. There is more water than gas. Is my opinion.

250. *Nice.*

251. Here`s cold water.

252. *Yeah.*

253. There`s very little movement.

254. *Okay.*

255. When you heat it up a bit.

256. *Yeah.*

257. Some of the gas has enough energy to escape.

258. *Right.*

259. As … and there is more movement within the molecules, being a gas.

260. *Right.*

261. And getting that energy from the heat. And then the last frame.

262. *Yeah.*

263. More of the gas has got enough, enough, you know, energy to escape, because it continues being heated. The water of course still has more energy.

264. *Yes.*

265. But less I suppose than the gas, you know …to let the gas escape.

266. *Okay.*

267. And sometimes you know there`s at least one gas molecule in here there`s some, it depends how much energy it has, I mean if you continue, you kept on heating it then I suppose all the gas would have gone.

268. *Okay.*

269. But you know at this, in this particular frame it is still being heated.

270. *You have got arrows pointing straight up, does that-*

271. Oh right that`s-

272. *Do those move in that direction?*

273. Uh, I suppose it, that moves in whichever direction to escape I suppose if you, I don't know what I want to say. Do you know if you have-

274. *Whichever direction to escape. Is that implying that it has a desire to escape or an ability to find its way or not?*

275. Okay, so less dense than water so it goes to the top. I don't know, I suppose if you had like a, in my experience, if you had a fizzy drink,

276. *Okay.*

277. The gas will go, rise to escape.

278. *Yeah,*

279. And so in bubble form I suppose it is lighter than the water.

280. *How big is this in comparison? How big is this area that you have shown me here in relation to the glass of coke for example. Is it, can you see this area?*

281. No. It is not, oh I suppose, take your take your cup tea, so say it has got coke in it yeah.

282. *Okay.*

283. You wouldn't be able to see the area with your eyes. I suppose it would be I suppose in relation-

284. *And you said these were less, these particles were less dense than these particles or were you saying that gas is less dense than the water?*

285. No these particular particles would be less dense than-

286. *The particles are less dense.*

287. Yeah.

288. *Okay.*

289. I suppose I mean that's the only, the only logical reason I can think.

290. *No that's interesting*

291. The rest might sink to the bottom.

292. *Nice. Um, and so they take you to the area above. If this is a closed system, as if I have got a square above here.*

293. Okay, do you want to draw it on? If you want.

294. *Yes, you do it. And I would like to see what is happening above that.*

295. Do you want an extra one on the bottom then?

296. *Just draw it above here.*

297. Okay, so it is closed, yeah?

298. *Yeah, it is a closed system. Yes so it is like the bottle of coke that you have opened up and then closed.*

299. In fact, this is a much smaller space than that isn`t it, we are looking at the particles.

300. *The gas will collect at the top.*

301. The gas will collect at the top.

302. *Yes.*

303. The top of this space or the top of the whole square.

304. *If that is the top of the water the gas would collect in the enclosed space above the water level.*

305. Above the water level.

306. *Yeah.*

307. Now is that gas moving fast or slow?

308. *It will be moving fast because it is under more pressure.*

309. Okay. So what happens when those fast gas particles are close to this?

310. *It will want to bring the water level down because it will be more pressure on the water.*

311. Okay there would be more pressure on the water.

312. *Interesting, thank you very much. Um, you have, already at the beginning, one of these questions. In which does gas dissolve more, in hot or cold water. We are doing that now. Would you use tasks like this as a teacher? As a chemistry teacher.*

313. As in tasks like the drawing.

314. *As in like the role play. That were done in the lesson yesterday.*

315. Okay, um. Occasionally.

316. *Okay, and why?*

317. Because, kinaesthetic

318. *Okay.*

319. You are trying to teach kinaesthetic.

320. *Okay.*

321. Is that right?

322. *I am not responding.*

323. Oh you are not allowed to say that?

324. *I am not going to respond. You can assume that and –*

325. So I assume that; from my experience people learn differently.

326. *Okay.*

327. Take myself for example. I generally don’t learn by doing things. Oh I suppose I can, because, if you take a computer game for example.

328. *Okay*

329. I don`t bother reading the manual, I just do it and see what happens. You know, learn from my mistakes. That`s doing, but generally if I have a test, I won`t do actions to it, right I suppose. I will look at the book and I will try and take in as much as possible. And I will, maybe I might write it down and then I will stare at the book a bit longer and see how much I get it. So, um, it would be good to do some of these methods such as role play on occasion.

330. Yeah.

331. To suit those people who are more adept at learning this way.

332. *Yep.*

333. How. Of if you do it constantly you are neglecting the people who don’t learn that way. Who learn it through reading a book.

334. *Yeah.*

335. If you get my.

336. *Yeah, that’s very good. And then any final thoughts about it?*

337. Um, yeah, I think I think if you did finally publish a book on it, I think it would be useful for those, for science lessons because it adds it adds. A different, a different view, because it lets people take sciences from a different from a different perspective.

338. *Yeah, yeah.*

339. Because adding it yeah, in a human, in a human you know way of thought. In a human background I suppose let's people see it in a different light. Because I suppose that why I didn't know very much. I mean I knew I knew basic solutions but now I can, I can see how it works and how because, I could see other people acting it out. But you can't see this in the microscope, well I suppose you can draw figures, but yeah I suppose that by doing it, it helped me understand.

340. *Very good. Good stuff.*

Appendix 6

A Delayed Stage Transcript, with Kelvin from chapter 3.0

1. *Can I ask you, what have you, do you remember the lesson that I was here for?*

2. Was that the lesson we did about covalent bonding... no, displacement reactions. Wasn't it?

3. *Can you tell me a bit about it? What are the things that you remember?*

4. There is a compound and an element and they react and the element by itself takes the place of one of the elements in the compound, because it is more reactive.

5. *Okay.*

6. And it combines with the elements that it displaced by itself.

7. *And you remember any images from the lesson? Itself?*

8. I remember when we used the performance thing. When a few groups performed their dash.

9. *Okay. At the back of the class?*

10. Yes.

11. *Excellent. Have you done any studying of that topic, over the last few months?*

12. Chemistry?

13. Not that particular topic. The stuff we were doing. Well, stuff that we were working on.

14. *On displacement reactions?*

15. Yes, all that stuff.

16. Well, recently we have been doing about acids and alkalis and salts.

17. *Okay.*

18. But we worked, before that we were doing a little more on that topic.

19. *Okay. Do you remember what sort of things you were doing on it?*

20. To me, what we have been doing is, there is that topic and then we started a new one which is quite similar.

21. *Okay.*

22. And so I'm not really sure during which lessons one start and the other one started.

23. *Gotcha. The quite similar one, was that the acids or was it something that was --*

24. It was before that.

25. *It was before that. Do, do you remember any terms that you were learning in at? At all? Just so that I can get a flavour of what it was.*

26. Well we were doing covalent bond is and then all the different types of bonds: ionic and that sort of thing.

27. *That sort of thing. That's kind of what I was asking about. Let's see from the lesson itself if you could remember back that far; do you have a memorable moment of that lesson.*

28. I remember when we were making up performance thing.

29. *Okay.*

30. And how we were going to show what was what.

31. *Who was the leader, was there, was everybody the leader in that group-*

32. We were all contributing differently.

33. *Okay. A science question here: do you know what an atom is? Could you give me a definition of an atom?*

34. It's something, part of a, an atom, or just forgotten.

35. *That's okay.*

36. It's got a nucleus made up of protons and neutrons with electrons in Shell's dash

37. *Okay.*

38. And in the first show there is to electrons that can fit and the

second 8 and in the third one 8.

