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Learning Processes in Chemistry:

Drawing upon Cognitive Resources to Learn about the Particulate Structure of Matter

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Abstract

This paper explores 11-16 year old students' explanations for phenomena commonly studied in school chemistry from an inclusive 'cognitive resources' or 'knowledge-in-pieces' perspective that considers student utterances may reflect the activation of knowledge elements at a range of levels of explicitness. We report five themes in student explanations that we consider derive from implicit knowledge elements activated in cognition. Student thinking in chemistry has commonly been examined from a 'misconceptions' or 'alternative conceptions/frameworks' perspective, where the focus has been on the status of learners' explicit conceptions. This approach has been valuable, but fails to explain the origins or nature of the full range of 'alternative' ideas reported. In physics education, the 'cognitive resources' perspective has led to work to characterise implicit knowledge elements - described as phenomenological primitives (p-prims) - that provide learners with an intuitive sense of mechanism. School chemistry offers a complementary knowledge domain, because of its focus on the nature of materials, and its domination by theoretical models that explain observable phenomena in terms of emergent properties of complex ensembles of 'quanticles' (molecules, ions, electrons, atoms etc.) The themes reported in this study suggest a need to recognise primitive knowledge elements beyond those reported from physics education, and that some previously characterised p-prims may be better considered to derive from more broadly applicable intuitive knowledge elements.

Keywords

chemistry learning; cognitive resources; knowledge-in-pieces; p-prims; implicit knowledge

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Introduction

This paper explores secondary students' explanations of basic phenomena met in school chemistry in terms of a 'knowledge-in-pieces' perspective (diSessa, 1993). The motivation for the present study derives from a long-standing debate in science education about the nature of the ideas students develop about scientific topics (variously labelled as alternative frameworks, intuitive theories, misconceptions and so forth), and the contribution made to this debate by studies of physics learning undertaken from a 'knowledge-in-pieces' or cognitive resources perspective. Research characterising ideas elicited from science learners as deriving from knowledge represented in cognitive structure as explicit propositional conceptions has proved valuable, but has been subject to considerable criticism (Taber, 2009a). Such alternative conceptions and conceptual frameworks seem to reflect the characteristics of some, but not all, of the non-canonical ideas that are significant for science learning. The 'knowledge-in-pieces' perspective that considers student knowledge to often be constructed on-the-fly, drawing upon more implicit cognitive elements, has proved fruitful in considering physics learning, but has received little attention in chemistry education. In this study we examine 11-16 year old students' explanations of some common phenomena met in school chemistry to explore how they made sense of these phenomena. The present study, then, sought to (a) explore whether a cognitive resources perspective could offer greater insights into students' chemical thinking than approaches tied to explicit propositional knowledge; and to (b) find out if the application of this analytical frame beyond physics learning could help refine suggestions for the range of implicit knowledge elements significant in understanding and learning science.

At secondary level, school students are taught to interpret phenomena in chemistry in terms of particle models, and this is well recognised to be a major source of learning difficulties. Working in the context of phenomena where canonical chemical explanations involve particle models, we were interested to find out if the knowledge-in-pieces approach which has offered valuable insights into learning difficulties in physics education has similar potential for interpreting learners' thinking in chemistry; and, if so, whether the shift to studying a different domain of science learning might contribute to our understanding of the range, scope and characteristics of knowledge elements that are activated when learning about science. In this paper we report five 'themes' that we identified in student explanations that we consider to be derived from intuitive knowledge elements, and we discuss how these themes might relate to previously-reported primitive knowledge elements.

Learning Difficulties in Science

Students' ideas about scientific concepts have been a major focus of science education research for thirty years (Driver & Easley, 1978). Science education has been dominated by a 'constructivist' perspective that gained popularity in the early 1980s (Driver & Erickson, 1983; Gilbert & Watts, 1983; Osborne & Wittrock, 1983). One of the main assumptions of this approach is that students come to science lessons with existing ideas that determine what it is that students will learn (Taber, 2006, 2009a). If learners' ideas act as interpretive *frameworks* through which students 'make sense' of phenomena (Driver, Squires, Rushworth, & Wood-Robinson, 1994), then research into the nature of those ideas can be understood as potentially significant to inform pedagogy. In particular, it is important to be able to advise teachers when their best response to students' ideas is to ignore them; when to actively challenge them; and when to consider them as suitable starting points for developing towards the scientific models

Students' ideas about a wide range of different topics have been elicited (Duit, 2007), and labelled in various ways (such as 'alternative conceptions/frameworks', 'naive theories', 'intuitive beliefs'). There has been a widespread debate about the extent to which elicited ideas reflect *stable* elements of cognition (Taber, 2009a), that students use (i) to explain a wide range of phenomena, and (ii) over a extended period of time (Driver & Erickson, 1983; Gilbert & Watts, 1983; Taber, 2008); and the degree to which they may be considered 'theory like' (McCloskey, 1983; Vosniadou, 1994).

The vast literature has shown that *sometimes* learners' own ways of thinking about science topics can be coherent, stable, and applied consistently and widely over a topic area (Taber, 2009a). However, it is also clear that students do not always have stable or consistent ways of explaining phenomena, and elicited ideas can often be strongly linked to context (diSessa, 1993; Engel Clough & Driver, 1986; Pozo & Gómez-Crespo, 2005). Indeed, it is evident that students may simultaneously hold different ways of understanding scientific concepts, or use different models to explain the same phenomenon (Flores-Camacho, Gallegos-Cázares, Garritz, & García-Franco, 2007; Harrison & Treagust, 2000; Taber, 2001b). Different perspectives have been used to conceptualize such multiplicity, including conceptual profiles (Mortimer, 1995), conceptual trajectories (Petri & Niedderer, 1998), manifold conceptions (Taber, 2001b), and multiple models (Harrison & Treagust, 2000).

The Knowledge-in-pieces Perspective

Our present research is informed by a perspective on cognition that considers that the human brain represents knowledge of the world in a multi-faceted way, and in particular at different levels of generality and explicit awareness (diSessa, 1993; Hammer, 2004; Karmiloff-Smith, 1996). Such an inclusive notion of cognition admits various elements and does not make a sharp distinction between perception and cognition (Taber, 2008). In our discussion we will use the term 'knowledge' to refer to information that can be represented in cognitive systems (i.e. personal knowledge), without reference to its 'truth' content (Matthews, 2002), following a common convention in cognitive science.

According to Smith, diSessa & Roschelle (1993) the instability and inconsistency of students' ideas can be addressed by considering that students have multiple *resources* from which they construct their explanations and whose activation is context dependent. That is, it is useful to focus on 'resources' that are at a more fundamental or 'primitive' level than alternative conceptions or frameworks that are explicitly represented in cognitive structure.

Karmiloff-Smith (1996) has proposed that knowledge that is initially purely implicit can, once well established, become re-represented through a series of more explicit levels that makes the transformed knowledge increasingly available to conscious thought. In her model, initially encapsulated implicit knowledge is first made available in a form that can be incorporated in new contexts, and can then be re-represented in forms that are available to mental imagery and ultimately verbal language. Such a model suggests that ideas elicited from students (in teaching or research) could either be generated in situ by mapping implicit knowledge elements onto question contexts, or by accessing explicit conceptions previously compiled and now forming part of the conscious thinking about a topic area (Redish, 2004: 24).

Applying the knowledge–in-pieces perspective to physics learning

Based on work exploring students' reasoning in physics (and particularly mechanics) concepts, diSessa (1993) proposed that 'intuitive physics' is an expression of an underlying sense of mechanism that in some cases leads to common outcomes but lacks the systematic aspect inherent in a scientific theory. In particular, diSessa proposed a class of elementary intuitive knowledge elements called 'phenomenological primitives' or p-prims (diSessa, 1983), which he described as "primitive elements of cognitive mechanism - as atomic and isolated a mental structure as one can find" (diSessa, 1993: 112). These hypothetical 'elements' of cognition are primitive in the sense of acting at an early (preconscious) stage of cognition, and identifying phenomena as matching common general patterns. P-prims are likely to originate in simple abstractions from familiar events and reflect patterns perceived in a broad range of situations (diSessa, 1996). According to this view, individuals tend to have multiple (and perhaps a great many) p-prims that can be very diverse, and do not have explicit and stable relations between them.

According to diSessa, Gillespie & Sterly (2004: 858) p-prims are "encoded preferentially in kinesthetic and visual-dynamic terms, making natural language description difficult and suspect". Individuals are not aware of the p-prims they hold or use to explain different phenomena, and neither are they aware of shifts in the p-prims that may be applied in the course of an explanation. Such p-prims, then, reflect aspects of the way the world is understood *that need no further explanation*. They provide a sense of satisfactory understanding of situations in which they are evoked as 'naturally' the way things are (Watts & Taber, 1996).

P-prims have proved useful to account for students' thinking in physics (diSessa, 1993, 2002; Hammer, 1996), and diSessa (1993) has offered a list of about three dozen candidate p-prims (classed in various ways, and characterised to differing degrees), based on his work exploring reasoning in physics.

Chemistry as a Context for Exploring Learning

The particulate nature of matter is acknowledged as being one of the key concept areas in learning chemistry (Taber, 2002), as well as potentially offering an exemplary case of the use of models in teaching about the nature of science (Harrison & Treagust, 2000; Justi & Gilbert, 2000). Research in this area has identified a wide variety of student conceptions regarding the nature of matter (Andersson, 1990; Eilam, 2004; Gómez-Crespo & Pozo, 2004; Harrison & Treagust, 2002; Mortimer, 1998; Novick & Nussbaum, 1981; Renström, Andersson, & Marton, 1990; Stavy, 1995; Tytler, 2000) and often these conceptions do not match the canonical target knowledge presented in the school curriculum.

Many of the conceptions that students are reported to hold are related to the tendency of students to interpret the microscopic world in macroscopic terms (Taber, 2001a) as well as to the difficulty of interpreting observable phenomena in terms of interactions between unfamiliar atoms and molecules (Gómez-Crespo, 2005). Among the most common conceptions reported in this topic are (Harrison & Treagust, 2002):

- macroscopic properties (hardness, conductivity etc) are attributed to particles;
- particles are considered to be mostly static.

The properties of matter emerge from a complex system

Chemistry is commonly taught at several 'levels' simultaneously (Jensen, 1998; Johnstone, 1991). Whilst some introductory chemistry teaching is based on the macroscopic properties and behaviour of substances, much school and college chemistry learning involves modelling matter at the 'sub-microscopic' level of 'particles'. These 'particles' are not the specks of dust and grains of salt or sand that learners are familiar with, but theoretical entities such as molecules, ions, atoms and electrons. Scientists tend to consider these entities as real, but they are not directly observable. Moreover, these 'particles' behave very differently from more familiar particles as they are on a small enough scale for quantum-mechanical effects to substantially determine their properties and behaviour.

