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Conceptual resources for learning science: issues of transience and grain-size in cognition and cognitive structure

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Abstract

Many studies into learners' ideas in science have reported that aspects of learners' thinking can be represented in terms of entities described in such terms as alternative conceptions or conceptual frameworks, which are considered to describe relatively stable aspects of conceptual knowledge that are represented in the learner's memory and accessed in certain contexts. Other researchers have suggested that learners' ideas elicited in research are often better understood as labile constructions formed in response to probes and generated from more elementary conceptual resources (e.g. phenomenological primitives or 'p-prims'). This 'knowledge-in-pieces perspective' (largely developed from studies of student thinking about physics topics), and the 'alternative conceptions perspective', suggest different pedagogic approaches. The present paper discusses issues raised by this area of work. Firstly, a model of cognition is considered within which the 'knowledge-in-pieces' and 'alternative conceptions' perspectives co-exist. Secondly, this model is explored in terms of whether such a synthesis could offer fruitful insights by considering some candidate p-prims from chemistry education. Finally, areas for developing testable predictions are outlined, to show how such a model can be a 'refutable variant' of a progressive research programme in learning science.

Conceptual resources for learning science: issues of transience and grain-size in cognition and cognitive structure

Introduction

This paper considers one aspect of the programme of research into learning in science, viz. the nature and status of learners' ideas reported in research. Studies have reported that learners' ideas have a range of characteristics, from well-established highly stable conceptual frameworks for thinking about topics (Gilbert & Watts, 1983), to highly transient thoughts generated in situ (Claxton, 1993) when the respondent is not able to offer a response by accessing a matching pre-existing conceptual structure represented in memory.

It is argued here that such a range is to be expected, but that it is important for researchers to be able to distinguish between thinking that reflects stable 'alternative conceptions' from thinking that constructs a viable but labile response to which the learner has little commitment. This issue is considered by reviewing the notion of 'p-prims' and the 'knowledge-in-pieces' (diSessa, 1993) perspective that has been offered by some physics education researchers as an alternative to the 'alternative conceptions' perspective for interpreting learners' ideas.

The question explored here is whether it is possible to offer a coherent model of cognition that synthesises the 'alternative conceptions' and 'knowledge-in pieces' perspectives, whilst having the potential to offer heuristic guidance for future research. This paper suggests how a model of cognition encompassing *both* perspectives can be a feature of a progressive research programme into learning science; and offers an initial exploration of how such a model might be applied in the context of learning *chemistry*.

This area of work is complicated by the intimate associations between the conceptual structures that may be *the products* of thought, the thinking *processes* themselves, and the physical substrate that allows such concepts to be *represented* in the brain: the importance of avoiding category errors across these distinctions has been highlighted by a number of commentators (Lakoff and Johnson, 1980; Ault, Novak and Gowin, 1984; and Phillips, 1987). Figure 1 provides a model using Popper's (1979) notion of the 3 Worlds to highlight the ontological differences between notions, such as 'cognitive structure' and 'alternative conception', which are commonly used in science education when discussing student ideas and learning.

(figure 1 about here)

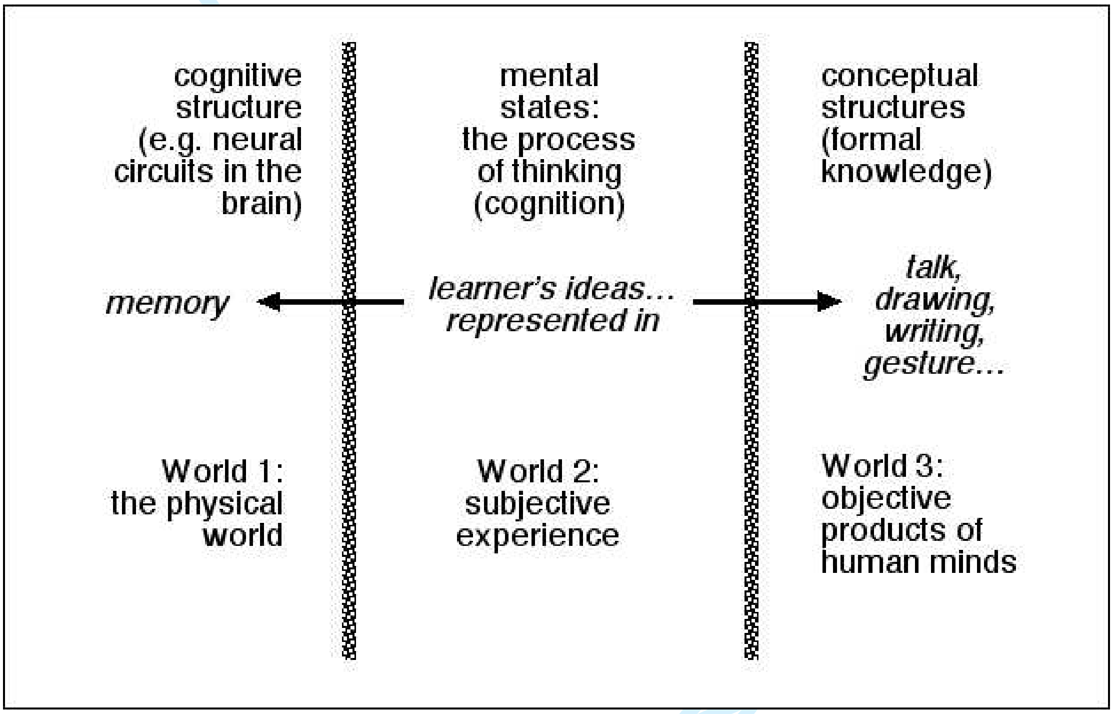

Figure 1: Cognitive structure, cognition, and conceptual structures

The *conceptual* structures that may be *the products* of thought (in 'World 3') would include formal theories published in the scientific literature, as well as propositions and explanations elicited from learners (spoken in interviews or written in tests for example), and theoretical entities such as 'alternative frameworks' that science education researchers use to model student thinking when reporting their studies.

Cognition itself (perceiving, thinking and remembering) is only directly experienced by the individual concerned, and so is part of Popper's 'World 2', although it may be reported in 'World 3'. Such cognitive *processes* are facilitated by the physical *structures* of the brain, and ultimately neural structure.