39. *Nice. Can you see an atom?*

40. Not not like this.

41. *Why is that?*

42. Because they are so small.

43. *Okay. How small?*

44. --

45. *Can we see one with a magnifying glass?*

46. I don't think so.

47. *What would we need?*

48. Not not not --

49. *Can we see them?*

50. Maybe if you zoom in and lots and lots and lots.

51. *Okay. So if we could see an atom, could we see an atom? Or is it something that is unsayable?*

52. I am not entirely sure. I think if you zoomed in very very far then you could, but --

53. *Okay.*

54. Yeah,

55. *What would it look like?*

56. Well there are to be --

57. Is it a colour, is it nothing?

58. *I'm not sure.*

59. Okay. I'm just pushing you on it to see sort of where the edges.

60. *Well done. For keeping up with me on that one. What do you know about halogens?*

61. Oh they are the group seven, I think.

62. *Yeah.*

63. Chlorine fluorine, iodine, and bromine.

64. *Brilliant. Is there anything special about those?*

65. I know they are all very reactive.

66. *Okay.*

67. And they get more reactive as they go, know they get less reactive as they go down the group.

68. *Okay, why is that?*

69. Because, I've forgotten.

70. *That's okay, that was very good; that was very good.*

71. (Interruption)

72. *Okay, what I'm going to do now, his I'm going to give you some terms which you may or may not know. And when you take a look at them, I would like you to push to the side and either you you are positive you don't know. And you can keep out any ones that you kind got a vague idea of the. Take a look at those. And you can move them around if you want.*

73. I think I know all of them.

74. *Okay. Well in that case of let's give it a shot. Just giving me your definitions, which you think these things are.*

75. That's a --

76. *Ion.*

77. That is a positively or negatively charged atom.

78. *Okay. So the ion positively or negatively charged. How about potassium bromide?*

79. It is a compound of potassium and bromine.

80. *Why is it potassium and bromide then?*

81. When bromine becomes an ion it changes into 'ide'.

82. *Okay. Atom.*

83. That's what makes up an element, all the different things and the structure they are in. There the proton and the nucleus, plus the neutrons and electrons in their shells.

84. *Excellent, okay. Attraction.*

85. That's when like a positive ion is attracted to a negatively charged I am and so that's how compounds can form.

86. *Excellent. Chlorine.*

87. One of the halogens.

88. *One of the halogens.*

89. And it is a yellowing gas. It is less dense than air. And it's dangerous.

90. *And it's dangerous. And, what about the electronic structure of chlorine?*

91. Oh it has a seven electrons in its outer shell. And that's why it's so reactive because it only needs to gain one to gain a full outer shell.

92. *Okay. Negative charge.*

93. When an electron has more you like, when it gains an electron I think.

94. *When an electron gains and electron?*

95. When an atom gains and electron it becomes a negatively charged.

96. *Okay, that's good. Displacement reactions.*

97. That's what we said earlier it when like to, and there is a compound and an element and when they react to the elements displaces one of the elements in the compound and then it's the element, and then the other element, and the one that is originally in the compound is moved.

98. *Well said. Shells.*

99. Those are the things that are part of an atom and that's what the electrons go on.

100. I'm not really sure.... but the electrons are on them.

101. *On them, so, their shells are a thing are they?*

102. I think they are more of a pathway that the electron follows.

103. *Okay. And reactivity finally.*

104. It's how reactive and element is, so how many electrons it needs to gain a full outer shell. Or lose it again another shell.

105. *Or lose to gain an outer shell. That was really well said. Now do you remember the concept map, do you remember the, what you had to do that?*

106. Was that --

107. *We put these down in any way on the piece of paper and then I gave you the --*

108. Oh yeah and then I connect them.

109. *In any way you want.*

110. Yeah.

111. *And you can have lines branching off and every time you connect them as like you to think of why you're connecting them because that's what I will ask you. Or that's what you will tell me. In two minutes.*

112. Okay.

113. *Okay. Go for it. (Long pause) Would you like 30 seconds more.*

114. I'm finished.

115. *Excellent. Talk me through it. Start with ion.*

116. I connected that to negative charge because ion is a positively or negatively charged atom depending on how many electrons are in the outer shell. Because if there is less than going to be positive, if there is one electron less it becomes positively charged, and if there's one electron more than the outer proton then it's negatively charged.

117. *So are you implying that there couldn't be two.*

118. Two?

119. *Two electrons. Could You have a negative charge of two.*

120. Yes.

121. *You could?*

122. Yeah. I think you can't get more than, I think we have a quick discussion about this when Mr Pollard said it was difficult to get more than three.

123. *Okay, okay. Go on:.*

124. And I connected it negative charge with the shells because it has to do with how many electrons are in the shells.

125. *Okay.*

126. An attraction was with negative charge because and I am with a negative charge is attracted to an ion with a a positive charge.

127. *Nice.*

128. And attraction for the shells because, all I already did that. Attraction displacement reaction because you could extend it to the element by itself is more attractive to one of the compounds, elements, then the elements in the compound which is less attractive so it's pushed away.

129. *Okay.*

130. I connected displacement reaction to potassium bromide because I think if that's reacted with chlorine it becomes potassium chloride. Oh I forgot to put back the line, I managed to put a line from chlorine to chlorine.

131. *Well, put one in now. That's great.*

132. And, then I connected displacement reaction to reactivity because if one, if the element by itself is more reactive than the element in the compound it will take its place.

133. *Okay.*

134. And then I connected atom with chlorine because chlorine is made up of lots of atoms.

135. *Made of lots of atoms?*

136. Well --

137. *Could you have one chlorine atom?*

138. Yes.

139. *You could.*

140. But then it would be very very little chlorine, I think.

141. *Well said. Okay, that was very good and any questions I I have I think we can pick up in a drawing that I'm going to ask you to do. I think I'd like to ask you, in fact I might rate an equation down fear. Let's have that. If I wrote that first of all to know where I'm going with that to know what this is?*

142. Is that potassium chloride?

143. *Okay. And* --

144. Is that a fluorine?

145. *Good. And what do you think it might become? If it becomes anything?*

146. I think because the fluorine is more reactive than the chlorine, so it takes its place.

147. *Okay. Now, do you know why I have a little (aq) there?*

148. Because it's aqueous, it is dissolved in water.

149. *Okay so you know that it's a solution. There's another issue here, I will ask you if you know about it at the moment. Those will have minor signs at the moment to know why that might be?*

150. Because they're negatively charged. They are atoms that are negatively charged. So if you had, if this was two minus and you had KCl to because you had to negatively charged ions wanting the two electrons there are extra in the outer Shell, because of its two.