At the quantum level, our world is very counter-intuitive. Molecules, ions and atoms can most precisely be modelled mathematically, although in chemistry a wide range of more visualisable models are used. 'Particles' at a scale where quantum-mechanical effects are highly significant can be understood as wave-particle hybrids – as fuzzy objects, without clear boundaries and so not having definite sizes, edges, volumes etc., and which are never strictly either touching or separated, but rather always overlap to varying extents. It has been suggested that referring to atoms, ions, molecules, electrons etc. as particles may therefore be misleading (as students often interpret the label as meaning these entities are just like grains of sand, only even smaller), and the collective term 'quanticles' has been suggested to mark this important distinction (Taber, 2005).

The macroscopic properties of matter – such as hardness, conductivity, immiscibility, melting temperature, solubility, reactivity etc. – and the behaviour of matter –evaporating, burning, reacting metals in acid with the release of hydrogen etc - are explained in chemistry in terms of extensive systems of quanticles. Phenomena observed in chemistry classes (and those used in the present research) are usually at such a scale that the macroscopic system comprises of many billions *of* billions *of* billions of quanticles.

Chemistry as a science, then, is concerned with complex systems, where the level of behaviour to be explained (the macroscopic) emerges from interactions at a very different level (quanticle models). In referring to 'levels' here "we are talking about the levels of description that can be used to characterize a system with lots of interacting parts" (Wilensky & Resnick, 1999). Wilensky & Resnick comment that

> We view confusion of levels (and "slippage" between levels) as the source of many of people's deep misunderstandings about patterns and phenomena in the world. These misunderstandings are evidenced not only in students' difficulties in the formal study of science but also in their misconceptions about experiences in their everyday lives. (p 4)

The significance of this issue for learning in chemistry cannot be over-emphasised. The most fundamental concepts such as 'substance', and the core distinctions between elements, compounds and mixtures need to be understood in terms of models at the quanticle level. Within modern chemistry, the rationale for considering hard slippery ice, our 'universal solvent' water, and scolding steam as the *same substance* (solid, liquid and gaseous phases of H_2O); but rust as *a different substance* to the iron that 'rusted' to form it, is largely in terms of models of the quanticles and their arrangements. Understanding the essence of chemical reactions, the core focus of the science of chemistry, depends in turn upon having a sound notion of 'substance', and appreciating how chemical change is modelled at the submicroscopic level.

Teachers have to find ways to 'construct' quanticles as conceptual entities for their students (Ogborn, Kress, Martins, & McGillicuddy, 1996). Chemistry tends to be taught by constant shifts between the phenomenological and quanticle model levels, using symbols (formulae, equations, names that apply at both levels) to mediate these shifts (Taber, 2009b). Overcoming students' learning difficulties in making sense of these shifts is one of the central problems of chemistry teaching (Gilbert & Treagust, 2009; Harrison & Treagust, 2002).

Physics, of course, also uses similar (and often the same) theoretical models at sub-microscopic scale, and many properties studied in physics (e.g. electrical resistance, elasticity) can also be seen as 'emerging' from extensive systems of 'quanticles'. However, it is in the nature of most physics concepts that much expert knowledge comprises of (often mathematical) formalisms that are independent of such models, which are not in any case usually extensively discussed in elementary physics teaching. The work of diSessa, Hammer and others on learners' intuitions in physics has therefore largely ignored this aspect to focus on the way students make sense of observable phenomena.

Applying the Knowledge-in-pieces Approach to Chemistry Learning

It has been recently been suggested that the 'knowledge in pieces' perspective with its focus on identifying primitive knowledge elements (such as p-prims) that are activated in cognition can offer insights into student conceptions in chemical topics (Taber, 2008; Taber & Tan, 2007) where students' ideas have commonly been described in terms of explicit knowledge structures such as alternative conceptions and conceptual frameworks. The present paper explores whether research into learners' ideas in chemistry might allow the identification of cognitive resources operating at the intuitive level. In the light of disciplinary differences between chemistry and physics this leads to the question of whether, should such studies in a chemistry context prove fruitful, they are likely to converge on conceptual resources already reported (such as diSessa's p-prims).

Our perspective in this study then is to approach our data (students' explanations of phenomena) from an inclusive cognitive resources perspective - that is not to rule out student responses being based on explicit theory-like knowledge structures (diSessa, 1993, 2002), but to make the "modest theoretical step to think of smaller parts than conceptions or naïve theories" (Hammer, 2004: 324) and to admit that student responses may often derive from implicit cognitive resources at a smaller 'grain size' (Smith et al., 1993) "that may be activated or not in any particular context" (Hammer, Elby, Scherr, & Redish, 2005: 92).

Available cognitive resources would *include* but not be limited to diSessa's p-prims, and might well comprise more complex notions such as 'coordination classes' (diSessa & Sherin, 1998) amongst many others. This perspective, which has been considered as "fine-grained constructivism" asks "what existing resources are activated and how are they used" when students construct their explanations (Redish, 2004: 9)

Significance of the perspective to informing pedagogy

Much of the research into learners' thinking in science has been framed in terms of seeing ideas elicited as alternative conceptions and conceptual frameworks which act as obstacles to science learning, and which need to be challenged and replaced (Taber, 2009a). This may sometimes be appropriate, but the knowledge-in-pieces perspective suggests that ideas elicited in research may instead often derive from the activation of resources for learning that can be refined and *developed towards* 'school physics' (and ultimately expert's physics) - rather than needing to be replaced (Duit, 1999; Smith et al., 1993).

Such a perspective certainly reflects findings from an early study of learners' notions of the 'molecule' concept carried out by Ault, Novak and Gowin (1984). They investigated the same individuals on two occasions (in second grade, and then in seventh grade) and found that it was better for a young pupil to have a variety of alternative conceptions rather than few conceptions at all, as understanding evolved more rapidly from a rich conceptualisation. If a pupil in an early grade held a range of idiosyncratic meanings these would tend to persist, but still provided a better structure for conceptual development than a limited range of notions.

Methodology

The data discussed here derive from an interpretative research project, which is based on qualitative data collected during semi-structured interviews with students in English secondary schools (11 – 16 years) using an iterative analytical approach to coding and interpreting data informed by the techniques used in grounded theory methodology (Glaser & Strauss, 1967; Strauss & Corbin, 1998; Taber, 2000a).

Interviews

The data was collected using semi-structured interviews about phenomena. The approach taken drew upon the widely used techniques of interviews-about-instances and interviews-about-events, as discussed by White and Gunstone (1992). The interview-about-instances approach is based on asking students about specific phenomena to elicit 'knowledge-in-action', rather than asking an informant to define a concept. For example, In Watts' (1983) study of learners' thinking about force, students were presented with line drawings (e.g. a figure playing golf) and asked whether the situation portrayed involved any force – rather than asking the student directly what a force was. As foci, we employed a collection of 14 different phenomena that relate to the different aspects of the particulate nature of matter that are commonly taught in school chemistry.

In interviews-about–events, phenomena are actually demonstrated rather than represented. In the present research, most phenomena were directly demonstrated, but a few familiar from everyday life were simply referred to in the interviewer's questions. The phenomena used in the study are listed and described in Table 1. The spreading of smells, the thermal expansion of metal, and the floating of ice on water were raised as 'thought' experiments, and the other phenomena were demonstrated during the interview.

Phenomena	Brief description
P1. Diffusion of vegetable dye in water.	A couple of drops of food dye (any colour) are added to water in a transparent glass. The dye starts diffusing as soon as it enters the water.
P2. Salt dissolving in water.	A pinch of salt is added to a glass with water. After some time (a few minutes), it is possible to observe that the amount of solid salt has diminished. Students are asked if the salt can be recovered from the solution
P3. Mixing of alcohol and water	50 mL of water (measured in a graduated cylinder) and 50 mL of alcohol (measured in a graduated cylinder) are mixed in a 100 mL volumetric flask. It is made evident that the total volume is not fully conserved. It is possible to set a mark on the flask and agitate the flask, so students can notice that volume diminishes even more
P4. Potassium permanganate crystal dissolving in water.	A small crystal of strongly coloured potassium permanganate is added to a beaker of water. The colour spreads from the crystal as the substances dissolves and diffuses, and eventually all of the water turns purple.
P5. Adding oil to water.	A small amount of oil is added to a glass with water. It is made evident that no mixing occurs.
P6. Adding sand to water.	A small amount of sand is added to a glass with water. It is made evident that no mixing occurs.
P7. Precipitation reaction.	A sodium chloride solution is added to a silver nitrate solution (both are transparent solutions). On adding, the mixture turns cloudy and some white solid slowly separates and settles to the bottom. The solid (precipitate) is silver chloride that is formed in the chemical reaction and is insoluble in water.
P8. Acid base reaction	A hydrochloric acid solution is laced with an indicator to give a red solution, and then some sodium hydroxide solution is slowly added until no further change of colour is noticed. The solution starts changing its colour due to the chemical reaction between aid and alkali. When the reaction is over, no further change of colour is noticed.
P9. Floating ice	Students are asked why ice floats in water.
P10. Evaporation	A small sample of water (in a glass) is heated with a hot plate.
P11. Heating wire	Students are asked to explain why it is that a metal expands on heating.
P12. Diffusing smell	Students are asked to explain how is that smell 'travels' from one end of the house to the other with reference to familiar events such as frying onion or smelling perfume.
P13. Compressing gas	Students are asked to explain why is it you can compress a sealed syringe when it is filled with air
P14. Combustion reaction	An alcohol burner is lit using matches.

Table 1: Brief description of phenomena discussed in interviews

During the interviews, students were asked to describe the phenomena, and to explain 'why does it happen that way'. The canonical explanations for these phenomena taught in school and college chemistry relate to the interactions (forces, bonds) between different molecules and ions, and the relative arrangements and motions of these quanticles. This leads to emergent behaviour - such as the colour of a dye spreading through a liquid. What is *observed* is a spreading-out of colour – not the movements and interactions of the quanticles. Where students did not spontaneously make any reference to particles in their explanation, they were then specifically asked to think about particles. The extent to which learners' responses matched the particle models presented in school science are reported elsewhere (García Franco & Taber, 2009).

The interviews typically lasted around 30 minutes, a reasonable time to expect students of this age to remain engaged, and a subset of the fourteen phenomena were discussed in each interview. Given the nature of the approach, it is necessary to try to follow-up students' thinking, so that the time spent exploring a particular phenomenon varied from case to case depending upon how much an individual student could tell us. That is, exploring students thinking in detail took priority over maximising the number of phenomena discussed. Interviews were fully transcribed for further analysis.

The sample

The interviews were conducted from April until July 2005. The interviews were undertaken with secondary age students from 5 comprehensive (non-selective, state funded) schools in the Cambridge area of England. All of these students were subject to the statutory requirements of the English National Curriculum, which set out the target knowledge that schools were required to teach in some detail (DfEE/QCA, 1999). Students were selected by their teachers; largely on the basis of those who would readily consent to an interview and were happy to answer our questions. Students were interviewed from across the secondary age range (11-16 years), and where we quote individual students below we indicate their grade level.