This physical, 'World 1', structure is here labelled *cognitive* structure. The term cognitive structure is well established (e.g. West & Pines, 1985) although there does not seem to be a single well-accepted meaning. "The facts, concepts, propositions, theories, and raw perceptual data that the learner has available to him [sic] at any point in time" (Ausubel and Robinson, 1971, p.51) would seem to be better considered as *components* of a learner's conceptual ecology (Duschl & Hamilton 1992), which will be *represented* in some form in the individual's cognitive structure. Cognitive structure also represents the individual's personal *organisation* of their knowledge (White, 1985), although at present we have a very limited understanding of how this representation takes place in terms of neural structures.

Reference to structure may seem to imply something rigid and permanent (Lakoff & Johnson, 1980), but cognitive structure is part of an organic being, and can include (a) aspects which once developed remain substantially unchanged over decades (e.g. perceptual apparatus); (b) aspects which are being slowly modified over periods of days to months (laying down and consolidating memories); and (c) aspects which are in continual flux (changing activation levels of different neural circuits).

Figure 1 reflects how the thinking that learners do is experienced *subjectively*, being only *directly* available to that individual. Such thinking may lead to ideas that are in some way represented physically in the brain (in cognitive structure), and which may also be expressed as objective ideas (in "the world of theories in themselves, and their logical relations; of arguments in themselves; and of problem situations in themselves" Popper, 1979:154).

As Popper (1979: 155) suggested "the first world and the third world cannot interact, save through the intervention of the second world". Researchers collect evidence of student thinking *as it is expressed (represented) in* Popper's World 3. As well as using this data to interpret student thinking (in World 2), researchers may make inferences about how such thinking could reflect aspects of cognitive structure (in World 1): but clearly the way ideas are coded in neural circuits, and how they are expressed in (for example) verbal language, involve very different forms of representation. In this paper references to concepts and conceptions 'stored' in memory should be taken to mean that the formal concepts and conceptions are represented (i.e. coded) in cognitive structure.

The significance of the issue within the context of an established research programme

There is a considerable body of research exploring learners' ideas in science: research that concerns many science topics, undertaken with learners over a wide range of ages (Duit, 2006). This research is diverse in terms of both the methodological approaches used, and the ways in which the research is conceptualised. Studies are underpinned by a range of assumptions about the natures of learning processes; of student thinking; of mental structures; and so forth, and the 'entities' reported as the outcomes of the research are therefore also disparate.

There has been considerable discussion of the assumptions underlying this area of research, and the status of the various models proposed by researchers as findings from their studies (discussed below). It has been argued elsewhere (Gilbert & Swift, 1985; Taber, 2006a) that this area of research may usefully be characterised as a scientific research programme in the sense suggested by Lakatos (1970). Within such a research programme there would be certain core ideas that are accepted by the various researchers in the field. It has been suggested (Taber, 2006a: 139) that in the research programme into learning in science, such 'hard core' commitments would *inter alia* include:

- Learners come to science learning with existing ideas about many natural phenomena
- Knowledge is represented in the brain as a conceptual structure
- It is possible to model learners' conceptual structures

In terms of the model presented in Figure 1, there is an assumption that some stable aspects of a learner's cognitive structure (World 1) tend to direct thinking (World 2) in particular ways, that students can report (represent in World 3) to teachers or researchers. Researchers can therefore develop models (also presented in World 3) of conceptual structures (conceptions, conceptual frameworks) that they consider to be in some sense 'coded for' in the learner's cognitive structure. Such assumptions lead to key research questions for the programme. So for these three 'hard core' assumptions, we might ask:

- What ideas do learners' bring to science classes, and what is the nature of these ideas?
- How is knowledge organised in the brain?
- What are the most appropriate models and representations of learners' conceptual structures?

Lakatos (1970: 135) referred to the answers to questions such as this, answers that build up the theoretical base of the programme, but which are open to dispute and development, as the 'refutable variants' of the programme.

One particular area of contention in this particular research programme has been whether proposed alternative conceptions and frameworks do indeed represent stable aspects of learners' mental structures, or whether they instead just reflect responses generated *in situ* when the researcher elicits data (or for that matter when a teacher asks a question in class, or when a student responds to an examination question).

There is general agreement that learners do generate responses to research questions by thinking (i.e. a process) that draws upon 'resources' (represented in cognitive structure, i.e. brain structures that support cognition). However, researchers have disagreed over the question of the 'grain-size' of these mental resources accessed: is the thinking process a matter of identifying the most applicable pre-existing conceptual framework and processing the question 'through' it; or more a matter of generating a suitable way of thinking by drawing upon a range of disparate resources that need to be coordinated into a suitable structure for the 'job in hand'.

Characterising learners' ideas along such dimensions is not purely an academic issue. Two other 'hard core' assumptions suggested for the research programme (Taber, 2006a) are that:

- Learners' existing ideas have consequences for the learning of science
- It is possible to teach science more effectively if account is taken of the learner's existing ideas

If research in science education is to inform pedagogy it is important to distinguish between ways of thinking that are well-established and tenacious and likely to impede new learning unless challenged; and ideas that may be romanced when a learner is asked an unanticipated question about a topic that she has previously given little thought to, and might well never be generated, let alone committed to, in the absence of being asked what seems an obscure question.

The stability of student thinking

Much of the research exploring learners' ideas about, and understanding of, science topics has been framed in terms of 'misconceptions', 'alternative conceptions' or 'alternative frameworks' (Driver & Erickson, 1983; Gilbert, & Watts, 1983). Unfortunately, different authors use these (and other related) terms in different ways (Abimbola, 1988) so it is not possible to offer a consensus definition of such terms (Taber, 2006b). However, these terms are usually taken to imply that students have a stable way of thinking about, and understanding, a topic. The general view is that 'conceptions' represent features stored in memory in some form, and activated as integral units.

Indeed, many researchers have interpreted research data as evidence that learners may construct alternative explanatory schemes that are theory-like: that is, consistent, coherent, applied over extended periods of time and being applicable across a range of phenomena (e.g. Driver & Easley, 1978; Driver, Guesne & Tiberghien, 1985; Vosniadou, 1992; de Posoda 1997; Tytler 1998; Taber, 1995a, 2000). The tenacious nature of such 'alternative frameworks' was emphasised by those researchers who first brought 'children's science' to wide notice (e.g. Gilbert, Osborne & Fensham, 1982; Driver 1983; Watts 1983a; Watts & Gilbert 1983); as was the way such alternative frameworks could be coherent and sensible from the child's perspective (Gilbert et al, 1982; Gilbert and Watts, 1983; Pope and Gilbert 1983; Watts 1983b).