151. *If I say that this is sort of half the equation, this is half the number of ions that would interact with each other. Does that help?*

152. --

153. *Just to make it look more simple I am going to draw the or write out of the full one. There, does that make sense to you?2kcl plus f2, what does that indicate about the fluorine?*

154. That they travel around in pairs, the atoms are in pairs.

155. *Okay.*

156. Because they are in a covalent bond.

157. *Okay good. And I'm going to ask you to do a drawing in a moment, so I have simplified it here so that we are just dealing with single ions okay? So, if I could get you to draw this equation here, now when you draw it are you going to draw reality for me or are you going to use a model, how do you --*

158. I think I will use a model.

159. *Okay. So we are clear on that. I would like you to provide a model for me, a diagram of what you think that might look like. As best you can, so putting everything you think of when you think of that. And you have got about a minute and a half for that, maybe two minutes. (Long pause) great now talk me through this you have, that's an interesting one K. the potassium and the flourine have two lines between them, why is that?*

160. Just to show that they are compounds together they are attached, they are not just floating around by themselves. And the F. is by itself.

161. *Okay.*

162. To show that it's an element and then that's the arrow that it reacts with.

163. *Now do you know the term valency?*

164. Valency? I don't think so.

165. *Okay. So I will talk in terms of shells. In the outermost shell there are different numbers of electrons as you pointed out earlier on. Would you be able to indicate to me how many electrons are in the outermost shell of these compounds and elements?*

166. I think so.

167. *Give it a shot.*

168. I have just forgotten how many there are.

169. *You can certainly take a look [He looks at the periodic table on the wall].*

170. This one has one electron in the outer Shell, so that... as well.

171. *Okay.*

172. On the outer shell it has a one, so you could draw a little --

173. *Okay.*

174. And this one has several electrons in the outer Shell. So, that's 6, I will put a 7th up there.

175. *Okay, isn't what they look like in the compound?*

176. No.

177. *Why is that?*

178. Because this one needs to lose electron to gain a full outer Shell, that's what they are all trying to achieve.

179. *Okay.*

180. And this needs to gain one.

181. *Okay.*

182. So --

183. *Now you used the language that* --

184. Oh, I drew eight, whoops. There.

185. *You use the language that they need to gain that extra electron. Do they have a desire to gain these?*

186. Not really.

187. *Okay, so what what does need to mean?*

188. Well, they are, once they are in a full outer Shell they become inert and they stop reacting with other things.

189. *Okay.*

190. And so I'm not sure really why they always do that but I know they do.

191. *Okay.*

192. And so this one needs to gain one to get a full outer Shell.

193. *Righto.*

194. It needs eight and this needs to lose one so this electron here would go there.

195. *Okay, now does anything happen at that stage, what does that do*

to the two ions? When it's transferred?

196. Oh, this one becomes positively charged and this one becomes negatively charged and this one would be minus then once it is lost that one and this one would be + then because it came that one and then the negative would attract a positive and they would stick together.

197. *Okay. That excellent. Can you tell me, now we said that these are in an aqueous solution can you tell me how on earth this because you said there is a displacement reaction here, as we've seen at the end of your equation, how they change partners?*

198. Show you or explain?

199. *Can you explain to me?*

200. Well I think the fluorine would drift past as it is dissolved in the water and then, a fluorine atom would meet his this compound and then because it it needs to gain one more electron but it's more reactive,

201. *Now why is it more reactive?, and what is it more reactive than, is it more reactive than the compound* --

202. More reactive than chlorine.

203. *Okay.*

204. So it takes that electron off the chlorine that originally came from the potassium and takes it to gain a full outer Shell.

205. *Excellent.*

206. And the chlorine then has seven and so it's neutral.

207. *Okay.*

208. And the fluorine becomes negatively charged because it's attached to the potassium.

209. *Okay. And why is fluorine more reactive than the chlorine? Do we just say it's more reactive than it does at? Or is there something more structural?*

210. I'm not sure. I think I must have forgotten that.

211. *That was a very good... at that point. But to leave it at that point there. Do you know what I mean by a diatomic molecule? If I say diatonic molecule?*

212. Erm.

213. *If I say diatomic.*

214. It means that atoms travel around in pairs. Because...

215. *They travel around in pairs, is there a word for that?*

216. Covalent bonds.

217. *Do they just stay hanging out with each other?*

218. They share electron so they both have a sort of half full outer Shell in a way and because they want to make a full outer Shell they will attached together and share one until something else comes along and then it will, so there's --

219. *So, I'm just wondering here if we go to this equation which would be closer to what we might have, how do these how does this work about if we've got a compound their and a diatomic molecule there how might they interact with each other... but need to come apart.*

220. So these 2 --

221. *Now they are in solution.*

222. Atoms, molecule of fluorine here and they are floating along in the water.

223. *Okay floating in the water. Where these particles floating in water, like bobbing?*

224. They are dissolving in it.

225. *So they are dissolved, they are bobbing about in liquid water.*

226. The gas and the atoms are all spaced out with the gas than the water goes in between that space which had resulted in an.

227. *Okay, so the water is watery? Is it? What you mean? Is there water particles?*

228. It gets in between.

229. *Or is the water watery and continuous?*

230. H2O atoms.

231. *Okay.*

232. Particles.

233. *So, those two types of particles. Is this what you're telling me?*

234. --

235. *Well fluorine and water particles.*

236. Well, fluorine is dissolved in the water.

237. *Yes, but I was wondering whether we had, for example balls of fluorine, you know particles of fluorine, bouncing around in water, but you said to me that the water is made of something as well -- is particles as well so I'm wondering what that might look like if I modelled it could you draw what that looks like if I modelled it, if you modelled it?*

238. Wouldn't it be, sort of.

239. *Just started out.*

240. With the fluorine if there was the fluorine and the other fluorine and there are going around and there would be like water here and here and here and here and there would be another chlorine like that and another water.

241. *I see and can I think of those as like plastic models?*

242. I guess you could, I think of them as they hydrogen and the oxygen together making water and then.

243. *But you are not picturing little letters with each other are you?*

244. Not in my mind.

245. *Okay. What is in your mind?*

246. It is hard to describe, actually it is sort of like that.

247. *Okay.*

248. It just isn't kind of H2O it's just water. But I know that it's got the H2O if that makes sense.

249. *Yeah, yeah. If I tell you that they water can be thought of as having a say class on that side and the miners there, a positive charge on that side and the negative charge on that side does that help you think of how these compounds for example can be separated in this solution?*

250. The compound separates in the solution?

251. *In order for us to get the ions separated.*

252. Oh then the ones here which is negatively charged which is, one chlorine would go to the side and the potassium would go to that side.