Our database from the interview study comprised a total of 48 interviews each concerning several different phenomena, and seeking to elicit students' explanations in depth. Seven of the early interviews in our research involved pairs of students from the same grade level, so that 55 students were involved in our study. However we found that for our purposes interviews from single informants offered fuller patterns of response, and so the majority of interviews were carried out with single informants.

The data discussed below derive from interviews with individual students: of which there were 41 in the database – from English school grades Y7 (3 interviewees); Y8 (8); Y9 (16); Y10 (13); Y11 (1). Students enter Y7 at age 11, so Y7 students interviewed would be 11 or 12 years of age; Y8 students would 12 or 13 years of age; and so forth. It was not our intention to either seek frequencies of particular responses nor age-related trends, but rather to look for the range of explanations that secondary students construct for these phenomena, so this sample was considered fit for purpose.

Data Analysis

Given our commitment to an 'inclusive' cognitive resources perspective we adopted an approach to analysis that started from a detailed consideration of individual cases using open-coding (Strauss & Corbin, 1998), to identify the features that seemed to reflect aspects of students' thinking about these phenomena. The analysis developed through iterative cycles of revisiting data using the process of constant comparison (Glaser, 1978; Taber, 2000a), allowing the development of categories reflecting commonalities between codes. It was possible to identify features that seemed to repeat in the interviews, allowing us to begin to develop 'category-like' constructs.

Some of the features that we identified (i.e. those discussed in this paper) appeared to derive from intuitive knowledge elements that were activated when the students responded to our questioning. In identifying features of student thinking which we consider to derive from intuitive cognitive resources we were informed by diSessa's (1993) heuristics for identifying p-prims as patterns perceived in common experiences, that come to be understood as the ways things are, and so the basis of intuitive notions of mechanism and (what seem to be) 'natural' ways of describing the world.

An explicitly represented conception is likely to be readily represented in verbal format ('an object needs a force to keep it moving', 'fires need oxygen', 'tress absorb material from the soil'): it is of the form of a proposition that allows it to be readily verbalised and used as a principle for an argument ('there must have been a force acting on the car because it continued to move along the road'). However an implicit knowledge element (such as a p-prim) is not directly available for use in this way: it leads to a form of *perception* that the student must then actively conceptualise in order to offer an explanation to the researcher (or teacher). DiSessa (2002) argues that p-prims have a problematic connection to language, and so describing them is difficult for the learner.

As such implicit knowledge elements are *not* applied in a principled way (i.e. in such terms as 'whenever I'm asked about covalent bonds, I think of atoms sharing electrons'), but are better considered aspects of perception or intuition, we can only expect student responses in explaining different phenomena to be consistent to the extent that those phenomena *are perceived* as matching the same basic intuitively identifiable patterns. It is of course this ability to potentially make sense of students' comments that seem inconsistent from a 'principled' conceptual perspective that has encouraged some physics educators to champion the usefulness of cognitive resources such as p-prims in explaining student thinking (diSessa, 2002; Hammer, 1996). Many complex phenomena may offer potential fits to a number of primitive patterns, so that it may not be obvious which features of a particular context appear most salient to any individual learner. That is, cognitive resources that are potentially applicable to a given phenomenon will not be activated in all circumstances.

So in identifying intuitive knowledge elements that students drew upon in their explanations we looked for instances where respondents were able to report features that they found obvious (e.g. rather than inferred from learnt theoretical principles) and natural (so as self-evident not to need further explanation) in describing the mechanisms or causes accounting for the phenomena discussed, but for which they were not able to spontaneously offer any deeper justification. Students are not able to offer an account of how they acquired such an understanding, but each of our themes can be understood as an abstraction for common familiar experience. As will be discussed below, these implicit notions related to identifying specific sources or causes for some types of changes, and perceiving natural tendencies to be sufficient explanation of other changes.

Some of the initial codes were related to actions of the particles (e. g. particles doing things such as washing, eroding, etc) and these codes became categorised under a theme relating to how some students tended to look for a 'more active' agent responsible for the reaction between different substances (our theme 3, below). There were also instances of students talking about properties being *transferred* (i.e. when the dye mixes with water, it transfers the green colour). This later category did not make it to the final analysis, but was incorporated in a more general one (our theme 1).

We were careful not to interpret and code individual utterances without consideration of the wider context of dialogue within an interview, aware of the danger that a student's phrasing may give a misleading impression of their thinking (especially when reporting the outcome of activating implicit knowledge elements). So for example, when Fred, a Y9 student, was asked about potassium permanganate dissolving in and diffusing through water (phenomenon 4, P4) he initially replied to the effect that the water was "making the dye come out, they are like dissolving". Although the first part of this response might be read as reflecting our theme 1 ('*component gives property*'), with the colour ('the dye') being seen as a discrete component, he later explained the colouring of the solution in terms that "the molecules of the purple thing would probably spread out", suggesting that for Fred the colour was an inherent aspect of the substance, and not a discrete quality.

Findings

We propose five themes, which allow us to make sense of the complex data gathered during the interviews, and that relate to an intuitive interpretation of phenomena. We will first present the themes we consider useful in describing students' explanations in our data and then we will illustrate them with some fragments from the interviews with different students. In order to identify students we have used assumed names (that respect gender) and identified the school year (grade level) they were in at the time of the interview.

Focus of theme	**Theme**	Brief description	Note
Inherent property	**T1: Component gives property**	Substances' properties derive from *components* that have an inherent property	e.g., a blue substance has some component that is inherently blue
Causation needs explaining:	**T2: Changes require active agents**	Change requires cause (unless 'natural')	e.g., something external (heat, mixing) causes change
Causation needs explaining:	**T3: There is one active partner**	A reaction involves an active partner acting on a passive partner	the active 'chemical' forces another chemical to *react*
Inherent nature	**T4: Substances (naturally) react**	Reacting is the natural process when certain substances interact	it is in the nature of certain chemicals to react with suitable substrates
Inherent nature	**T5: Things have a (natural) predetermined configuration**	Certain configurations are natural	systems will spontaneously evolve towards certain 'natural' configurations

Table 2: Five themes identified in the study

The themes that we have identified in the study are listed in Table 2. Each of these reflects some aspect of how we believe students intuitively perceive the phenomena we presented, and as such seem to need no further explanation. These five themes relate to patterns that reflect the nature of things (inherent properties) and the nature of causality.

Theme 1: Component gives Property

The idea that there is 'something' in substances responsible for their properties is familiar to chemistry teachers. Research has found that it is common for students to inappropriately assign to a compound, properties of its 'constituent' elements, such as suggesting that *a compound of* fluorine must be a gas because fluorine *is a gaseous element* (Levy Nahum, Hofstein, Mamlok-Naaman, & Bar-Dov, 2004).

Our data suggests that this might reflect a broader thinking pattern: considering that a property of a substance (such as being blue, or reacting with another substance) derives from some component responsible for that specific property. It is as if the single substance is considered as a complex of *qualities as components* each contributing a property that may be considered in isolation. This often seems sufficient for students as an explanation of changes that occur when mixing substances or during chemical reactions.

For example, when asked to explain what happened in a precipitation reaction (P7, phenomena 7 in Table 1), Harold, a Y9 student, states that:

> It's the silver in there or one of the parts from the silver nitrate that is in there has made it all milky because it is a cloudier substance…You've got the salt in there, you have the salt, and then you have the hydrogen and the oxygen and then there is some, that is the silver and I think it's the silver that is making it all cloudy because that is the metal, is it a metal? Yeah! Silver is definitely a metal.

It seems that Harold is attempting to construct an explanation that starts by reporting the components in the mixture "parts from the silver nitrate…the salt…the hydrogen and the oxygen". When he thinks of silver (and reasons in terms of the properties of metals, i.e. colour and texture) he seems to need no further explanation: "it's the silver that is making it all cloudy because that is the metal". Later on, when noticing that there is a solid in the bottom of the beaker, he says "I don't think silver dissolves because I don't think it's soluble, so I think that [solid in the bottom] is silver". For Harold, silver, a metal with its solid properties, is a component of the clear silver nitrate solution.

Similar comments were offered by other students. When Charlene, a Y8 student, discussed salt dissolving in water (P2 – see Table 1), she refers to both the pure substances involved as having components: "is there *something in the water* that … reacts with the salt… *something in the salt* reacts with the water".

Considering this phenomenon, Y9 student Katherine referred to how the water molecules would "react with the chemicals *in* the salt". In Katherine's discussion of the precipitation reaction (P7), she suggested that the cloudiness observed when the two clear solutions were mixed might be due to a component of the salt: "perhaps a chemical *in* the salt that makes it cloudy…maybe the sodium or something that reacts with the silver or the nitrate" to "make it cloudy".

Elicia, a Y8 student, explained why potassium permanganate leaves colour trails in the water (P4) in terms of *the colour* leaving the crystals: "the colour is like coming off them [potassium permanganate crystals], not all of them, it leaves like trails and is kind of dyeing the water" and later "the colour just come off, it's kind of like [pause], it's like when you have something solid that is pink and then it comes off". Elicia 'explains' the phenomena observed with the potassium permanganate crystals in terms of a general pattern she has abstracted from observations with everyday coloured solids. However, this is not an explanation in the sense of applying a theoretical framework, as Elicia said that she did not know *why* the pink might 'come off' something. Rather this is a just a commonly observed pattern.

When prompted to think about particles Elicia then tentatively suggested "maybe it's like the particles are just packed together in a solid and they come off in the water (…) I don't know". This seemed consistent with her explanation of salt dissolving in terms of how "particles like separate and join into the water". However, Elicia did not *spontaneously* think about the potassium permanganate in terms of particles when describing how "it's kind of dying the water…it just changes the water".

In these examples the students seem to be treating a property as linked to one component of (what to a chemist is) a pure single substance: silver in silver nitrate; 'colour' in potassium permanganate; something (perhaps 'a chemical') in the water or the salt. From a canonical chemical perspective it is clearly inappropriate to consider properties of pure single substances as being due to components. One interpretation of this theme is that these students have not acquired the chemical concept of a substance, and so do not appreciate why it is inappropriate to think in terms of components in this context. We are not arguing against such an interpretation. Rather, we suggest that where students already have a readily activated intuitive knowledge element which (often quite appropriately) assigns specific properties to components, then this is likely to be activated in observing phenomena in chemistry classes. When this happens it fits these phenomena into a familiar way of seeing the world: one that enables the student to interpret what they see without appreciating the chemical perspective.

We feel this reflects activation of some primitive element within the cognitive system. It can be understood as a commonly experienced pattern that could be readily abstracted into a primitive intuition – in diSessa's terms it can be seen to have unproblematic genesis. There are many mixtures, composite materials and complex systems where it is perfectly appropriate to identify particular properties of the whole as due to particular components. The challenge for the chemistry teacher is to guide the students to appreciate pure substances as being in a sense fundamental units of material that cannot be understood as having subsidiary parts.