Other authors have interpreted research data from studies into students' ideas as implying that learners' thinking tends to be incoherent and inconsistent, fragmentary, context-bound and transient (e.g. Viennot 1979; BouJaoude, 1991; Solomon, 1992, 1993; Claxton, 1993; Hennessy, 1993; Linder, 1993; Russell, 1993; Kuiper 1994) - and perhaps sometimes simply created in response to the social pressure of the researcher's questions (Solomon 1993). So Hammer argues,

> Research in science education, including physics, has mostly adopted unitary models of student thinking as reflecting naïve theoretical frameworks, robust misconceptions, and stages of development in reasoning abilities. As models of cognitive structure, these fit well with a phenomenology of consistency over time and coherence among ideas. The phenomenology I have sketched … has been more variegated and complex, and it confutes attributions of consistency and coherence to student reasoning. I … argue that student knowledge and reasoning is better modeled in terms of a manifold ontology of more fine-grained, context sensitive resources.
>
> Hammer, 2004a: 12

From this perspective, the resources students draw upon when responding to questions (in class, in tests, in research interviews) are *in themselves* stable, but are used as components of a novel conceptual structure constructed in response to a specific context.

Conceptual resources as 'knowledge-in-pieces'

Smith, diSessa and Roschelle (1993) considered that there must be fundamental or primitive elements of cognition that learners use to construct their conceptions and conceptual frameworks. They highlighted the importance of "identifying a range of cognitive resources that can support the bootstrapping of more advanced cognitive structures" (p.125). diSessa (1993: 112) proposed such a class of "hypothetical knowledge structures" that he called phenomenological primitives, or 'p-prims' and which could act as "primitive elements of cognitive mechanism - as atomic and isolated a mental structure as one can find".

Conceptions are *specific* notions that are of the form of propositions ('objects slow down because they run out of force', 'plants grow by taking material from the soil', 'chemical reactions occur so that atoms can fill their shells'). By contrast, the hypothetical 'atoms' of cognition are primitive in the sense of acting at an early (preconscious) stage of cognition,

> [phenomenological primitives' are] kinds of basic, in a sense axiomatic, intuitions that govern the understanding of physics phenomena on which students reflect even before undertaking any formal learning of physics. … relatively minimal abstractions of simple common phenomena which need no explicit justification for their existence
>
> Reiner & Gilbert, 2000: 501

These p-prims identify phenomena as matching common *general* patterns,

> P-prim are rather small knowledge structures, typically involving configurations of only a few parts, that act largely by being recognised in a physical system or in the system's behaviour or hypothesized behaviour.
>
> diSessa, 1993: 111

This 'pattern spotting' is central to Gestalt psychology (Wertheimer, 1966), and indeed Andersson (1986) has discussed a p-prim labeled as 'the experiential gestalt of causation'. Andersson believes that youngsters abstract a basic pattern that commonly recurs, involving an *agent* bringing about an *effect* through an *instrument*. Once such a p-prim is established, matching phenomena will be perceived as fitting this pattern and so 'cause and effect' will be 'understood' (i.e. these phenomena will fit the individual's intuitions).

From this perspective, the person has 'knowledge-in-pieces' – i.e. conceptual resources that can act as the elements for constructing knowledge *in situ*. DiSessa developed his ideas in some detail, and based on a range of empirical evidence proposed a substantial list of candidates for p-prims: intuitive notions which when verbalized can be described in such terms (1993: 219) as:

- all motion, especially impulsively or violently caused, gradually dies away
- changes take time to 'blossom'

P-Prims as resources for knowledge construction

DiSessa and colleagues do not suggest that *all* of our knowledge is held and applied in the form of such fundamental elements as p-prims. P-prims are a hypothetical way of explaining both how people can provide answers to questions where they have no pre-existing answer in place, *and* for explaining *the origins* of more complex and stable conceptual structures, i.e. at the levels of conceptions and conceptual frameworks (cf. Caravita & Halldén, 1994). An important part of the suggested roles of p-prims is to provide the 'conceptual atoms' to form complexes which will acquire their own permanence through being represented in cognitive structure,

> P-prims are, in general, rather small and particular knowledge elements among a large collection...likely, p-prims will be used in clusters or in combination with other kinds of reasoning.
>
> diSessa, 1993: 118

This clustering process (the building of more complex conceptual structures) has a direct analogy with the way we tend to use scientific knowledge. Complex scientific ideas can be explained in terms of 'first principles', but once we have developed the more advanced concepts we tend to use these directly (Taber, 1995b). In the same way, individual learners construct conceptual structures from primitive elements, and if these structures are found to be useful and so consolidated through repeated use, they themselves become stable aspects of cognition.

Conceptual resources of varying grain-sizes

Research reports that *in some topics* learners *of certain ages* appear to *sometimes* hold stable extended theory-like conceptual frameworks, but at other times researchers find respondents constructing responses *in situ*. Indeed, research that explores a learner's thinking in a topic area over extended periods, can readily identify both labile and stable conceptions (Taber, 1995a).

The work reviewed here suggests that it should be possible for researchers eliciting learners' ideas in science to distinguish between stable ideas and those constructed in situ. This suggests that appropriate research questions are not *whether or not* learners' ideas are stable (or coherent and so forth), as they sometimes, but not always, are; but rather *which* ideas tend to be stable; and what are the *circumstances* under which they stable (Taber, 2006a). The nature of the scientific concepts themselves, and the contexts in which they are evoked, are likely to be significant factors that interact with features of the individual's cognitive structure.

Nor is there a dichotomy here between two clusters of characteristics – it seems clear that in some topic areas students can hold several stable ways of explaining the same phenomena, with a particular idea being elicited according to various contextual cues (Taber, 2000 cf. Pope & Denicolo, 1986).

Smith, diSessa and Roschelle (1993: 117) claimed that human "knowledge systems [are] composed of many interrelated elements that can change in complex ways" and argued that “presumptions about the diversity and grain size of knowledge involved in mathematical and scientific expertise have typically been too few and too large” p.145).

Thus, the researcher exploring students’ thinking and understanding has to be open to finding a range of different types of features, some of these being transient current combinations of more elementary stable features. Niedderer (2001: 400) discusses the “different types of stable cognitive elements in a model of the cognitive system”. Hammer and Elby (2003, p.58) use “the term ‘facets’ as a general reference to students’ conceptual resources”, where diSessa (1993: 111) refers to ‘elements’, i.e. “knowledge structures of different size and character (e.g. ideas, categories, concepts, models and theories)”.