253. *Interesting.*

254. And the fluorine comes along and it takes chlorine's place there and the potassium and the fluorine. I'm really confused now.

255. *Actually, I remember our last interview and you are following your lines part quite clearly this time you are like sequencing the positive and negative charges and really following them sequentially in your mind and you were doing it yet again and it's really good to see. Okay. And have you used role-play in any of your lessons since I'd seen you?*

256. I don't think we have.

257. *Okay, and* --

258. We've been doing a lot of experiments and stuff

259. *Excellent.*

260. Which is fun.

261. *Yeah. Have you been working in groups or in pairs or in threes?*

262. I have been working on it for usually and sometimes it becomes a three.

263. *Okay. Excellent. And how do you get on with that? Do you work well together?*

264. We all do different bits and then we, if there is like something that you have to do lots of we take it in turns, so it's good.

265. *Okay, okay that's grand. I really tried to pushing their and you were putting your head in a place where you haven't gone yet before, and he did very well with that. Good stuff.*

Appendix 7

A teacher interview from chapter 6.0, which includes a stimulated recall episode

1. *What was your impression, just a really simple question, what was your impression of the lesson?*

2. I thought it went really well; I was really impressed with how well they behaved; but then how much they got out of it as well. And you see them thinking these things, like I said to you about Alex doing this as he was talking to you.

3. *With his gestures.*

4. Yeah. And so I think it wasn't just be brighter ones that picked things up. I think it was, yeah, it worked for all of them, they all got some things from the lesson I think. From what I actually, but yes, yeah, we, I have tried to use a bit of role-play and obviously not with this class because I just started with them; but it's usually much more limited. You know, kind of 10 minutes and modelling the different states and, and changes of state usually so, yeah there were lots of things that I picked up from there that I would like to try really.

5. *So what sorts of things did you*--

6. I think that, things like thinking about the 3-D movement; it was never, I never really talked to them about that and so.

7. *But when you did, then, and had them standing up, how would you arrange them? Would it be a teacher demonstration, with the students? --*

8. No it would be students. And I have always got them to link arms as a solid so with the bonds. I don't know whether you kind of tried that and decided not to do that.

9. *No, I have not tried it, I am just, you know we have all got this sort of different flavours of it. And so I am very interested in collecting them I suppose.*

10. Yeah, yeah so I usually get them to link arms to try to show the bonds and then vibrating; so rather than hand movement, and I think that is valid because I think, I think it's very valuable because then they use that when they are thinking about it a bit more, when they are using the whole person. Yeah, so I liked that. And yes so, so the whole person is a particle and then, yeah moving around into a liquid, and then into a solid.

11. *Do you do it in groups? Or the whole class?*

12. Usually I get people to volunteer to demonstrate and then use the whole class and split them into bigger groups; so I was interested to see, because you have got four or five in the group, so, I usually try and have about eight, possibly split the class into three smaller groups, and so, and then they do a change of state, so it comes much later on in their scheme of work, but and then they try and they do their role-play without words, for others in the class to guess which change of state they are trying to show. But I liked, I liked the way you got them to do things without speaking because that brought out a lot, there was always somebody that plays a leadership role within the group I think, and this was kind of moving people in two different places. Not from thinking about the Science input and thinking about how the group work, that was quite nice to see. Yeah, how the different roles come out and, so that may be something worth thinking about trying.

13. *Now one of my next questions is, in fact, was: What was your most memorable moment? Basically an interesting moment good or bad; does anything stand out as an image? And it could be about the students themselves, about the way they acted.*

14. Well, I think there were, I mean there were a lot of good points of kind of, their interaction, I think that, kind, of- You got halfway through your lesson, role-play and the other groups had turns and almost there were so many questions --

15. *Oh where we stopped and talked.*

16. Yeah, yeah, yeah --

17. *A deluge wasn't it?*

18. Yeah, yeah and so you know at that stage in the lesson they should be tired but they were really, really wanting to ask about things. So, yeah I thought, I can't, I can't remember what, yeah, I have put Alex using his hands to describe dissolving. Oh there's the questions about a solid melting which, you know, that's one of the misconceptions that a whole lot of them have about, you know, water everything melts at 0°, and therefore a solid is below zero, and at zero everything turns into a liquid. And so you know using the particle theory to think about why it was that Iona`s sugar wasn't melting when she put it in a glass of water and, so that was, yeah, and the difference between chemical and physical reactions. So they have not done that. I can't remember, one of the boys asked that.

19. *On the side yes.*

20. But it was pulling together a lot of, obviously, things that they've picked up, and you know they hadn't fully understood and yet hopefully with the thinking about the particle theory and the evidence; they can then actually explain it and --

21. *Roll with it.*

22. Yeah.

23. *Yes, no that is good. I think I concur on that, very interesting moment for me. Shame it was five minutes before the end. Wasn't it, wanted to keep rolling with it. [I turn to the computer]. Now which one? We are going to take a quick look at one of the scenes here. Which one is this? Yes, so this will last thirty seconds really to the end of the role-play. It will be quite obvious when it happens so just tell me when it has ended. So if we could start there [long pause]. Now what did you notice about the behaviour of the students, just looking at that.*

24. I love that they are checking to see how their neighbours are doing, if they are doing the right thing. I think, I think they get more enthusiastic as their hands go more quickly [gestures] and I'm now, I didn't notice it so much, I was looking, but that was when you were talking about how lots of them were opening their hands up --

25. *Afterwards, yeah. Now was there a utility to that sort of use a gesture, to think about the group at that point?*

26. What do you mean?

27. *Was is it useful? To have them in a line, doing that style--?*

28. Yes, I would definitely I think, yeah.

29. *And then, it always falls on to this question: Why do you think so?*

30. Well they, I think they do, they do pick it up because they can see other people doing it, but I think the value, is the value of it later on, when Alex was using it in his response to things so --

31. *So when you are saying that Alex responded, I just want to be clear of where of this was; he was in one of the groups was he?*

32. No, it was when he was talking about dissolving and you were asking and he was talking to you and he was --

33. *Using his gestures*

34. Yeah.

35. *I am with you.*

36. Yeah.

37. *Okay so and the students in the video at look comfortable there, they are happily cheating on purpose, and are allowed to.*

38. Yeah, yeah, yeah.

39. *Can you see any pitfalls that situation?*

40. I guess if you have got somebody who is hasn't understood it but he is a leader and so therefore people end up following that person rather than --

41. *Was there a situation where that might have been* --

42. I think I didn't see that no.

43. *Grand, what do you recall as some of the teaching objectives of the lesson?*

44. Thinking about particles was there, and the differences in the three states of matter, and how particles behave.

45. *Was there anything useful or not useful in the way that, in these sort of features of particle theory that you saw.*

46. What do you mean?

47. *Well did you find at any, let`s say, clangers, that was inappropriate modelling or language or that there were particularly appropriate things? Perhaps with attraction, or movement.*

48. I don't, I don't think so. Things like, they have not done elements or compounds yet, because that's a kind of a year eight topic and I think that was apparent when you asked for an element and someone said ice or something. But you know that it's not like it's not that that's not a problem, we just talk about the particles and that's fine and then in year eight they will build on what they know already.