Whereas 'alternative conceptions' are *necessarily* inappropriate (representing explicit propositional knowledge elements contrary to canonical science), the cognitive resources perspective does not seek to classify 'right' or 'wrong' conceptions among student utterances, but rather looks for underlying intuitions which may lead to appropriate scientific thinking in some contexts, but not in others.

Component gives property can be a very powerful conceptual resource when thinking in macroscopic terms because when dealing with mixtures or composite materials it *is* often actually different components of a given material that give it its characteristic properties. However, when applied to explain properties of single substances this would imply that there are quasi-independent qualities within pure materials. The scientific explanation would not be in terms of a set of distinct components, but rather the emergent properties of vast numbers of similar quanticles interacting. This theme then reflects a pattern that is useful in many macroscopic contexts, but which generally channels student thinking in inappropriate directions when used to make sense of macroscopic phenomena in terms of the particle models of science.

To reinforce the point that an implicit knowledge element such as '*component gives property*' should not be considered in itself to be 'wrong', it is worth considering that some of the properties of aqueous silver nitrate *are* understood in terms of the properties of the silver cation in the context of various solution systems, i.e. in the presence of various counter ions such as the chloride anion;

just as some of the very different properties of silver metal are understood in terms of the properties of the same silver cation as part of the rather different system of the silver metallic lattice. The challenge for the teacher here is to refocus the student's intuitive thinking away from seeing the solution as having macroscopic components (there is no metal silver in silver nitrate solution), to thinking about the quanticles present (such as the silver *ion* which is a common system 'component' in silver metal, solid silver nitrate, silver nitrate solution, and the silver chloride precipitate formed in the precipitation reaction demonstrated in our study).

An intuition that '*component gives property*' can also prove fruitful in other contexts. Chemistry students are taught the concept of a functional group, where certain parts of a complex organic molecule are associated with particular properties. Students will be asked to appreciate that, for example, a molecule that includes the feature 'C=C' (a carbon-carbon double bond) will usually readily undergo a class of reactions called addition reactions, and so will exhibit particular behaviour with certain types of reagent. Learning such a principle so that it becomes represented explicitly in cognitive structure, and so open to conscious access and ready application and verbal report, may well be more easily facilitated if the learner initially perceives teaching about functional groups in terms of implicit activation of the '*component gives property*' pattern.

Theme 2: Changes require Active Agents

Mixing (and diffusing) are primarily the consequences of the intrinsic motion and interaction of the quanticles. When such mixing phenomena were presented to students in these interviews, their responses often suggested an intuition of the need for an actuating agent (commonly heating or stirring) that could explain the observed changes. William (Y7) did not expect salt to dissolve in water (P2) without heat and 'mixing' (e.g. stirring).

> 1. I: So, what happens if I put some salt in here [in water]?
>
> 2. W: It just goes to the bottom.
>
> 3. I: Do you think it's ever going to dissolve?
>
> 4. W: I think it's just gonna stay at the bottom.
>
> 5. I: What would we need for it to dissolve?
>
> 6. W: You mean, hot water, and mixing.

> 7. I: Why does hot water help?
>
> 8. W: Because it is hot and makes the salt dissolve faster.
>
> 9. I: Why does it make the salt dissolve faster?
>
> 10. W: Because of the heat, mainly because of the heat.
>
> 11. I: So, what does the heat does to the water?
>
> 12. W: I don't know.
>
> (I: Interviewer, AGF; W: William, Y7 student).

William seems to neither be aware of (line 12), nor have any motivation to seek (as it seems obvious), a mechanism by which heating might facilitate dissolving (lines 8, 10): but to his mind heat provides a suitable agency, without which the salt will remain at the bottom (lines 2, 4).

As another example, after coloured potassium permanganate crystals were added to water (P4), Jerome (Y9), seems to actively seek an external agent even when it is not evidently present in the situation:

> 1. I: Why do you think is making like this, funny lines?
>
> 2. J: Oh! Isn't it that a convection current, or something?
>
> 3. I: Why a convection current?
>
> 4. J: I don't know, because the water might be warmer at the top, I think [pause], no at the bottom, and then if it's more denser, then it would go up to the top and then as it gets colder at the top, then it would become less dense and then go to the bottom again.
>
> 5. I: Okay, so why should it be more warm at the bottom than at the top? We are not heating it up or anything.
>
> [pause]
>
> 6. J: The paper [beneath the beaker] might be warmer [pause] because the reaction is increasing heat, the reaction might be.
>
> 7. I: So [pause] we necessarily, we need it to be different temperatures for it to move?
>
> 8. J: Yeah.

> 9. I: If I assure you that it's all the same temperature, would it be moving or not?
>
> 10. J: Probably wouldn't be moving, no
>
> (I: interviewer, AGF; J: Jerome, Y9 student)

In this extract Jerome explains the 'funny lines' (as the coloured permanganate ions diffuse through the solution) as being due to a 'convection current or something' (line 2). Although there was no obvious reason for there to be a convection current, we note that Jerome appears to appreciate something of the nature of convection, relating it to density variations, which would be due to temperature differences (line 4). What we find significant is Jerome's confidence that the colour would not be able to spread without heat or some other external agent to cause movement (lines 8 and 10). Jerome was asked to think about what has happening in terms of particles

> 11. I: How do you imagine these particles? Can you draw for me, how do you imagine these particles?
>
> 12. J: Well, like, what is it? The purple stuff, what was it?
>
> 12. I: Potassium permanganate.
>
> 13. J: They'd might be like, say, this, they might be just going down, and then in the water, they might just be joining together with like the H-2-O, water and then [pause], they join onto other ones.
>
> 14. I: Ok, so they are getting together?
>
> 15. J: Yeah.
>
> 16. I: Why do you think they are joining together?
>
> 17. J: Why?
>
> 18. I: Yeah, why do you think they are joining together?
>
> 19. J: Because it is all spreading out, if they didn't join together, the potassium permanganate would just go to the bottom and it wouldn't do anything
>
> (I: interviewer, AGF; J: Jerome, Y9 student)

As elsewhere in our presentation of data, we are wary of over-interpretation, but there are two points we find of interest here. Firstly the notion that the potassium permanganate would not 'do anything' (line 19) of its own accord seems to show that even when asked to think in terms of particles, Jerome still sought an identifiable active agent to bring about change. Secondly, Jerome's repeating of 'why' in line 17 suggests that at this point he was reporting what seemed obvious to him (Watts & Taber, 1996).

A similar response to this phenomenon was offered by Bert (Y8). Bert expected the purple colour to spread through the solution, even though "the purple stuff looks heavier". When asked why, he volunteered that "maybe, because there is heat, and makes it rise". There was no obvious source of heat in the interview situation, and Bert could only suggest the sun as the source.

Another causative agent invoked to explain how dissolving could occur was stirring. This possibility was suggested by Andrea, a Y9 student, when observing some salt that had been added to a beaker of water (P2):

1. I: How is this process of salt dissolving going to happen?

2. A: It will start to dissolve, if you stir it

3. I: If I don't stir it, you don't think it is going to dissolve?

4. A: I think some of it will

5. I: Why is it?

6. A: Because the particles move around more, so they can still dissolve

7. I: So, if I don't move it, do you think it is going to dissolve?

8. A: No

(I: interviewer, AGF; A: Andrea Y9 student)

Presumably this was not the first experience of salt dissolving in water for this 13-14year old girl, but she introduced the notion of stirring being required, despite the interviewer having made no attempt to stir. Later in the interview, Andrea was asked again about the dissolving salt, and she suggested that "at some point the water will be saturated, it can't dissolve any more. [Pause] I think it will dissolve if you stirred it". When asked why, she explained that "it will dissolve pretty slowly because they [the particles] are not moving that much". When asked whether salt left in water would dissolve over several days, Andrea remained uncertain,

9. I: If I just put water with salt in it for like three days, do you think it will dissolve
or you necessarily have to stir it?

10. A: I don't know

11. I: What's your guess? Do you think it will dissolve?

12. A: I think it's very hard. I don't know if it would actually dissolve

(I: interviewer, AGF; A: Andrea Y9 student)

It seems Andrea's intuition tells her that particles do not move of their own accord, and she finds it hard to consider salt could dissolving spontaneously.

Fred, a Y9 student, refers to both stirring and heating as possible actuating agents in the context of salt dissolving in water (P2), suggesting first that when added to water, salt "would sink to the bottom, but if you stirred it, it would become a solution" and later that if the mixture was heated, then "the heat is pushing like the convection current, so eventually it would all dissolve into the water". In these examples students tend to look for extrinsic causes even when these are not needed from a scientific perspective.

Intuitions about agents being responsible for bringing about changes are considered to have their origins in very early life experiences. The examples we present of students activating such intuitions involve the mapping of a macroscopic cause (stirring, heating) to a context where the canonical cause is located at a different level of analysis (inherent motion of quanticles). Both stirring and heating are regularly used to increase the rate of mixing and dissolving (in science lessons, and in everyday life – such as in cooking), providing opportunities for young people to recognise agency at work in facilitating these processes.

Although the solubility of salt is not changed significantly by increasing the temperature many students are likely to be familiar with situations where heating *will* increase the amount of a solute that will dissolve in a certain volume of solvent – the number of spoons of sugar that will dissolve in a cup of tea or coffee for example. Students are likely to be much less familiar with observing situations where solutes are left to dissolve without heating or stirring (which is often an inconveniently slow process).

If Andrea's suggestion that salt needs to be stirred into water to dissolve was considered to be a report of a specific belief that is explicitly represented in cognitive structure, then it might be described as an alternative conception to be challenged. However, if her comments are understood to reflect the activation of an implicit knowledge element that primes her to seek a cause when material changes its form, then the teacher's task is to harness the intuition to support learning about the canonical cause.

So such an intuition can potentially be fruitful in teaching chemistry. Close observation of solutes dissolving at room temperature without stirring, followed by observations of the same systems but with stirring or heating could shift the activation of the intuited need for agency *to explain the change in rate*, rather than the dissolving process itself. This would allow the intuitive element to act as a starting point in considering why stirring or heating might 'speed-up' dissolving, with the focus on what is happening in terms of the quanticles in the solute-solvent system.

Similarly, a teacher could also demonstrate examples of reactions that are clearly perceptible despite the reaction mixture being kept at low temperatures (as when using an ice bath to limit the rate of a normally very vigorous reaction). Having established that some reactions obviously occur when there is clearly no heat source, the teacher could turn to a reaction that was imperceptibly slow until heated (for example a sample of a metal of moderate reactivity with a dilute acid solution). This could provide a context for asking why heating appears to be necessary in some cases, but not others, as an introduction to thinking about the effect of heat on the inherent motion of the quanticles present.

So, a sense of agency, and the expectation that effects have causes (*changes require active agents*) are not in themselves to be discouraged: there are many places where this could be a useful intuition in learning chemistry. For example, many reactions that do not occur to any perceptible extent under standard conditions will occur at substantially greater rates when a suitable catalyst is introduced. Perceiving the catalyst as a kind of change agent would be a suitable starting point for exploring the role of the catalyst in the system.