Two frames for interpreting research data

Hammer (1996) has explored how both ideas about p-prims and ‘misconceptions’ can be applied to teaching and learning in physics. He and his colleagues point out, that many isolated examples of students’ thinking could well be interpreted in terms of *either* knowledge-in-pieces being constructed from something like p-prims, *or* the application of existing conceptions (which have *previously* been so constructed),

> In some cases, attributing robust conceptions is appropriate, but resources-based accounts afford the alternative of understanding the conception as a local or momentary activation of another sort of cognitive structure.
>
> Hammer, Elby, Scherr & Redish, 2005: 6.

It may be difficult to distinguish between these two types of mechanism when exploring an individual response to a single question on one occasion (see below: ‘testing for ‘knowledge-in-pieces’). Research that provides examples of in-depth and extended questioning, or attempts to explore ideas in a range of contexts, does however offer *indications*. So where responses are consistent over time and context, and where the respondent shows strong commitment to answers, it seems more *likely* that they derive from a pre-existing stable conception or conceptual framework.

A knowledge-in-pieces account, then, may be particularly useful in explaining research that elicits inconsistent responses from the students. Such inconsistency is not in itself firm evidence that knowledge is being constructed *in situ*: responses judged inconsistent from the scientific perspective may well seem consistent if appreciated from the students' alternative perspective. Even when the student acknowledges that they are being inconsistent in their use of ideas, it is possible that they are *inconsistently selecting* from a toolkit of stable, pre-existing, notions (Mortimer, 1995; Taber, 1995b; 2000) and indeed the availability of alternative well-developed conceptual structures may be an important requirement for some types of conceptual change (Thagard, 1992; Taber 2001; cf. Petri & Niedderer, 1998; Harrison & Treagust, 2000).

However, where learners are asked questions about a topic where they lack any established and stable ways of thinking, they will need to construct their responses *in situ*, from more elementary conceptual facets (e.g. p-prims) and so are *more likely* to produce inconsistent answers as they can be strongly influenced by contextual features of particular questions or examples.

An existing way of thinking about a topic allows subconscious processing of information that filters out (what are from that viewpoint) irrelevant features and selectively attends to the pertinent ones. In the absence of such a way of thinking, those features of new information seen as most salient are likely to vary across particular questions and examples, leading to less consistent responses.

The inclusive view

The reading of the literature taken here, then, is that when people are asked to think about natural phenomena, they sometimes draw upon well-established conceptual frameworks, and at other times they are only able to generate an appropriate response by constructing a framework for answering *in situ*, drawing upon available discrete conceptual assets. Clearly in both cases thinking has to rely upon the available mental resources, and the 'apparatus' of an individual's cognitive structure has features that support both phenomena. Sometimes thinking involves accessing a complex stable conceptual element represented ('stored') in cognitive structure, re-cognised as suitable to 'do the job', whereas when such a ready thinking tool is not available we have to be creative. This is clearly linked with familiarity with the field concerned: an expert will have previously constructed conceptual frameworks 'stored' in memory that are not available to the novice (Mestre, 1994; Abdullah, 2006).

The present paper sets out to build upon this view by considering a model of cognition that is inclusive in that it encompasses both the 'alternative conceptions' and the 'knowledge-in-pieces' perspectives. Clearly the present state of brain science is such that aspects of cognitive functioning are not understood in detail. Therefore models of cognition tend to be based around a 'black box' approach, where mental faculties are identified from patterns in empirical data, and cognitive modules posited without necessarily being associated with an identifiable brain structure (e.g. Dawson, 1998). So notions such as 'working memory' (Baddeley, 1986) and the 'language acquisition device' (Chomsky, 1999) may be proposed, and characterised in terms of their functions without being mapped onto identifiable anatomical features.

The model discussed here is derived from well-accepted principles and ideas (e.g. Baddeley, 1990; Eysenck & Keane, 1990; Kellogg, 1995), and has the following major components:

- perception;
- conscious and unconscious thinking;
- 'genetic' predispositions built into the cognitive apparatus;
- conceptual structures stored in memory (i.e. represented in cognitive structure);
- development and learning.

Perception: the brain receives information inputs from the senses. Although sensory information relates to colour, pitch, hotness, intensity of pressure, etc, most has already been filtered and interpreted by the time we are consciously aware of it – e.g. we perceive a person smiling, a researcher asking a question, a bird flying overhead, or some other identified phenomenon. There is clearly a great deal of information processing in the form of pattern-recognition that precedes the conscious perception of objects, people, or situations.

Conscious and unconscious thinking: Thinking involves processing information – e.g. to answer a question or solve a problem. We are aware of our conscious thinking, but there is clearly a great deal of mental processing that is part of our thinking that is usually subconscious (Boden, 1992). In conscious thinking we can be aware of the concepts we may draw upon, and so may make an argument explicit. Subconscious thinking presents its outcomes to consciousness as insight - the 'aha' moment (Koestler, 1982) - but does not give us access to how the outcomes were arrived at. Subconscious thinking is 'automatic', drawing upon mechanisms we may label as intuitive (Brock, 2006). Conscious thinking is required where no automatic routine is available, and is necessary where we wish to understand or are expected to justify our decisions.

Genetic predispositions built into the cognitive apparatus: human brains have evolved to process information in ways that have allowed their 'owners' to survive long enough to leave offspring. Certain ways of thinking have proved adaptive and have been selected. These may include aspects of pattern recognition, such as readily 'seeing' faces when minimal cues are available (Mehler & Dupoux, 1994), and perhaps explains thinking about 'natural kinds' (such as readily accepting, and establishing membership of, classes such as 'tree') that seem to be widespread among human cultures (Kuhn, 1989; Keil, 1992). The development of language is believed to be supported by an evolved predisposition to learn a certain kind of grammar (Chomsky, 1999).

Conceptual structures represented in memory: we can represent in memory, i.e. in *cognitive* structure, (a) specific entities in our environment (*my* wife, *your* computer) to allow us to recognise them readily, and (b) general concepts (wife, computer, acid, plant, force) that allow us to classify novel instances and so activate 'appropriate' responses, and (c) abstract relationships between concepts (element to compound; Newton's third law; humans as primates as mammals as chordates as animals as living things) that may be used to understand and explain aspects of the natural (and social) world.