49. *I presume within the, the way you would teach this, that you are avoiding the use of atoms?*

50. Yeah.

51. *Because everybody does it differently but* --

52. Yeah.

53. *But you avoid the use of term item. And you stick with particles.*

54. Yeah, yeah.

55. *Okay. Just so I can clear with that. Because we brought it up and I could be, you know, the sort of flavour of things.*

56. Yeah and just because, it's kind of how, where do you stop really? So I tend just to talk about particles and therefore, because otherwise you can spend the whole lesson -- you've got so much background that they need before you can actually get on to what you are trying to teach them and maybe it's because we operate the rotation system here, and I've finally seen them for another six weeks and I have got to finish my unit of work in that six weeks and then they go somewhere else. So the class-

57. *Do you feel pressed for time?*

58. No. No. I mean I think I've got to fit what I want to in there but I haven't got time to fit in extra things usually so yeah so it is more, yes, so that was very -- Yet I noticed that the elements and molecules they hadn't quite got, but I wouldn't have expected them to have, to be able to answer you on that. And I don't, I don't think I noticed anything else.

59. *Do you think their understanding of diffusion and dissolving was developed over the course of the lesson?*

60. I would hope so. That would be interesting to see what you are, because I mean I didn't question any of them afterwards so I don't know but I would hope so.

61. *I meant in terms of where they were, perhaps specific moments where you might see them and think, or a group, or thinking you are on track or you are off track.*

62. Some of them were starting to answer their own questions at the end when I, I can't remember what of the things they, they were talking about: heat energy, and where the heat energy comes from, and you know I think definitely they had learnt something through the process and so, and I mean even the solids and the difference between chemical reactions -- I think they got to their answers eventually so they were definitely learning them. One thing I noticed a lot of of them I think hadn't: so when you were talking about the sugar particles dissolving, they were running around madly as though they were gas particles, and I wonder if they really grasped the difference between; maybe, maybe it was just that that they hadn't really sat down and thought about it and so that's just what they were during, but the day. If there was more

time I might have wanted to remind them that they were now liquid particles, what would they look like -- because they were kind of charging around.

63. *That is a very good point.*

64. It was funny that they were able to charge around.

65. *I would have tackled that too; it was a funny thing. They were gas particles or very heated up water particles. Okay let's see what I have on clip two; I believe this is the preparation for the diffusion --*

66. Okay.

67. *Okay. And so this is the, do you remember that? With the diffusion.*

68. Yes.

69. *Okay. And I just wanted you to take a look at their behaviour to remind you of their behaviour as they were preparing. And if I could get you to comment on that behaviour.*

70. I think they are all engaged, I mean they were.

71. *It was quite prolonged. I might put to you, was that length, did you feel like it was too much for them or not enough?*

72. No, I think it was about right. I think was that the time where Louis once kind of--

73. *Louis.*

74. He was the boy in the far corner and there were four girls and him.

75. *He was standing back, it was the second one, the dissolving.*

76. Okay, you, you are right so it was when they were doing ABCD in the dissolving.

77. *Yes.*

78. So I think that it --

79. *And you think that the situation resolved itself or that it was, was there was an issue there?*

80. Yeah I think it was, no, because they did their role-play, he was doing what the girls wanted him to do and you know.

81. *I like how you said that, what the girls wanted him to do. [Laughter]*

82. Not that he sat back and kind and let them get on with it, and I don't think they had noticed that he was sitting back and really, it was just, they were getting on with it and he wasn't.

83. *And in terms of participation for the class was there quite a lot of participation, or was it spotty?*

84. Now I think there was a lot of participation.

85. Okay. I think and I think that there, as I say there were some characters too in the class that I would think would be more likely to step back, but when I spoke to them as we were going around they seemed to know what they were doing, even if they might give off the vibes that they were kind of not really involved, but they knew what they were doing and they were engaging, I think even if they were the people that put up the barriers are little bit, but.

86. *This brings me back to something that you referred to right at the beginning. Where there any specifics; you sort of talked about ability, where there specific students that this approach seemed to help. And it doesn't have to be ability; it could even be individual skills.*

87. I think there were a lot of bouncy boys that got involved and would probably find it quite difficult to see it through, you know, if there was not as much kinaesthetic going on, so yeah.

88. *At which, yeah, so might imply, so I will push this one; with quiet girls as opposed to bouncy boys would it have been an issue for those girls?*

89. Well Agnes was quiet and she enjoyed it.

90. *I was just wondering if you had noticed in the class.*

91. Well there were, there was a girl who is quiet and: Agnes, she's a ginger haired girl who --

92. *Right, right.*

93. Who I didn't go around and talk to but she seemed quite happy with things.

94. *She was moving around quite a lot.*

95. I don't think, I think it was good the way that you changed the

groups that they were working in quite quickly; because they didn't get fed up with each other or fed up with being bossed around if somebody was taking the lead and others were having to do what they said.

96. Right.

97. So that was, that was good, and avoided, I think perhaps some of the problems with group work, the same groups are less good to go along too long.

98. *To fester.*

99. Yeah.

100. *So in the lesson itself, in the pedagogy and the style of teaching was there anything that you found interesting in that style of teaching? So you talked about the gestures. Was there anything else about the, anything really, the pace, the types of images that were presented, the types of dialogue, back and forth.*

101. I think that I was surprised that we had the, kind of 20 minutes when you, it was not Science, it could have been anything in a drama lesson or whatever, but then I think doing that was valuable for what they were then going on to do so that wouldn't have been something that I would have tried. But it worked.

102. *Worked in that context, yes.*

103. *Yeah. No an interesting issue with coming, coming into a new class --*

104. Yeah.

105. *I need to create a context before I can leap off from that.*

106. Yeah.

107. *So, Yes, Thank you. How might it have been improved? So I am reflecting here, slaying --*

108. I guess it, it is time isn't it? I think that.

109. *Would you have liked it to have been framed more, would you like more in a perfect world, more written work?*

110. I guess having the time at the end to do the test that you had already thought of would have been good to see how much has been learned and whether they could particularly show what they'd learned in the process.

111. *And perhaps the question and answer session could have just kept moving on.*

112. And I noticed something else. You talked about the fart and diffusion and they were suddenly really interested. When it was perfume it wasn't very interesting but when it was a fart it was.

113. *That is an interesting point.*

114. And also didn't somebody ask why it goes away?, So that was, you know again they were thinking, and then somebody else answered the question. I think.