Theme 3: There is One Active Partner

We also found that students commonly suggest that when substances interact, *one* of the substances is considered responsible for the changes: e.g. the substance that is perceived as "strongest". One substance is viewed as the active partner whereas the other substance involved has a more passive role.

For example, we found that when a precipitate is formed after silver nitrate solution is added to a sodium chloride solution (P7), some students consider the silver nitrate as the active agent, and so ultimately responsible for the changes perceived. For example, Vernon (Y9) talked of the silver nitrate "making the water cloudy", being "a stronger substance than water". Jerome (Y9) seemed genuinely surprised by the immediate formation of the precipitate when shown this phenomenon, but he readily constructed an explanation in terms of one of the chemical substances acting upon the other: the silver nitrate *acting upon* the salt (sodium chloride):

> I think silver nitrate is putting like a coating in all the salt particles because of the silver, maybe [pause] it's making it, like, visible, because before, when it is dissolved you can't see it, so maybe the silver nitrate makes it more visible because [pause] it's making it shiny, so you see it better.

That Jerome attributed the change to the silver nitrate appears to be an example of associating it with the properties of silver metal (i.e. '*component gives property*').

Lizzie, a Y9 student, predicted that when salt was added to water (P2), "the salt is going to dissolve, because the grains of salt would kind of be absorbed by the water, then it would turn into saltwater rather than water with salt". Later when asked about the reaction between sodium chloride (salt) and silver nitrate (P7), she referred to how "the silver nitrate thing…reacts with the water *to make it* coloured" (again seeming to suggest one partner acted upon the other). As she had referred to salt particles earlier, Lizzie was asked about them, and she suggested that "the salt particles have been *changed by* the water" and that "maybe those particles from the silver nitrate" could be "changing the water particles".

Lizzie's ideas do not seem to represent some sort of pre-established conceptual framework about what happens at the particle level during such processes. Rather she seemed to be making sense of the phenomena by using her intuitive understandings to construct a particle-based narrative. Her attempts to tell a story at the particle level were based upon one type of particle acting unilaterally upon another, so when observing the precipitation reaction (P7) Lizzie suggested that "it's changing the water particles".

Bert (Y8) was shown some potassium permanganate crystals being added to water (P4). He described how the crystals "are dissolving in the water and they change colour", where dissolving meant "the water is reacted with it and turned it into a different colour liquid". Later in the interview, Bert was asked about dissolving again, in the more everyday context of salt added to water (P2):

> 1. I: What if I just put water again and salt again, what happens with that?

> 2. B: Well it's kind of like dissolving either into the water, or the water is like eroding it, you could say it's mixing in with the water.
>
> 3. I: What do you mean by eroding it?
>
> 4. B: When it hit the water, kind of make the material [pause] melts, they can totally, it was a liquid but it turned to a solid, but when the solid goes back to a liquid, the water kind of erodes it and washes it.
>
> 5. I: So, the solid is turning into a liquid?
>
> 6. B: Yeah.
>
> 7. I: … How do you imagine the salt particles are being broken off?
>
> 8. B: You pour in the salt, and then it kind of disappears, and then, …so, the salt crystal, this bit here, it's where the water slowly dissolving it and making into a liquid and soon it would all be dissolved
>
> …
>
> 9 I: If you think there are particles in the water, would [this] help you to explain this eroding, dissolving, mixing…?
>
> 10: B: Well, the particles of the salt, when they go into the water, they might react with the particles in the water and the water particles might destroy, you could say, but not really destroy them, they make their way and then this bit mixes in with the water.
>
> (I: interviewer, AGF; B: Bert, Y8 student; '…' indicates extraneous material omitted)

The explanation seems somewhat confused, seeming to offer a hybrid of taught and more implicit ideas, but there is a clear sense that Bert's intuition was that the water was *doing something* to the salt, something described in rich vocabulary – *eroding* it (lines 2 and 4); *washing* it (4); *dissolving* it (8); *making* it into a liquid (8) – if not actually *destroying* it (10).

When Charlene (Y8) was shown salt added to water (P2), she also described dissolving in terms of the water acting on the salt:

> 1. I: I'm just going to put tap water in here and then this is just salt, so I'm going to put some salt in here and I just want you to tell me what is going on in here, what is happening with the salt?
>
> 2. C: The salt dissolves, it's dissolving in the water.

> 3. I: How is this process of dissolving?
>
> 4. C: The water is kind of making it smaller and smaller.
>
> 5. I: How is it… that the water makes it become smaller and smaller? Because we have these grains we can see, and after it dissolves we are not going to be able to see them any more. How is this? How do you imagine this process?
>
> 6. C: Is there something in the water that makes it [pause] that reacts with the salt? Kind of just makes it smaller and smaller.
>
> …
>
> 7. I: Why is it the water can do this, how is the water like? How do you imagine the water?
>
> 8. C: I just imagine the water would erode it in a way [pause] rubs against the salt, [pause] something in the salt reacts with the water, so [pause] it kind of makes it smaller and smaller either by compressing the salt in some kind of way or like just making each grain of salt gradually just like fade away into little particles and makes it like little particles come apart and eventually each grain of salt must have lots of little particles, it just splits in half and then again, and then again…
>
> (I: interviewer, AGF; C: Charlene, Y8 student; '…' indicates extraneous material omitted).

For Charlene water seems to be the active partner, doing something to the salt: "the water is kind of *making* it smaller and smaller" (line 4); "the water would *erode* it in a way [pause] *rubs* against the salt, [pause] it kind of *makes* it smaller and smaller either by *compressing* the salt in some kind of way or like just *making* each grain of salt gradually just fade away" (line 10). It is possible to infer in this excerpt an anthropomorphic sense of the water's *intentionality* in rubbing against the salt, and it is the water's actions that lead to the observed change.

As we suggested in considering theme 2 (*Changes require active agents*), an intuition that changes are brought about by some agent is considered an early-developing feature of human cognition. Children's earliest conceptions will be tied to actions: they pull, push, suck, cry etc, to bring about desired changes. Where such actions are intended to bring about an effect there is a clear asymmetry in the relation between the active agent and the passive subject. In terms of canonical physics, the baby and the blanket pull upon each other to an equal extent, but for the newborn making sense of the world in human terms, there is a clear distinction between the conscious agent and the passive subject of that agency.

Such a common and well-established pattern can readily be activated - in diSessa's (1983) term, there is a high cuing priority. We have offered examples of students inappropriately describing the interactions between quanticles in terms of one type of particle acting upon a passive partner. This will generally be unhelpful in learning about the nature of quanticle interactions.

However, this need not always be the case. Greg (Y8) explained that "the water washes away all the particles from the salt and ends up into like single particles, surrounded by water and then it is not visible anymore", identifying the water as the active agent which determines the outcome of the mixing of both substances. Katherine (Y9) explained how water molecules "react with the chemicals in the salt, and they break it down, they break particles down in smaller pieces so, you can't see them anymore". Whilst such descriptions do not consider the interactions *between* quanticles that are important for solvation to occur, they none-the-less offer a rich starting point for visualising dissolving in terms of particle models. The imagery suggested by these accounts offers a teacher the basis for developing canonical accounts: for example discussing the extent to which the interactions represented in suitable computer simulations fit with pupils' own explanations.

Theme 4: Substances (Naturally) React

Whilst 'reaction' has a precise and central meaning in chemistry, this is not always appreciated by learners, so in students' accounts of 'reactions' they are sometimes using this term in an everyday sense, to label a much more inclusive class of events than those intended when a chemistry teacher uses the term. Whilst this distinction is of great importance to learning chemistry, we here simply acknowledge that what our informants meant by 'reaction' may not fit the canonical chemical meaning. So for Y8 student Bert a reaction meant "two things when put together, either change or something happens…Like, they might change form or something might happen, like something might come out and like might change its form".

When Dave (Y10) was shown the mixing of water and ethanol (P3), he suggested that "they are coming together forming a new product", and explained that this was "[be]cause they are different and they collide and form new products". He confirmed that it was his expectation that *whenever* two different substances were put together, they would form new products.

Lizzie (Y9) described the precipitation reaction (P7) as "some sort of reaction" where "maybe like two substances put together and gives you kind of an acid or something, like the things that are in it, they kind of make other things".

Katherine (Y9) seemed to activate an implicit knowledge element that allowed her to make sense of a variety of phenomena in terms of a reaction being the natural outcome of adding different substances together. So, when asked about when water and ethanol were mixed (P3), Katherine considered this a form of 'reaction', suggesting that in particle terms "one of the particles from the alcohol would probably join the particles from the water…Because they react together, because there would be a reaction…Because you put them together, so they will form a compound". Katherine predicted that the total volume of the liquid would not be conserved "because some of the water will react with the alcohol, so they'll join". Her prediction was confirmed, and she explained that "there were two different elements, there was water and there was alcohol, but now they have reacted together, they are joined together so they take up less space because they are joined together…I think they are all joined together, all the ethanol and all the water, so they took up less space".

When Katherine was then shown some salt added to water (P2), she suggested that "the salt would gradually start to dissolve" and that this was "because it reacts with the water (…) and when it reacts it starts to dissolve into it". Later in the interview Katherine was shown the precipitation reaction between silver nitrate and sodium chloride solutions (P7). She explained that "the nitrate will react with the salt and the water…*because when you put two things together they will always react*".

The theme '*substances (naturally) react*' implies that substances react because that is the way things are and so there is no need to explain further what goes on during a chemical reaction. From this perspective, it is in the nature of some combinations of 'chemicals' to react. Presumably, this relates to familiarity with common phenomena from a young age, probably reinforced by the way such ideas are described in usual 'life-world' dialogue (Jegede & Aikenhead, 1999). This theme does not obviously directly relate to any of diSessa's p-prims, but given that the deliberate addition of one substance to another (in everyday life, as well as in school science laboratories) is usually intended to bring about a perceivable change, the origins of an abstracted intuitive pattern that substances naturally react would not seem problematic (cf. diSessa's (1993) principle of unproblematic genesis).

Clearly, it is equally common that many combinations of substances do not spontaneously react (to any meaningful degree), else our surroundings would always be in a state of significant flux: it should be apparent to Dave, Katherine and other students that "*when you put two things together they will [not] always react*". Salience is likely to be significant here: non-reaction does not present an obvious phenomenon to be explained, and may be akin to those classes of event that diSessa (1983) has noted tend not to be readily noticed (such as deflection, and the role of pivoting in rolling) unless the context is manipulated to increase their salience.

In everyday life, most materials (e.g. those in furniture, clothes, even food) are not usually considered in terms of being composed of chemical substances (or composites of chemical substances), but simply in terms of their functions in relation to people (e.g. to be sat on, worn or eaten). Cues likely to lead to materials being recognised as a chemical substance – such as being found in glass bottles in school laboratories, for example, or household cleaners labelled with chemical hazard symbols – activate expectations about reactivity that are otherwise dormant.