Development and learning: over time we change our behaviour in response to some stimuli. The way we process information changes. For example, we may make certain thinking tasks routine (and so subconscious) that previously required active concentration (Kellog, 1995). Some of this may be considered due to 'developmental processes'. Hearing the sounds of a particular language fine-tunes perception to more readily discriminate the sounds of that language (Saffran & Thiessen, 2003) and, by corollary, makes it more difficult to *perceive* the different discriminations used in other languages. The learning of the particular grammar of a specific language requires hearing sufficient examples of the use of the language, but is underdetermined by the available data (implying a genetic component) and can be successfully achieved through any of myriad sub-samples of the possible linguistic permutations that become available to the learner (Pinker, 1995).

Other changes may be dependent upon specific sensory input: being taught about calculus, watching a film about astronauts on the moon, listening to recordings by the Beatles, reading about Charles Darwin's campaign for a public service pension for Alfred Russel Wallace – are all potentially learning experiences that can facilitate *specific* changes in cognitive structure.

Aspects of cognitive structure representing our knowledge systems are available to subconscious as well as conscious processing: we perceive our house or our friend, not a building or person that we then have to identify by consciously accessing memory.

(figure 2 about here)

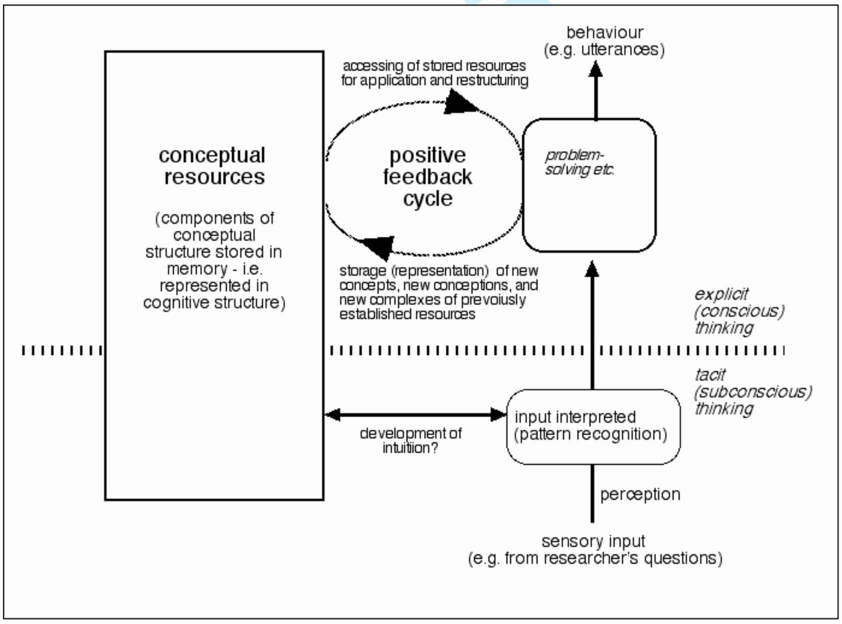

Figure 2: A representation of cognition reflecting the model discussed in this paper

Considering just these components of cognition leads to a complex model (which is at least partially represented in figure 2). In particular, it leads us to consider two key issues:

Process and structure: cognition is a set of processes, such as ‘perception’, ‘thinking’ and ‘remembering’. However, these processes are facilitated by the cognitive apparatus, that is part of the physical structure of the brain itself. Conceptual structures are *represented* in cognitive structure when learning is encoded in memory - itself part of brain structure. Often in science education, research results are presented in terms of conjectured features of cognitive structure (cf. Phillips, 1987), although these are not directly observable (see figure 1). Reports of aspects of learners’ cognitive structures (World 1) are based on inferences from the learners’ reports (or other observed behaviour expressed in World 3), which are indirect evidence of cognition (experienced by the learner in World 2). That is, reports of cognitive ‘structure’ (representing learned conceptual knowledge) are always mediated by ‘process’ (thinking).

Tacit and explicit thinking: if much of our cognition, the actual processing, is at the level of perception and intuitive or other subconscious processing, then even the learners themselves only have direct access to the *outcomes* of these processes, not the processes themselves.

These considerations are further complicated by the dynamic nature of the physical ‘substrate’ through which processing occurs. Part of the complexity (and utility value) of the human brain derives from the cognitive ‘system’ being organic. It has a structure that channels cognition, but which also *evolves in response to* those very processes of cognition (so that human behaviour can be culturally mediated and is not purely instinctive). So when abstract concepts (perhaps such as natural kinds like ‘tree’ that the human brain has a propensity to develop; perhaps formal concepts such as ‘plant’ taught in a science class) are formed, they become represented in cognitive structure and later available as both the objects of thought, and tools to think with.

Thinking with concepts allows the possibility of forming associations, which may leave permanent traces in cognitive structure in terms of changing the way thinking about one concept promotes or suppresses the activation of another.

Considering relationships between concepts, may lead to new conceptions (perhaps inferred through intuitive pattern recognition mechanisms, the p-prims; perhaps folk-beliefs communicated from the life-world; perhaps formal science knowledge learnt in class). A conception may itself then become represented in cognitive structure (and so may then be considered as a 'stored' conceptual structure subsequently available to the learner). This then becomes a 'pre-packaged' tool for thinking, and so a potential element for constructing *more* elaborate conceptual structures, that may then in turn also be represented in cognitive structure. This is the positive feedback cycle referred to in figure 2. Over time, quite extensive complexes of concepts and their relationships may become established, 'stored' and readily activated – something that may be characterised (in World 3, e.g. in research reports) as a conceptual *framework* becomes represented as a stable aspect of the learner's cognitive structure.

According to constructivist notions of learning, new learning builds upon existing knowledge, and in time can act as the foundations of further learning: giving the potential for building and storing ever more complex knowledge structures. In this model, the more basic units, such as concepts and conceptions, are both available as discrete objects and tools of thought, and also represented as components of more complex structures that can be accessed holistically.

Thinking of elementary knowledge structures as 'bricks' for constructing knowledge may be misleading, as this is a non-conservative process: that is, there is a form of re-representation (Karmiloff-Smith, 1996: 21) of an original that is itself retained,

> the original … representations remain intact in the child's mind and can continue to be called for particular cognitive goals which require speed and automaticity. The redescribed representations are used for other goals where explicit knowledge is required.

Karmiloff-Smith's theory of representational redescription assumes a change in the 'coding' format (such as producing a verbal description of an image), but human cognition also seems to involve the ability to use 'the same' basic conceptual units as components of different 'stored' complexes, and it may be that authentic modelling of *cognitive* structure requires 'copying' of conceptual elements for use in different parts of the *conceptual* structure (cf. Thagard, 1992), rather than the form of a web of highly interconnected concepts where each concept occupies a single node.