115. *Yes. Actually going back to the fart: did you think there was less or more or the same amount of humour as there would be in a normal lesson?*

116. Aah.

117. *Is that even an issue?*

118. No, it's probably. Well it depends on teachers doesn't it?

119. *I don't mean my humour, I mean just a general question, a general what is going on in the class* --

120. Yeah, yeah. No, probably about the same I think.

121. *Okay, okay.*

122. I mean they are a fairly relaxed. Sometimes they can be a bit too relaxed.

123. *Right, right. So this is 'medium' for them.*

124. *Yeah.*

125. *And it, does this pedagogy fit into a secondary school teaching approach, in your mind? Like I could contextualise it by saying there is interest, there has been much earlier interest in it as a primary approach.*

126. Oh no, definitely, and like I said I do try and do some role-play with them but this is just extending this to other contexts really; diffusion and solutions, dissolving. It is just trying to push that through. And I guess, yeah I guess the choice would be whether you do a bit of it or whether it is several opportunities or whether you do like you did, a double lesson where you know that's what they do and then and then it's more kind of written work about

what happens between the three changes of state later on. I don't know what it's worth thinking about how it is best delivered, whether it is just one package or whether it is broken down into the different -- yeah.

127. *And use their- this is basically the end of the interview. So, anything else you want to say about the lesson?*

128. I really enjoyed it. Thank you, I just, you know, you're, it was great. It was nice for me to stand back and just observe them as well.

Appendix 8

Transcript of the balancing equations demonstration and the subsequent student task

9a Balancing equations task demonstration transcript

First I would like to turn this into a human model. So if I could have, let's do: need hydrogen atoms for boys and oxygen atoms for girls. Often Science teachers, when they are doing role play, it is a nice easy thing to colour the models with boys and girls so we need one girl, would you mind standing up? And two boys, can you two stand up. And I just want you to stand, kind of near each other, over there with your arms crossed and you are a molecule, a water molecule, just over there. Excellent, so these are our products of the reaction. What, now, I need to get to those products. I need to have a reaction so, often when we write; I have an arrow down between the molecules of the reactants and the products, so I need an arrow. I am going to have a human arrow. Do you mind being an arrow? Excellent and you can lie down there. Guys can you back up just a little bit further. I would like you to lie down, I was going to say… but if you put your head towards them then you are pointing in the direction of the reaction. Brilliant. What do we need to make this? Take a look at that, we have got a water molecule, we have got one oxygen, we have got two hydrogen. What do we need to make that? How many atoms do we need [asks one in particular. Okay do you want to phone a friend? Okay. Pick on somebody. Well if we have got two hydrogen atoms over there, how many hydrogen atoms might we need over here? If there are two over there?]

Kevin: Two.

Badabing. So we need two atoms over here. You two guys. You stand over here. Now you guys what you are, let's say that you are a hydrogen molecule. Okay. That goes around in twos. What's the other thing that we need? Ted?

Ted: An oxygen.

An oxygen. Brilliant. Ma'am can you be my oxygen atom? Thank you. The only problem is oxygen as a gas hangs out as a molecule, so it cannot be on its own, so we need another oxygen atom. Could you stand up? So we have our oxygen and our hydrogen. And that looks like this [shows a paper: H2 +02, and there's the Hs and the oxygen over there. We have got these guys and we have those guys. Now. Let's even make this more like an equation. If you guys could move closer to their feet. And if you could sit in the middle and you here so we could have a nice straight line. Okay what is she? She's the plus! Okay so, Oxygen plus hydrogen reacts to become the product [I stand up and gesture as if to frame each unit of the equation as I narrate: hydrogen plus oxygen reacts to become the product water. Marvellous. What's the problem, Ben.

Ben: I don't know how to put these together.

Don't know how to put these together. Excellent.

Kevin: What reaction?

What reaction. I want to know what the problem is to do with the number of particles. I want to have the perfect amount of resources over here that are reacted together to create my water. What is the problem with this?

Jeremy: There's two oxygens over there and there's just one back here.

Doh, okay, mad scientist sees that there's two oxygens and only one oxygen over there. That means that my reaction wastes an oxygen. That means that there's millions of balloons of oxygen that I am just wasting in a reaction, that I brought along specifically. So I can't have that, I need this as an, the exactly balanced. Balanced equation. Right, so when we talk about balanced equations we are talking about the amount of particles, the amount of atoms on each side. The Forum Theatre part, well we have already been doing it, but how do we change this? We cannot cut things in half. So what else can we do?

Geoff: we could slice an oxygen.

Well that's interesting. But let's say that we can add more. We can add more oxygen. We can add more hydrogen, or we can add more water. To this equation. Any ideas what we might have to add more of?

Kevin: We need more water [someone else calls out 'More hydrogen'.]

Okay, well, let's add more water. Let's have you [girl] stand up, and let's have you two guys stand up here. Okay so that's two water thing, now if we did that, it's unbalanced, how many more hydrogen do we need?

Ben: Two.

We need two more hydrogen. Do we have two? [To boy] come over here. Is there another guy? Okay, its me. We have got us two as hydrogen. Have we equalled the amount of hydrogen on that side? Okay. Have we equalled everything yet? We've got two oxygen. You guys, in a millisecond, balanced this equation. And how can you tell that you've balanced an equation?

Ted: There's the exact same number of molecules on this side as on that side.

There's the exact, exact same number of hydrogen atoms on this side. Exact same number of oxygen atoms on this side, as there is on that side. And we did it by adding extra things until they were all balanced out. Okay, everyone sit back down again.

9b The Student Task Transcript

I am going to give you...so I don't know who's going to lead and who's going to support. But the problem is NaCl: Sodium and chlorine gas becomes *sodium salt. You have two minutes to create that equation. You can ask me any question.*

Hand shoots up from interviewee girl: ‘Are we allowed to talk?’

You are allowed to talk.

[Nobody moves.]
What might we need to do?

[Hand up], ‘people get up.’

Okay, and I can see people are reticent. So how about you be sodium and you be chlorine.

[Girl stands up and then a boy, quickly in agreement and stand together facing me in centre of the circle]

Okay so we have sodium chloride: our products. Does anyone want to take a role?

Kevin moves, raises hand, ‘I’ll be the arrow’

You’ll be the arrow, great.

He moves up and lies down.

We have NaCl on one side- now I said there was Chlorine gas.

[Ben and Kevin pointing now to another girl where to stand.]
Ben -How many have to be the sodium?

One.

Ben – One. Okay, so who’s the sodium?

[Boy next to him raises hand, he moves quickly near the girls as Cl2]

Kevin tells reactants where to stand

Ben - we need a plus sign.

Karen - I will be the plus sign.

Jeremy interrupts to leap in from beside me – I step in to say we need a better balance of boys and girls

Ben – I guess we need another over [points to the products]. Do you want to [looks at a boy and girl interviewee beside him]. They quickly get up and stand next to the others in a group.