The issue here, then, is not one of an always-inappropriate intuition, but the blanket activation of the intuition in contexts where substances are considered 'chemicals'. The teacher could actively build upon such intuition, using a similar approach to that suggested under theme 2 (*changes require active agents*) by demonstrating different combinations of 'chemicals' that both meet and confound such expectations. This can provide the contexts to help the student move beyond the intuition, to consider the chemical models for *why* some substances are considered more reactive than others.

Theme 5: Things have a (Natural) Predetermined Configuration

We identified a theme in learners' explanations that some changes occur, because there is a ('natural') tendency to achieve a predetermined configuration or disposition, at which point change ceases. So for example, Patrick (Y10) explains why food colouring spreads through a beaker of water (P1):

> 1. I: I have here tap water, and I'm just going to put two drops of this food dye, what happens and why does it happen that way?
>
> 2. P: It's diffusing.
>
> 3. I: What do you mean by diffusing?
>
> 4. P: It's spreading out.

5. I: Why is it that it diffuses?

6. P: 'Cause it tries to move from a high concentration to low concentration

7. I: Why is it that it moves from a high to low concentration?

8. P: 'Cause, I don't know how to explain it. It's like it needs to balance out. I don't think I can really explain it.

9. I: It's kind of balancing out?

10. P: It's balancing out and then it gets even.

11. I: When you say even it's…?

[Pause]

12. P: The colour is spreading out everywhere.

13. I: If we leave it like that, we don't stir it, we don't heat it, do you think it is going to eventually become all red, the water? Now it's a little bit, on the bottom.

14. P: Because the food dye is heavier than the water, you have to wait for it to diffuse out.

15. I: So if we leave it like that, what do you think is going to happen?

16. P: It depends how heavy the colour is, if the colour is really heavy or quite heavy, it is going to stay in the bottom, if it is similar to the bottom it is going to spread out.

17. I: So, what do you think? Is it heavier?

18. P: It's going to spread out, because that is what is supposed to be.

(I: interviewer, AGF; P: Patrick, Y10 student)

In this extract Patrick seems to be weighing up (or balancing we might say), two intuitions about the behaviour of substances. He thinks that food colouring will 'spread out' (line 4), but also that when two substances are mixed, a large discrepancy in heaviness can impede this spreading (16). In scientific dialogue heavy implies weight, but we feel Patrick's use of 'heavy' is better understood in terms of density (students often use such terms in undifferentiated ways). There were a number of references to heaviness and related ideas in our data, which were sometimes quite appropriate in terms of the mixing phenomena discussed.

The extract ends with Patrick suggesting that here the outcome will be spreading out (rather than collecting at the bottom) as "that is what is supposed to be" (18). However, when Patrick was asked to explain why diffusion (spreading out) occurred (4), he seemed to be tapping into an intuitive understanding of diffusion: the food colouring "tries to move from a high concentration to low concentration" because "it needs to balance out" (8) and "get even" (10), so it was "spreading out everywhere" (12).

We consider this exchange to draw upon cognitive resources at the level of intuitive knowledge, as Patrick seems to have a clear expectation that diffusion is something that occurs, presumably because seeing coloured materials (food colouring, ink, bath salts) spread through water is a common experience (cf. diSessa's principle of unproblematic genesis). When asked to explain why this should be, Patrick's responses become tautological: spreading out occurs - to move material from a high concentration to a low concentration - to balance out - to get even - to spread out. His explanation is circular and so in effect a series of re-descriptions (Taber & Watts, 2000) - and he seems to have a clear intuition of what is occurring that he finds hard to phrase verbally (cf. diSessa's principles of impenetrability): "I don't know how to explain it, it's like it needs to balance out, I don't think I can really explain it" (8). This seems to be a report of a familiar pattern (spreading out, evening out) linked to a notion that things 'naturally' balance out, such that there is a teleological sense to the explanation (signaled by the anthropomorphism of "it tries to…" in line 6).

In the context of dissolving and diffusing potassium permanganate (P4), Bert (Y8) suggested that that "the purple stuff looks heavier than the water because it is mainly at the bottom and kind of spread out through the bottom", but he did think that "the whole thing will become purple": either "because there is heat" or because "it just spreads out slowly and becomes more liquidy". The use of the word 'just' may seem incongruous, as the spreading out was what needed to be explained – however, we suspect 'just' stands for that which needs no further explanation – that which 'just' naturally happens - without the intervention of heating in this case.

Andrea (Y9) used anthropomorphic language when asked to explain the purple potassium permanganate spreading through water (P4), referring to how "the particles sort of, spread as far as they can". When asked why things mix, she paused before suggesting that "there is like convection currents and stuff, in the water, would help things mix". Although the reference to convection currents reflects our Theme 2 ('*changes require active agents*'), it seems that the spreading was something that Andrea spontaneously perceived as natural and not needing an explanation.

The genesis of this intuition is unproblematic, given that spreading out is a pattern that can be abstracted in many situations – bath salts in water, cooking smells around a house, mud walked into a house, powders and liquids spilled form their containers, etc.

The issue for the teacher is not to challenge this intuition, but rather to link it to appropriate scientific models. Particularly relevant to the phenomena discussed here, once again is the counter-intuitive but important notion of particles having intrinsic motion: and in this regard computer simulations could be used to relate a scientifically appropriate mechanism to students' intuitive understanding of the world. The challenge is to make problematic something that is just accepted as natural: i.e. drawing students' attention to their being a phenomenon to be explained. This might involve comparing examples where mixing is clearly seen, and those (such as shaking oil and water) where after active mixing there is readily observed spontaneous separation.

Whilst 'things have a (natural) predetermined configuration' can stand in place of seeking scientific explanations, it could also be a productive starting point for more advanced teaching about the importance of energy minima (in understanding reaction profiles and aspects of molecular geometry) and the role of entropy as a factor in determining reaction equilibria.

Exploring Students' Ideas in Chemistry from an Inclusive Cognitive Resources Perspective

Much previous research in chemical education has described students' ideas in terms of misconceptions or alternative conceptions. It is not our intention to dismiss this way of understanding some research data. Students' comments about chemistry can be based upon the representation in cognitive structure of explicit conceptions that are accessed and applied when students are asked about chemical phenomena. Sometimes these conceptions are contrary to the canonical knowledge of the subject. As one example, students very commonly make statements that chemical reactions occur so that atoms can obtain full electron shells (Taber, 1998). This is an idea that appears to often derive from a very well established explicit representation in cognitive structure, which may be highly integrated into the students' conceptual understanding of the subject. This conception might well be so common because its initial development is facilitated by an intuitive knowledge element (about the properties of complete or highly symmetrical configurations), but it becomes represented in cognitive structure in an explicit form.

There are clearly many other examples of student utterances reflecting non-canonical chemical knowledge reported in the research literature, which whilst not seeming to be well integrated into systematically used knowledge structures, do none-the-less appear to form part of a student's explicit knowledge, apparently readily available as verbal propositions. For example, 17 year-old Annie held a non-canonical interpretation of the '+' and '-' symbols used to indicate ions (Taber, 1995): and reported her understanding that Na^+ "signifies that the atom is sort of, has one extra electron in it [compared with "the noble gas structure"], so it's got a plus charge, so it's got an extra electron". This appeared to be a simple misconception of teaching, which Annie was able to apply in a wide range of chemical learning contexts, but without it being strongly integrated into an extensive knowledge framework. Similarly, the notion that the products of a neutralisation reaction are *necessarily* neutral (Schmidt, 1991), would appear to be a common (false) conception, with its origins in an understandable linguistic inference (of what is implied by the term 'neutralisation'), rather than being based upon a particular implicit cognitive element.

Such 'islands of knowledge' do appear to be held by students as accessible explicit knowledge elements justifying labelling as alternative conceptions. By comparison, the themes identified in the present study reflect implicit intuitive knowledge – albeit intuitions quite likely to lead to explicit conceptions if regularly activated (as when answering our, or a teacher's, questions).

Our concern in analysing our data in this study was not to exclude interpretations of some student utterances as deriving from alternative conceptions, but rather to assume that *not all* student responses would derive from the activation of such explicit knowledge elements that are open to principled application and fairly ready verbal report. In this paper we have reported themes that indicate thinking based on the activation of more implicit knowledge elements.

Indeed, in our data we found that students' ideas often seem to be an uneasy hybrid of their intuitive understandings and their interpretations of taught knowledge. Oswald, a Y10 student, offers an example of what seems to be an attempt to make sense of school science notions (e.g. molecules) in terms of his intuitive ideas about how the world works. So when shown some food dye added to water (P1) Oswald predicted that "the water will turn green…because the food dye is a dye, so it stains it", i.e. a teleological explanation in terms of the function of dyes. Oswald observed that after first sinking to the bottom of the water (as "it is heavier than the water"), "it spreads out". When asked to explain the spreading out, Oswald seemed to draw upon his school science learning:

> 1. I: How does it spread out?
>
> 2. O: Because it is a liquid it needs to fill the container that is been put in.
>
> 3 I: Why is it that the liquid always fills the container?
>
> 4. O: Because it can't take it's own shape, it takes the shape of whatever it is in
>
> 5. A: Why is that? If it's a solid it's compact.
>
> [pause]
>
> 6. O: Because the molecules are spread out and they are moving around
>
> (I: Interviewer, AGF; O: Oswald, Y10 student)

There are three stages to Oswald's answers here. The use of 'needs' in his initial response – a liquid 'needs' to fill the container (line 2) - hints at intuitive understanding (theme 5: *things have a (natural) predetermined configuration*), whereas the reference to taking the shape of the container (4) would seem reflect standard school science instruction on the differences between solids, liquids and gases. However, Oswald's final response in this extract would seem to show that he actually has a more theoretical understanding, in terms of the particle models he has been taught.

DiSessa (1993) comments how shifts in explanations during interviews can give clues to the relative status of different cognitive elements that are activated,

> First answers must make use of the most ready vocabulary, especially if they are firm. P-prims of generally high priority may be evoked ('things that usually work' are almost always a good guess to start with), then retracted on closer consideration of the situation particulars. Later descriptions are indicative of reliability in the context more than they are indicative of direct and simple cuing. (p.123)

Oswald's switch to use of the molecule concept suggests that he recognised its greater reliability as a source of acceptable explanations in school chemistry, and that his initial use of anthropomorphic language and its apparent implication of the liquid as an active agent, whilst readily activated, did not represent his most sophisticated thinking. In the context of learning mechanics, diSessa (1983: 24) has commented that "anthropomorphism of this sort is frequently offered by physics-naive people as a primitive explanation, but its priority in the context of purely mechanical situations drops quickly as technical sophistication increases", and something similar has been proposed in the context of learning chemistry (Taber & Watts, 1996).