The overall *conceptual* structure represented in a person's cognitive structure can be considered as a single extensive network: but perhaps one including considerable redundancy of conceptual elements, as well as some degree of clustering into domains (Hirschfeld & Gelman, 1994) such that thinking 'within' a domain is easier than 'between' domains (cf. Solomon, 1993). Whether such a network model can be consistent with the branching ontological trees envisioned by Chi (1992) is not clear – but it *is* clear that there is much more work to be done in this area.

Whatever the details, such a model of cognition allows thinking that is generative and creative ('knowledge-in-pieces' that may produce ideas that may often be quite labile), as well as thinking that is largely running accessed 'stored' conceptual schemes of various complexity (and so is *likely* to show stable patterns of thought, e.g. those deserving reification as 'alternative conceptions'). Basic processing at the level of p-prims may play a role both in the interpretation of new 'input', and also by virtue of having channeled the formation of the 'stored' (represented) concepts and conceptions that are later used as the basis for building up more complex knowledge structures.

This is a synthetic or inclusive model that, following the approach of diSessa and Hammer and their colleagues (Smith et al, 1993; Hammer et al, 2005), admits the interpretation of research data *both* in terms of (i) the extent to which findings represent permanent structure or just *in vivo* processing; and (ii) in the range of 'grain-sizes' of conceptual structures that may be accessed in studying student thinking. Such a model has great potential for explaining research findings (as will be discussed in the next section). However, it also clearly has the potential to support multiple interpretations of data and so, potentially, make researchers' conclusions immune from refutation (something that will be addressed in the final part of this paper).

Some findings from studies into learning chemistry

Much of the work on p-prims and the 'knowledge-in-pieces' derives from studies of learning and thinking in physics contexts. Certainly physics offers a domain where 'intuitive theories' may be expected (Espinoza, 2005). It is very common for learners to develop an understanding of force and motion such that motion is assumed to imply an acting force (Watts & Zylbersztajn, 1981), and it is easy to see this as an abstraction of common patterns (in common experience: pushing, lifting, kicking, jumping and throwing all involve motion that soon stops). When researchers ask about such phenomena, learners often offer explanations that suggest they are using notions such as speed depending upon applied force (Viennot, 1979) or forces providing some kind of 'impetus' that is exhausted by the motion (Gilbert & Zylbersztajn, 1985). At the point where these explanations are elicited the learners seem to 'have' such conceptions of motion.

However, it is less clear if learners have formed *explicit* conceptions of this type prior to being asked to offer verbal accounts of such situations. It may well be that their beliefs were previously 'intuitive physics', being at the level of the ability to mentally simulate such situations on the basis of prior experience (Georgiou, 2005), and so visualise mooted scenarios (Gilbert, 2005), rather than formalised knowledge available as verbal propositions relating concepts of force, speed, velocity and acceleration.

So, as Hammer (1996) pointed out, reports of thinking elicited in Physics contexts such as these could potentially be explained either (a) in terms of the application of previously 'stored' alternative conceptions and frameworks, *or* (b) the generation of an account based on mental simulations using implicit knowledge at the level of p-prims. It seems informative to consider the value of the p-prims notion and the 'knowledge-in-pieces' perspective beyond physics learning. Research into student thinking in chemistry can offer a usefully different context.

In chemistry there have been many reports of alternative conceptions or alternative frameworks that would seem to offer a more demanding test of the usefulness of the p-prims notion and the 'knowledge-in-pieces' approach. Many studies of student thinking in chemistry do not concern learners' ideas about directly observable phenomena (such as moving balls) but rather concern the submicroscopic world of particles such as electrons, ions and molecules (Harrison & Treagust, 2002). It is fairly clear that students' ideas about the nature and properties of atomic level particles are not abstractions from their own *direct* experiences of the phenomena.

Knowledge of the atomic world is knowledge of models developed by humans, and communicated within our culture through talk, books and so forth. Where students develop incorrect ideas in this realm it seems that either they have been 'mis-taught', or they have misinterpreted the teaching they have received (or some combination of both).

An alternative conceptual framework from chemistry

For example, it has been reported that learners commonly develop thinking that has been represented as an alternative conceptual framework for thinking about chemical bonding and reactions – the octet framework. This has been described as an extensive set of related conceptions concerning the types of chemical bond that are formed, the nature and status of different forms of bonds, the rationale for reaction, and mechanisms of bond formation (Taber, 1998a). It has been shown that in at least some cases key aspects of the framework are very stable, with students offering consistent responses in a wide range of question contexts, and over extended periods of time (Taber, 1995a, 2000, 2003a).

So here we have a complex and inter-related set of ideas, not based upon personal experience of the phenomena, and considered to be stable. The interpretation offered was that students developed complex permanent representations in memory that were accessed and applied when they were asked to discuss a wide range of atomic level scenarios. This is not to suggest that students were not *generating* responses in interviews. General ideas were applied to a range of specific examples, and it is not claimed that research interviews were merely eliciting recall. A question about the bonding in, say potassium iodide, could lead to the respondent identifying 'ionic bonding' as the key concept (based on some learned criteria), and then discussing the example in terms of the propositions that were part of a conceptual framework that was activated through thinking about that concept.

However, given what is understood about the limitations of human cognitive processing and in particular the capacity of working memory (Miller, 1968), it does not seem feasible that the framework of general propositions was itself generated anew from totally discrete conceptions in memory in response to each new question. Rather it seems likely that many students do hold in memory (have represented in cognitive structure) an extensive framework of conceptions about chemical bonding that becomes increasingly 'robust' and integrated during their learning of the subject (Taber, 2003a).

This would seem to be an example where the 'alternative conceptions/conceptual frameworks' perspective can explain the research findings, but the 'knowledge-in-pieces' approach has difficulties (unlike the case of the relationship of forces and motion which would seem to be explainable from either perspective). Evidence of stable, extended patterns of thinking in such an abstract area would seem to imply that the learner has constructed permanent representations of conceptual frameworks in long-term memory.

A role for p-prims in learning chemistry

However, although it is argued that the 'knowledge-in-pieces' approach does not offer a feasible explanation of research findings in this case, this does not imply there is no role for cognitive processing at the level of p-prims. The core feature of the octet framework is an explanatory principle that atoms strive to fill their shells. Although it is a useful chemical heuristic that species (atoms, ions, molecules) with certain electronic structures tend to be more stable, students commonly adopt this principle and elevate it to (inappropriately) 'explain' chemical processes. The extent to which this common adoption of an invalid principle is a common misinterpretation of teaching, or is recycled through inaccurate teaching, remains an open question. However, it is clearly the case that the notion of a 'full shell' having special properties is intuitively attractive to, and so readily adopted by, learners.