Ben- I will go add to the sodium.

Okay so you have got two NaCl on one side. You have two sodium atoms on the other side. Is it balanced? How many say yes? Yes. It is balanced! That's spectacular.

Appendix 9

Student Pre-Interview Schedule

The following interview schedule template was tailored to individual cases. The semi-structured protocol (§4.5) allowed for further prompts to be defined and followed during the interview

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- What have you done this year in Science?
    - prompt for Chemistry activities, if this is not initially forthcoming
- What was your most memorable moment in Chemistry this year?
- What are your perceptions of [the topic concept]?
- Introduce the show card (§4.6d) Can you define any of these terms?
    - Prompt for extended descriptions that may include connections between show card terms.
    - Prompt to elicit their level of understanding of the representational levels (i.e. macro; micro; sub-micro)
- Introduce concept map by providing an example
- Student creates a concept map (§4.6d; Appendix 2)
- Elicit extended description of a topic concept process (i.e. 'Can you describe what happens when you stir salt into water?)
    - Prompt for when the student believes that he/she may have learned the topic concept
- Students are to draw a before, middle, and after expression of the process that they described above
    - Prompt for student's justification of chosen signifiers and their perception of the representational level

- Repeat the previous two tasks (bullet points) with a new topic concept. If deemed appropriate, ask a TE-type question
- Have you used role play or drama in your lessons before?
    - If yes, then prompt for further details of the episode
- How do you usually work: groups, pairs, alone?
    - Prompt for a suggestion of the frequency of different configurations
- Thank you.

Appendix 10

Student Post-Interview Schedule

The following interview schedule template was tailored to individual cases. The semi-structured protocol (§4.5) allowed for further prompts to be defined and followed during the interview

- What was your impression of the lesson?
- What was your most memorable moment?
- Introduce Stimulated Recall (§4.6d):
    - Watch the video. Can you comment on this activity in the lesson?
    - Who directed whom? What were your ideas?
    - During your preparation for the recall episode, what ideas did you/the group come up with?
- Ask student to try to define the pre-interview show card terms.
    - If students use gesture during their responses, ask them to clarify the signification of particular gestures
    - Prompt for detail as to the level of terminology and level of understanding of representational level of their descriptions (i.e. macro; micro; sub-micro level)
- Ask the student to create the concept map with the show card terms (§4.6b; Appendix 2)
- Elicit extended description of a topic concept process (i.e. ‘Can you describe what happens when you stir salt into water?)
    - Prompt for whether or when they believed that they learned this concept

- Student draws a before, middle and after expression of the process described above
    - Prompt for student’s justification of chosen signifiers and their perception of the representational level
- Repeat the previous two tasks with a TE-type question on a new problem related to the topic concept
- How do you imagine particles?
    - Prompt for details of shape, proximity, plurality, and action
- If you were a teacher would you use these activities?
    - Prompt for which activities are more, or less, useful, and why
- Any final thoughts?
- Thank you.

Appendix 11

Student Delayed-Interview Schedule

The following interview schedule template was tailored to individual cases. The semi-structured protocol (§4.5) allowed for further prompts to be defined and followed during the interview

- Do you remember the lesson?
  - Prompt for details of specific memories
- What was your impression of the lesson?
- What was your most memorable moment?
- Ask student to try to define the pre-interview show card terms.
  - If students use gesture during their responses, ask them to clarify the signification of particular gestures
  - Prompt for detail as to the level of terminology and level of understanding of representational level of their descriptions (i.e. macro; micro; sub-micro level)
- Ask the student to create the concept map with the show card terms (§4.6b; Appendix 2)
- Elicit an extended description of a topic concept process (i.e. 'Can you describe what happens when you stir salt into water?)
- Student draws a 'before', 'middle' and 'after' expression of the process described above
  - Prompt for student's justification of chosen signifiers and their perception of the representational level

- Repeat the previous two tasks with a TE-type question on a new problem related to the topic concept
- How do you imagine particles?
- The question does not suggest a visual perspective. However, if the student does not understand, then rephrase with, ‘What do you see when you think of them?’ may be used
    - Prompt for details of shape, proximity, plurality, and action
- If you were a teacher would you use these activities?
    - Prompt for which activities are more, or less, useful, and why
- Any final thoughts?
- Thank you.

Appendix 12

Teacher Interview Schedule

The follow interview schedule template was tailored to individual cases. The semi-structured protocol allowed for further prompts to be defined and followed during the interview (§4.5).

- What was your impression of the lesson?
    - What do you think were the learning objectives?
- What was your most memorable moment?
    - Prompt for further details of the episode: These could include aspects of student behaviour, interpretations of students' thoughts, and features of their personalities.
- Were there specific features of this pedagogy that you found good or bad?
- Stimulated Recall Episodes
    - Prompt for further details of the episode: These could include aspects of student behaviour, interpretations of students' thoughts, and features of their personalities.
- Were there any other moments that interested you?
- Were there particular personalities who came to the fore?
- At what points did students appear to be either more engaged or less engaged in the lesson?
- Do you think their understanding of [the topic] was developed over the course of the lesson?
    - If yes, prompt for how the teacher perceived this development
- Do you think their understanding of [one of the individual concepts within the

topic] was developed in the lesson?

- Within the context of the personalities in your classroom, was there quite a lot of participation, or was there very little participation?
- Do you think that the Human Analogy Models aided the students or not?
- Does this pedagogy fit into a secondary school teaching approach or not, in your mind?
- Were there specific students that this approach seemed to hinder or help?
- Were there discernable changes between teacher-centred and student-centred tasks?
    - Prompt for perceptions of the degree of teacher control
- Have you used role play before?
- Do you have anything to add?
- Thank you.

Appendix 13

Two Examples of Video Analysis

Example 1: The following video analysis is from Case 4.

The task begins with my command, ‘I am going to give you thirty seconds to create the largest atom that this room can hold. Go!’

One boy stands quickly on the command, while two others nearby begin to stand quickly but then slow down, seemingly noticing that the other students are less quick to move. However, within two seconds the majority of the group stands. The students group together in a large huddle, and talk and laughter are audible, over which one boy is heard to say, ‘everyone should go in a circle.’ This is immediately shouted down by another boy with, ‘No, no’. The huddle remains, while several voices call out (inaudibly), until one voice is heard to call, ‘one group in the middle and electrons around the outside. Two boys immediately step back away from the group. These boys played electrons in the previous ideal atom models; their movement suggests that they associate their roles with electrons now. They are the only ones to separate themselves from the group. Seemingly unconfident, they step forward again into the huddle. As they do so, two actors in the centre of the circle can be seen to create crossed-gesture signs that the students had used to denote positive charges that they had mimicked from my initial ideal atom demonstration, when they produced their ideal atom models. The gesture is reproduced quickly by others, including a short boy who turns towards the two boys who had initially moved to the outside of the circle. The two boys step backwards again, laughing. One raises his hands and seems to cower. There is a sense of signifying repulsion, but also a sense of fun and a seeming reference to a Vampire film in which the cross is raised to Dracula. They stop within three seconds, as a girl and another boy move with them into their own grouping about two feet away from the central huddle. They stand and look, as if for instructions from the inner group, who do not pay attention but focus inwards.