Such analysis suggests the need for more extensive in-depth exploration of learners' ideas in examples such as this. In Oswald's case, he also used the notion of molecules when he was asked about salt dissolving in water (P2),

> 7. I: Okay, so what if we put salt in water? It is a solid.
>
> 8. O: It will just sink to the bottom.
>
> 9. I: Okay, so we'll put more water, and then some salt [demonstrating].
>
> 10. O: It sank to the bottom. It doesn't spread out like the food dye does.
>
> 11. I: Do you think it is going to stay pretty much like that, or do you think it is going to change?
>
> 12. O: It might dissolve.
>
> 13. I: Why do you think it might dissolve?
>
> 14. O: I have no idea, sorry about that.
>
> 15. I: Okay, but something makes you think it will probably dissolve?
>
> 16. O: 'Cause the molecules are broken down by the water, probably.
>
> 17. I: If you use this idea, things made of molecules, molecules spreading out?
>
> [Pause]
>
> 18. O: I don't think I understand it.
>
> 19. I: So, you don't think this idea, doesn't help you understand why it spreads out or doesn't?
>
> 20. O: Sometimes you learn it because you have to learn it, but you don't understand it.
>
> (I: Interviewer, AGF; J: Oswald, Y10 student)

Oswald thinks that salt will not immediately spread into the water in the way dye does (line 10), but predicts that it might dissolve (12). Like most students of this age, he would no doubt have experienced salt's solubility. However, Oswald can offer no reason why salt *should* dissolve (14), something that reflects the comments of students discussed under our Theme 2 (‘*changes require active agents*’), where dissolving without an external agent such as heating or stirring appeared mysterious. Oswald ventures a mechanism using the school science notion of molecules: that the ‘molecules’ (of salt) are broken down by water. This is a tentative suggestion, apparently drawing on the class of intuition we have discussed under our theme 3 (‘*there is one active partner*’): in this case, the water does something to the salt.

Despite introducing the molecule notion spontaneously in both of these contexts, Oswald does not feel he understands the idea (18). For Oswald (like many other students), particle ideas seem to be an additional learning demand, not a useful conceptual tool for understanding and explaining chemistry. Our own tentative interpretation here is that Oswald is drawing upon his intuitive knowledge of how the world seems to work, and doing his best to make sense of taught ideas such as molecules within this framework.

Variability in activation of implicit knowledge elements

One of the long-standing criticisms of interpreting learners’ ideas in science in terms of explicit knowledge elements such as alternative conceptions and conceptual frameworks has been the apparent variability in student thinking elicited in research (Claxton, 1993). The argument is that if students are accessing formally (verbally) coded knowledge represented in cognitive structure, that is available to conscious reflection, then they should use their knowledge in a principled way. That is, an available conception should be applied whenever it is applicable.

Responses to this criticism include the possibility that the students’ conception has not been well characterised (so that the range of application has not been understood); or that the student’s conceptual knowledge is multifaceted – so that in effect there could be several potentially relevant conceptions, and there is some rule or other basis for deciding which takes priority in particular cases. However, as the basis for such complications is knowledge accessible through explicit representation in cognitive structure, then it is - at least in principle - possible for researchers to elicit fuller descriptions to counter the criticism (e.g. Taber, 2000b).

Where student responses are not based on such explicit knowledge, but upon the activation of implicit knowledge elements such further characterisation of the system is more problematic. There must be a reason why one element is activated in one context, and a different one in what seems a similar context (i.e. cuing priority), but there is no explicit reasoning that the student can report. The absence of such a conscious process also, however, leads us to expect that such variation may be quite common without being appreciated by the learner. One clear example in our data is that the common perception that some 'reactions' naturally occur (theme 4) would seem to be at odds with the expectation that others require an initiating agent (theme 2). Yet students do not perceive such a contradiction, nor a need to explicitly justify why different cases fall under one or the other rule, as they are reporting the outcome of matching observations to abstracted patterns subconsciously.

We reported above that Katherine (Y9) fitted our *substances (naturally) react* theme in her explanations of three different phenomena that each involved two substances being added together. She had stated that "*when you put two things together they will always react*". However, despite the absolute nature of her verbal account, Katherine did not characterise the spreading of food dye in water - where she also observed two things being put together (P1) - as a reaction, but rather in terms of 'spreading out'. This suggests to us that although Katherine's statement that "when you put two things together they will always react" has the form of an explicit general law, it is better understood as her reporting the activation of an implicit knowledge element abstracted from many observed examples. Her observation of food dye in water was instead perceived differently, and triggered a different knowledge element.

We detected a similar effect in some of the accounts of the acid-base neutralisation reaction. So when Miriam (Y10) observed indicator being added to an acidic solution she described this as a reaction where "the particles are colliding and they change colour". She did not think that the acid was changed: "this is still sulphuric acid… I think the acid changes the colour of the indicator". Miriam thought that in a reaction "something new" was made, but confirmed that in this case she thought it was just the indicator that had changed. This fits with our theme 3 of "*there is one active partner"*- that the acid acts upon the indicator to change it. However, when Miriam observed alkali being added to the mixture, she described how "the indicator changes colour because the alkali neutralizes the acid… I think they react together, because they are neutralizing, so *they just balance each other out*". Miriam admitted to being uncertain how to interpret this reaction but thought that the mixture still contained "sodium hydroxide particles, sulphuric acid particles…I think they stay sodium hydroxide and sulphuric acid". It is almost as if 'acid' can force 'indicator' to change, but meets its match in 'alkali' which forces a stalemate - leading to a balance where the effects of the two opposing chemicals are 'neutralised'. (This is not the canonical understanding, which is more analogous to mutual annihilation than Cold War posturing.)

When Tim (Y10) discussed salt dissolving in water (P2) he talked of how "the water makes them [salt grains] like fall apart"; and when potassium permanganate was added to water (P4) he suggested that "the water like wets it then it like spreads, the crystal is hard and if you wet it then it is soft and spreads". In both of these examples he seemed to consider water as the active agent (*there is one active partner*) changing the other substance. However, he suggested that when alkali was added to acid "it balances out, it is neutral". For Tim the alkali and acid particles were both present and unchanged, but if an excess of alkali was added "then since you put more, then it would go like alkaline" and then there would be "lots of sodium hydroxide…well, more than of hydrochloric acid". So for Tim, the balancing again seems to be a kind of stalemate when there are enough acid and alkali particles to cancel the effects of the other.

This type of variability is to be expected when students' responses are largely based on the activation of implicit knowledge elements, which each have their own patterns of cuing priorities, such that the wider context for activation includes internal mental factors ("previously activated elements", diSessa, 1993: 112) as well as features of the phenomenon or questions being considered.

Discussion

We have identified five themes in student responses that we feel derive from the activation of intuitive knowledge elements - where observed phenomena are perceived as patterns matching existing abstractions from prior experience.

Our findings will be considered in terms of what they suggest about (a) how a knowledge-in-pieces approach can inform research into learning chemistry; (b) the adequacy of diSessa's (1993) proposed 'p-prims' when studying learning outside the original context of diSessa's work.

Informing Chemistry Teaching

The wide literature into student's non-canonical ideas in chemistry has highlighted the conceptual difficulties that many learners experience in the subject. Yet the characterisation of many of these ideas as misconceptions or alternative conceptions has proved inadequate. We are not the first to question the adequacy of accounts of alternative conceptions reported in the literature (Claxton, 1993; Solomon, 1993); however we do not criticise the notions of alternative conceptions or frameworks as characterisations of *some* non-canonical student thinking. Rather, adopting a cognitive resources perspective, we do not expect all or perhaps even most non-canonical ideas elicited from students to reflect knowledge elements of this type.

Where characterisation of elicited students ideas does justify labels such as 'alternative conception' and 'alternative framework', published research has been of value in warning teachers of common examples, and suggesting how to diagnose them: but often the teacher is then simply advised to 'challenge' the inappropriate conceptions. Research aimed at understanding *the origins* of such explicit knowledge elements has greater potential to inform teaching. To the extent that many alternative conceptions that students develop are likely to have evolved over time through the activation and application of intuitive knowledge elements, a greater knowledge of the implicit knowledge elements likely to be activated in learning chemistry offers an approach to developing specific testable strategies to teaching topics in ways supported by student intuitions.

The present study suggests that considering student responses to *always* draw upon explicit knowledge that is consciously accessed and applied in a principled way is misguided. Misidentifying the activation of intuitive cognitive elements as the principled application of explicit propositional knowledge may misdirect teachers' efforts. It seems likely to be more fruitful for teachers to find ways to link teaching to available intuitions, rather than concentrate on challenging ideas that are specific *in situ* outcomes of activating and subconsciously applying intuitions in particular contexts *as if* they represent explicit principled beliefs. So in teaching the canonical chemical accounts of the phenomena discussed in this paper, the role of the teacher would be to find a way to harness students' intuitions about the world, in the context of the formally taught ideas about the particulate nature of matter. This can support the kind of conceptual development process envisaged by Vygotsky (1934/1986) as a convergence and interaction between (what he described) as 'spontaneous concepts' and 'scientific (i.e. taught) concepts'; where over time spontaneous concepts would acquire a formal structure and become available to conscious access, and formal scientific concepts would evolve connections with real experience.

We then see pedagogic value in identifying and characterising the implicit knowledge elements that are activated during the study of chemistry. It may not be that all activated intuitions have obvious potential for learning about the concepts being studied in the context where activation occurs; nor perhaps even elsewhere in learning chemistry. However, the repertoire of available cognitive resources will offer many potential links of value in teaching. Informing teachers when particular implicit knowledge elements are likely to be cued and activated could allow them to seek to avoid unhelpful activation and to tap into potentially fruitful intuitions.

Moreover, recognising the role of such implicit knowledge elements in student thinking may offer an important insight into some of the challenges of learning and teaching chemistry. Perhaps one of the reasons that chemistry so commonly leads to learning difficulties is because the ready activation of implicit knowledge elements negates the need for the canonical explanations. That is, in subconsciously interpreting an observed event in terms of an existing, familiar pattern, there is no phenomenon (in the sense of something to be explained) presented to consciousness. Teachers may be laboring away offering canonical explanations where the student has no epistemic motivation for adopting them (Posner, Strike, Hewson, & Gertzog, 1982). It is difficult to make sense of a solution, or appreciate its significance, if you have not recognised the existence of the problem. In this regard, asking students to explicitly reflect upon and explain why apparently similar situations have different outcomes (dissolving, or not dissolving; mixing or not mixing; reacting or not reacting), should be more effective in generating epistemic motivation than simply asking students to explain singular cases.

Intuitive Knowledge of the Nature of the Material World

In his account of college students' thinking about mechanism in physics learning, diSessa (1993) reports a catalogue of p-prims activated when students consider phenomena in physics. DiSessa does not suggest his set of p-prims is likely to be complete, nor to account for thinking in all contexts. However, p-prims are general abstractions from experience, and should not be domain-specific as their activation in the cognitive system will occur *prior* to any judgment about a phenomenon falling within the scope of a particular knowledge domain. Yet, whilst p-prims are not themselves bound within particular domains of knowledge (his principle of invariance), diSessa also warns against premature unification (his principle of diversity). Our study of learners' thinking in chemistry provides an alternative context in which to refine the characterisation of primitive knowledge elements available to learners to interpret phenomena.