No school student can have direct experience of electronic structures of atomic-level species, or any way of empirically judging the stability of different electronic arrangements. So, it *is conjectured* that in learning about the molecular world as mediated by the models presented in class, some intuitive pattern recognition process acts to assign special significance to 'full shells'.

Here we have a candidate for a p-prim that may well be operating in the learning of chemistry. This leads to the hypothesis that in processing the information that *most stable structures have particular electronic arrangements* (full shells in relation to the first two periods of elements) some p-prim identifies something about the 'fullness', or perhaps the symmetry, of the pattern and marks it out as especially significant.

Such a pattern becomes considered as 'desirable', and a sufficient driver and rationale for chemical processes (reactions; bond formation; ion formation). There is a predisposition to interpreting information according to certain patterns, leading to new conceptions, which can then be applied and acted upon as conceptual resources themselves.

At the present time this suggestion is presented as no more than a hypothesis. If we seek to understand learning in science then phenomena such as the widespread occurrence of a tenacious, but scientifically invalid, 'full shells explanatory principle' need to be explained. Some form of intuitive pattern-recognition process that foregrounds the 'full shells' gestalt in student thinking seems a strong candidate mechanism in this case.

Other candidates for p-prims operating in learning chemistry

This is not the only example of common alternative ways of student thinking in chemistry where p-prims may help explain research findings. Another example concerns the way students conceptualise the electrical interactions within in an atom or ion (Taber, 1998b).

Students commonly seem to expect either that forces act on the electrons from the nucleus, but not vice versa, or at least that the force on the electrons from the nucleus will be larger than the force on the nucleus. This pattern seems to be very similar to one that may be proposed in much larger systems – for example considering the sun to exert a force on the orbiting planets, but not being subject to a (Newton third-law pair) force itself. One way of interpreting these ways of thinking is to suggest that whereas the scientist makes a clear distinction between the size of a force (the same on both bodies) and the effect of the force (larger on the less massive body), the learner does not make such a distinction, and conflates the force with its effect. It seems there is a candidate p-prim here: common experience leads to recognising the pattern that the bigger/'stronger' body has the greatest effect, and when the student considers a diagram of an atom or ion it may well be perceived in terms of such a pattern, with the nucleus as the larger and more influential body.

However, it may be that *the centrality* of the nucleus is also significant here. Work being undertaken at Kalmar University in Sweden by Karina Adbo (personal correspondence) suggests that many students may well see the nucleus of an atom as fixed in space. From the *scientific* point of view we might simply consider this as an explicit and suitable choice of a frame of reference when modelling the atom: but when this 'choice' is made tacitly at some *intuitive* level by the learner, then the nucleus may well be considered as stationary in a more 'absolute' sense.

To return to the electrical interactions, it is common for students to consider that somehow an atomic nucleus can produce a fixed amount of attraction, which is somehow shared out among the electrons (so that removing an electron allows a redistribution of its share). This was originally reported from a UK interview study (Taber, 1998b) and the finding was later replicated in surveys of UK learners (Taber, 2003b). The same conception has since been found in a survey of learners in Singapore (Tan, Taber, Goh & Chia, 2005) and among learners in a number of other countries (Tan, Goh, Chia, Taber, Liu, Coll, Lorenzo & Li, accepted for publication). The notion of 'sharing out' does not match the scientific model, but would again seem a suitable candidate for the operation of a pattern recognition process at early levels of cognitive processing: a p-prim (Taber & Tan, 2007).

Further candidate p-prims have been suggested by an interview study using the 'interviews-about-events' approach (White & Gunstone, 1992) to elicit explanations of phenomena such as mixing, dissolving and reacting from secondary age students in the UK (García Franco & Taber, 2006). The findings of the study suggested a number of patterns in student explanations that would seem to be candidates for deriving from p-prims. For example, in chemical reactions between two reactants, it was common for students to see one of the reactants as the 'active' cause of the reaction, whilst the other was a passive partner being acted upon. A related idea was the common attempt to identify an external agent responsible for causing a change. This is certainly a reasonable principle, but in science processes such as diffusion and mixing, or evaporation, may be explained in terms of 'internal' causes - the energy and inherent movement of particles. Such inherent motion is unintuitive (cf. Piaget, 1973/1929), so the reasonable expectation of an active cause leads to students assigning causality to irrelevant features.

P-prims in other science disciplines

It is suggested then that the knowledge-in-pieces perspective that has been the focus of much attention in physics education may also be useful in exploring learning trajectories and difficulties in chemistry. The synthetic model discussed in this paper could also be useful in the life and environmental sciences. For example, the common notion that the 'stuff' that plants are comprised of largely originates in the soil is considered a very common and tenacious alternative conception (Bell & Brook, 1984), that could derive from some form of p-prim(s). Similarly, life-world ontologies of the living world (Kuhn, 1989) – that trees are a natural kind, that fungi are plants, that spiders should be grouped with insects, that mammals are a major taxonomic group (often identified as 'animals') – would seem strong candidates from deriving from 'primitive' pattern-recognition features of cognition. Such aspects of students' scientific thinking about the living world may well be illuminated by research informed by the type of inclusive view of conceptual resources discussed here.

Indeed, although there may well be reason to consider knowledge of the living world and the material world as forming somewhat distinct domains (Mithen, 1998), knowledge construction about all aspects of the natural world would be channeled by the same p-prims. For example, it was suggested above that the salience of aspects of symmetry could be significant in the development of some alternative conceptions in chemistry. A very different context from biology would be learning about photosynthesis and respiration. Here some students seem to readily develop the alternative conception that respiration only occurs at night (Alparslan, Tekkaya & Geban, 2003), despite this being inconsistent with the target curriculum knowledge that emphasises the energy requirements of ongoing cellular metabolism. The intuitive attractiveness of this notion, despite it being inconsistent with other learning, could well be linked to some similar basic perceptual bias for identifying symmetry: i.e. that if photosynthesis (represented as $6CO_2 + 6H_20 \rightarrow C_6H_{12}O_6 + 6O_2$) can only occur during the day, then the 'opposite' process ($C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_20$) should only occur at night. This is, at present, purely a conjecture, but illustrates the *potential* for p-prims to play a role in the formation of biological conceptions.