Two more students separate themselves from the main group and stand facing inwards. They appear to have chosen the electron-actor positions, but are seemingly unsure, or unconfident, as to what to do.

In the centre of the huddle/circle, the question 'Who are you?' and the answer, 'I am a neutron' are audible.

One boy holds up his crossed hands up and dances with them close to his face. He appears to be showing off to the girl in front of him. He stops dancing within two seconds, but keeps his hands up. Sightlines are difficult but from two video angles (V1;V2) there are four students with crossed-hand gestures. Pairs of gesturing and non-gesturing students align themselves so that they can look at each other, while the huddle stays quite compressed. The pairing seems to echo the pairing of neutron and protons in the ideal atoms, but occurs while the group stays tight together, suggesting a sense of the cohesion of all particles in the nucleus.

One boy in the group of four outside the huddle points towards the circle. It appears that he noted the gestures; the second boy follows the deixis and moves his flat hand in a sliding motion horizontally, but tentatively. The first boy then exaggerates this gesture by sliding his whole arm, rather than just the hand. These movements echo the negative gesture signs from the ideal atom model. He also tentatively crouches, or rather, slouches, as he looks at his hand, presumably mimicking the code for the relative size of the particle that students used in their previous ideal atom models. He stands and turns back to the second boy, who is still making sliding gestures. Meanwhile a third boy in their group begins to crouch tentatively, but stands up seemingly self-consciously when another girl walks out of the main huddle to their smaller group. She turns and stands with the other girl from the group of four to watch the larger group. At this point, the first boy crouches down and duck-walks with his sliding gesture. He looks at the second boy who laughs, and who is heard to say, 'keep going'. The first boy continues and is quickly followed by the others in his little group, who mimic his levels and gesture. He passes the two electron-actors who had stood separately around the back of the large huddle, but who now crouch and turn and walk. The boy at the back of the group turns in the opposite (counter clockwise direction) to the others, but halfway around the circle, when confronted by the other electron actors moving clockwise, he turns in their direction.

Now that I percieve the image of a central nucleus of protons and neutrons, and a dynamic representation of the outer shell electrons, I say, 'Okay now stop and stay there.'

The episode lasts 53 seconds.

Example 2: The second episode comes after my demonstrations of a dipole molecule.

Following my demonstrations of a water molecule and then a simplified dipole molecule, I say, 'Stand up, you have positive charges on your front, negative charges on your back. Let’s just see what sort of formation you guys end up in. You are a whole bunch of positive and negatively charged particles.’

The group stands almost simultaneously. I move towards the right side of the room and together they face me and orient themselves to me, as if I am a charged particle. I stop. Two students, on the right of the group, move together so as to suggest that they ‘stick’ together. I say to the class, ‘You don’t have to touch each other. Just try to angle yourself.’ The students in view all hold crossed-hand gestures on their fronts; a small boy at the back of the still side-facing group stands straight with his left hand clenched in a fist on his chest and his right hand opened and horizontal against his back, as if pragmatically changing the crossed hand gesture to a fist so that he can maintain signification of both positive and negative charges simultaneously. He arches his neck to look around the taller boy in front of him.

In what seems to be a moment of exuberance, one boy on the right side turns away from the front of another and runs backwards, bumping, into another student, and pushing another. His movements, and sudden cessation, suggested that he enjoyed the humour of his sudden movement but also seemed to suggest that there would be a strong pull, because, being on the edge of the group there was no counter-pull in the other direction. The moment is brief and ends in laughter and stillness, after which the three boys orient themselves to the students around them.

Since turning to follow me, students who had initially sat at the front of the class aligned themselves behind each other (positive to negative charge). The line of five students then returns to face the front, perhaps in realisation that I am not acting as a particle. The front line is briefly reordered, as one boy spins and orients himself behind another, leaving a gap which is filled by another boy who moves sideways, seemingly with little attempt to consider charges. The front line now attracts a second row; a coalescing crystalline structure is suggested in this rigid pattern. The rest of the group is still in a random pattern. Watching the small boy peer around others suggests that varying heights of students mean there will be some students who have a rather poor view of the whole group (and some who have a good view). The small boy remains where he is at the side, but a girl behind him moves into the second row, also with no concern to orient towards her ‘charges’. The small boy moves behind her and then peers around the front of the group before moving back to his place at the side. In the centre of the group, three boys re-orient themselves continually. One boy from the back corner spins diagonally from the back right to the centre, and stops, and reorients himself toward the front. He makes a 180 degree turn when a girl turns towards him. Facing another girl, he then spins back, as if suggesting that the particle is unstable in its positioning. This suggests the potential for an embodied feeling of continual movement as he shifts quickly from each orientation. He then turns towards a student in the front. Lines of students are beginning to coalesce now. Four girls at the back row turn to the left in a line, so that they align according to their charges, but without respect to the charges of those outside the line. One girl places her head against the back of the girl in front, as if hiding, or as if she’s shy. The first girl ends standing with her shoulder near a boy facing forward. The second girl now puts her hands on the arms of the first girl and turns her to face the back of a boy who has just turned forward to face another boy’s back. This suggests that she is directing her peer, rather than following her own particle-actor rules. This move to direct another student is noticeable when a tall boy beside the small boy beckons him to the back of their line.

However, the small boy only moves half-in and out of that line and orients himself forward, still with the negative sign gesture on his back.

The group is now taking on the shape of a square composed of four lines. Students either pivot in their places, as if moved by the forces around them, or they stand still. A ginger haired boy on the right side of the group – the student who initially bumped into his classmates -- seems to look around and check continually, reorienting himself as if trying to find an equilibrium between position and charge. He appears to have taken this on as a challenge. For example, his movement places him behind another student who is has moved off to the right side of the group so that the two create a 'pig's tail' to the otherwise square-ish shape of the whole group (Other students look at these two, as if to suggest that they are waiting for them to fall in line). The first boy does so, but as the ginger haired boy follows him, he moves closer other 'particles' and breaks-off from his following position to stick with his back the group halfway down the line. There is humour in this, and the students laugh at the move, which seems to suggest an awareness of their objectives, to act according to the attraction and repulsion between different and like charges. That narrow perspective seems to coexist with an understanding of the developing pattern, suggested in that some direct themselves and others into the crystalline formation.

At this point I stop the task. The episode lasts thirty three seconds.

Appendix 14
Example of Coding Procedure for Interview transcripts
(With Atlas.ti)

Codes were drawn from Themes (§4.8) and features of the topic concept (i.e. liquid, solid, gas, energy) which arose within the case.