As diSessa's (1993: 105) work was grounded in the learning of physics, his focus was on "the intuitive sense of mechanism that accounts for commonsense predictions, expectations, explanations, and judgments of plausibility concerning mechanically causal situations and to understand how those intuitive ideas contribute to and develop into school physics". Whilst mechanism was certainly a feature of some of the explanations students offered for our phenomena (water eroding away salt to explain dissolving, for example), it did not seem to be central to all of our themes.

So *component gives property* does not seem to match any of the p-prims diSessa reported, and indeed is less about an intuitive sense of mechanism than an intuitive sense of the nature of the material world – perhaps more akin to an intuitive rule such as 'everything can be divided' (Stavy & Tirosh, 2000). Similarly, *substances (that) naturally react* was more about the nature (perhaps perceived essence) of certain substances rather than how reactions came about. Watts and Taber's (1996) notion of the '*explanatory gestalt of essence*' was based on the common observation that students differ in the depth (or layers) of responses they offer when asked to explain a phenomenon: there was often a point in a sequence of 'and why is that?' questions where the response is 'that's just the way it is'. In the present study it seemed some students we interviewed had developed an intuition about the nature of the world that when chemicals are mixed, there is often a reaction, and changes just occur. Where scientists have learnt to see this as a phenomenon to be explained, for many students it is just what happens – just the way things are – because of the inherent nature of the material world. This would seem to be a feature that deserves further investigation and characterisation.

The Role of Agency

The belief that events have causes is a well-established element of science, although intuitive judgements about cause may not match accepted scientific explanations. So 'action-at-a-distance' was long considered to 'save the phenomena' rather than represent an acceptable physical mechanism, and it is common for people to seek an active cause for the continuation of uniform motion (whereas physics suggests that it is changes in motion, such as decelerating, where causes should be sought). Individuals have from a young age myriad opportunities to abstract a generalised expectation that an effect should have an identifiable cause, and diSessa (1993) has suggested a number of discrete p-prims that relate to these intuitions (e.g. force as mover, force as deflector, continuous force, force as spinner).

Agency is regarded as a crucial attribute in developing many aspects of cognition. According to Ogborn and Bliss (1990), children's conceptions of motion are originated through actions on the physical world and adult reasoning derives from these categories developed very early in life. Taking a Piagetian position, they state that "in the beginning there is action and movement" (p. 380). DiSessa (1993: 151) has pointed out that: "agency is a crucial attribute in the development of many aspects of cognition. It is likely that developing some sense of personal agency is one of the first important learning tasks for babies".

Although our theme *changes require active agents* does not seem to match any of diSessa's specific p-prims it might be considered to reflect a more fundamental intuition of causal mechanism, perhaps more closely reflecting Hammer's (1996) re-description of diSessa's 'force as mover' p-prim as 'actuating agency', or the '*experiential gestalt of causation'* championed by Andersson (1986) as a common core to students' explanations in different domains. This gestalt ("a structure in terms of which a person understands some external occurrence and that identifies that occurrence as being of a certain kind") had been proposed by Lakoff and Johnson (1980: 205), and necessarily involves an 'agent' which affects a 'patient'. Therefore, agents are a fundamental element of the *causal syntax* that allows us to explain many of the observed effects we experience in our daily lives.

When discussing neutralisation reactions we found a tendency for some students to think in terms of a balance between acid and alkali, which could be overcome if one reactant was in excess. These ways of thinking about acid-alkali reactions might link to p-prims about balancing and overcoming that diSessa identified in physics contexts: e.g. the 'dynamic balance' p-prim where "a pair of forces or directed influences are in conflict and happen to balance each other" (diSessa, 1993: 222).

However, in most phenomena that students considered as reactions they perceived an active (or more active) partner acting upon a more passive partner, which might again better be linked to Andersson's (1986) experiential gestalt of causation, according to which changes are explained by identifying one active agent, one patient and an instrument. In this chemical case, it is the coming together (mixing) of two substances that can be regarded as the instrument that leads to the reaction or other change. So, the causal syntax could be that one of the substances (or a component of the substance) acts upon the other substance (which only has a passive role) by means of being added to it it. (We might tentatively suggest that the activation of different intuitions in the case of neutralisation reactions might be linked to the common approach of first introducing alkalis as 'the opposite of' acids.)

There is a parallel here with the tendency of students to consider forces to act on one body due to another, rather than being mutual interactions as required by Newton's third law. So for example, a student may believe that the nucleus attracts electrons, but is not itself subject to a 'reaction' force (Taber, 2000a). That is, this may be a primitive element in cognition being commonly activated in both chemistry and physics contexts, which can not be clearly identified with any of diSessa's p-prims.

Our final theme (*things have a (natural) predetermined configuration)* indicated an intuitive sense that substances will spread out. There is clearly some similarly between our informants' intuitions that substances naturally tend to spread out, and diSessa's (1993: 219) p-prim 'vacuums impel' with its principle that "emptiness requires filling". However, whereas students have limited direct experience of vacuums, there is obvious scope for the genesis of a primitive notion that things spread out abstracted from common experiences of spreading smells, spilt liquids, and the general entropic tendency for the contents of any orderly toy cupboard to become disorderly. Our findings lead us to wonder whether diSessa's 'vacuums impel' needs to be reconsidered as deriving from a primitive with a much more general theme of 'stuff tends to spread around'.

We reported in the findings section how Patrick and Bert seemed to hold intuitions about both differences in heaviness restricting mixing, and the tendency for things to spread. Possibly here the effect of the heaviness is to impede and slow, but not sufficient to prevent the natural tendency for the colour to spread (so "it just spreads out slowly"), something that clearly has parallels in diSessa's (1993: 217) Ohm's p-prim where "an agent or causal impetus acts through a resistance or interference to produce a result".

Given Patrick's reference to food dye needing to "balance out…and then it gets even" we considered a link here with diSessa's (1993) p-prims about balancing and equilibrium. However, intuitive knowledge elements operate well below the level of verbal language, and our interviewees' thinking seemed instead to reflect a tendency to perceive certain configurations as somehow naturally privileged (or preferred). This type of thinking has previously been suggested as an explanation for why senior secondary and college students seem to think that certain electronic configurations tend to be naturally stable (Taber, 2008; Taber & Tan, 2007). In those studies, a perceived 'natural' configuration has been conjectured to relate to aspects of symmetry (Taber, 2008), so that 'complete' shells of electrons are necessarily perceived as stable and desirable.

If our interpretation is correct, students are in some sense seeing some configurations as more 'natural', and *perceiving a tendency to form such configurations as a sufficient cause of some changes*. Whilst from the perspective of understanding the canonical models of chemistry, such a 'cause' may stand in place of seeking a physical mechanism (the action of forces between quanticles), such intuitions about the significance of geometric arrangements certainly have the potential to be drawn upon productively in teaching science. Indeed, diSessa (1993: 156) has argued that in learning physics "a relatively global change such as the shift toward seeing geometry as causative is helpful". DiSessa reports that "students invoke a strong agentive causality in learning physics" (p.125), but that the causal syntax which sees an agent acting on a passive patient is restrictive, both because it excludes phenomena without an obvious active agent, and because it is an asymmetric model (so for example forces are seen as acting from one body to another, with a logically subsequent 'reaction', rather than being the symmetrical *mutual* interactions of canonical physics). DiSessa suggests that "one of the general developments that aids novices in seeing the world in less directed, less agent-initiated terms is to shift toward seeing geometry as playing a causative role." (p.155). He argues that,

> If geometry is taken as causal, neither of the interacting objects in an action-reaction pair needs to be seen as the instigating agent. Within the naive sense of mechanism, the use of geometry and configurations as causal initiators is lower in priority than causal syntax in mechanical situations. Moving toward causative geometry is a needed step toward compatibility with the Newtonian world view. (pp.155-156)

Our present study suggests that such geometric considerations may be quite readily cued in some chemistry contexts, offering insights into the activation of cognitive elements that may be of interest to physics teachers. Implicit cognitive resources are based on patterns perceived in familiar contexts, and are not inherently tied to formal subject disciplines. The exploration of how an approach that has proved fruitful in physics education may be productive in the context of chemistry learning, may also offer insights that can feed back to inform physics teaching.

Conclusion

In this study we have set out to undertake an analysis of interview data to explore student explanations of phenomena commonly experienced and discussed in school chemistry, with a view to identifying any features of cognition that seem to derive from the activation of elementary knowledge elements. We looked to see if we could find evidence of implicit cognitive resources at primitive levels of the cognitive system as described by Karmiloff-Smith (1996), similar to the set of p-prims reported by diSessa (1993) from his studies of physics learning.

From interview studies with 41 English secondary level students we identified 5 themes where students' explanations appeared to derive from spontaneous ways of thinking about phenomena, that seemed for students to reflect natural aspects of the way the world is, and which were applied both to macroscopic observable effects, and to conjectured particles that they had learnt about in school lessons.

We suggest that the identification of these themes has potential to inform pedagogy in chemistry. Learners' well established difficulties in understanding particle models in chemistry in the ways intended are in part due to the activation of implicit knowledge elements which offer a way of understanding that is contrary to canonical science (substances have components that give rise to different properties), or de-problematise phenomena by presenting them to consciousness as 'natural' and not in need of further explanation.

We were able to find some commonality between these themes and the p-prims posited by diSessa. However, our results suggest that when considering learning in chemistry, these previously mooted p-prims may not represent the most useful ways of interpreting students' intuitions. In particular we found:

a) that some of the implicit knowledge elements activated in chemical contexts are less about an intuitive sense of mechanism, and are more about the fundamental nature of the material world: that specific properties of materials derive from particular component parts; that some combinations of materials 'naturally react'; that certain configurations, are naturally preferred (leading to spreading out of concentrated materials).

b. other 'chemical' phenomena do invoke intuitive agentive notions about causation, but these may be better described by a very broad primitive such as the experiential gestalt of causation, than by diSessa's specific p-prims.

We therefore believe that the present study complements work in physics learning by both identifying a set of contexts that may not be best understood in terms of previously reported p-prims; and by showing how moving beyond the domain of physics learning provides insights into how reported p-prims may themselves reflect more general abstracted patterns, and could in effect be facets reflecting a more basic reasoning principle (Redish, 2004). The identification of implicit knowledge elements activated during learning in any domain advances understanding of the broad repertoire of intrinsically content-free resources that learners have available to be cued in learning any curriculum subject.

In this study we have shown that applying a knowledge-in-pieces perspective to learning in chemistry is both feasible and fruitful. This perspective has potential to assist teaching, by offering guidance on which common intuitions teachers should seek to avoid activating and which might fruitfully be stimulated in teaching particular scientific concepts (Wagner, 2006). Further research is indicated both to better understand the nature and degree of commonality of learners' intuitive knowledge elements, to relate this to the development of more explicit knowledge about chemistry, and to explore the practical application of this research to classroom teaching.

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