'Just so' stories and progressive research into science learning

The starting point for this paper was a discussion about the status of findings reporting student ideas in science, and in particular whether researchers are uncovering thinking (a) that reflects well-established, stable features of cognitive structure (i.e. conceptual knowledge coded in long-term memory), deserving such labels as 'conceptual frameworks'; or (b) generated *in situ* from 'knowledge-in-pieces': separate discrete and more elementary knowledge elements, such as p-prims.

Research that derives largely from studies of physics learning and which suggests that a 'knowledge-in-pieces' approach explains many research findings was reviewed, although it was pointed out that the key theorists do not suggest that *all* student thinking is the outcome of knowledge structures generated *in situ*, but rather that *much* elicited thinking is of this form.

This approach was developed in terms of a descriptive model of cognition that assumed both elementary and largely intuitive aspects of cognitive apparatus, as well as the formation of concepts and conceptions that could be 'stored' (i.e. represented in cognitive structure) and accessed explicitly, and which could be used to construct more extensive knowledge structures that might through reinforcement themselves become 'stored' in memory: allowing complex and integrated conceptual learning.

This perspective was then applied to consider some examples of findings from studies into student thinking in chemical topics. It was argued that although the 'knowledge-in-pieces' perspective cannot *fully* explain the reported research findings, there nevertheless are some feasible candidates for p-prims that may be operating to filter and channel student thinking as they construct conceptions of the unfamiliar molecular world – conceptions that will provide components for the building of the more extensive knowledge structures. It was also suggested, in terms of some albeit tentative examples, that a similar perspective could be valuable in exploring learning in the life sciences.

The inclusive approach taken here would seem to be consistent with both a good deal of thinking about cognition and memory (Baddeley, 1990; Eysenck & Keane, 1990; Kellogg, 1995), and a basic constructivist perspective on learning (Taber, 2006a). The model assumes that thinking draws upon both cognitive biases in the human brain, and conceptual structures that have become established through previous cognition and represented permanently in cognitive structure. Thinking accesses the existing conceptual resources (i.e. activates the representation in cognitive structure), and in doing so generates more complex knowledge structures, at least some of which will leave permanent traces in memory - so building up the sophistication of the available conceptual resources for subsequent thinking.

A key point then is the iterative nature of this process. This means that over time knowledge may be 'chunked' to overcome the inherent limitations of working memory (Kellogg, 1995). It also means that initial perceptual or other biases in processing may become fossilised in knowledge structures (cf. Bachelard, 1968). This can lead to students developing complex and well-integrated knowledge structures that have been shaped by pre-conscious 'intuitive' pattern-recognition processes which may put them at odds with scientific thinking. If this is at the level of '*re*-cognising', for example, the teacher's description of heat as being a kind of material fluid, or intuitively perceiving full electron shells as having inherent stability, or classifying insects as something other than animals, then it may be that such processes can direct knowledge construction away from the direction intended in teaching.

Using the model to develop bold conjectures

So this model of cognition can be used to make sense of a lot of research data, and to explain why we should *expect* learners' ideas to show considerable variations in terms of stability, level of commitment, and degrees of sophistication. This, however, may be a weakness as well as a strength. A model that offers interpretations of such a range of data brings the danger that we can use it to provide 'just so' stories that can interpret any findings from our research. However, 'just so' stories do not form a good basis for informing pedagogy. Teachers do not need a model that can explain away whatever ideas their students offer, but advice on how to teach to support students in developing ways of thinking that better match curriculum models.

In Lakatos' (1970) notion of scientific research programmes, the different theoretical models that are developed are called 'refutable variants'. As Popper (1989) has emphasised, to be refutable a theory has to offer predictions that are testable and capable of being (in principle) falsified. Indeed, for Popper (1979: 53), the best science involves the production of 'bold conjectures'. For Lakatos, a research programme may degenerate if theory is only modified *to fit* to existing data. To remain 'scientific' a research programme must be progressive. Lakatos argues that a research programme,

> is *theoretically progressive* if each modification leads to new unexpected predictions and it is *empirically progressive* if at least some of these novel predictions are corroborated. It is always easy for a scientist to deal with a given anomaly by making suitable adjustments to his programme … Such maneuvers are *ad hoc*, and the programme is *degenerating*, unless they not only explain the given facts they were intended to explain, but also predict some new facts as well.
>
> Lakatos, 1978: 179.

The model of cognition discussed in this paper can explain the wide range of findings from published research into learners' ideas in science, even though the underlying assumptions of different studies are often *in themselves* offering inconsistent views of the nature of the phenomenon studied. The synthetic model discussed can 'save the phenomenon' by offering a range of categories that can accommodate most research findings in the field. Whatever the researcher claims about the nature of the ideas elicited (romanced, tenacious, stable, labile, committed, and so forth), the model allows the findings to fit.

An analogy might be a research programme that looked to characterise books in a library. Different research groups, using different approaches to sampling libraries might come to very different conclusions: regarding, for example, what books are about, whether they are factual or fantasy (or something in between), how big they are, whether they include diagrams, the kind of binding, the reading demands made by the text, the size of print, and even the language in which they are written. Clearly an inclusive model might make sense of these different findings by suggesting that there are all kinds of books available in the library, and just going to one shelf is likely to give a distorted and limited view. This would *explain* the different interpretations that have been offered, but does not help anyone who wants to locate particular books in the library.

What is needed is some sort of model of where to locate different kinds of books. However, if our analogy is to offer a good comparison with research into learners' ideas, we should acknowledge that the existing studies have not only used a range of methodological approaches, but have sampled the books from different libraries. It may be that all these libraries, with their different holdings and physical spaces, use similar *basic principles* for acquiring and organising their stock, but that may not be immediately obvious from the data which is available!

This analogy leads us to ask if the synthetic model discussed here can be more than a *ad hoc* attempt to patch theory to data. To contribute to a progressive research programme the model must offer predictions that are testable. This means that the predictions must be falsifiable – more than just predicting that research will continue to find that learners' ideas *seem* to have a range of characteristics. It is suggested that the synthetic model can offer predictions that could be tested.

Testing for 'knowledge-in-pieces'

The model allows elicited ideas about science to be an application of a stable complex conceptual framework, or be constructed *in situ* from more elementary conceptual resources. Distinguishing these situations may be important in informing teaching. Tenacious alternative conceptions and frameworks may need to be made explicit and directly challenged if students are to be persuaded to shift from using them (Driver & Oldham, 1986). However if alternative ideas found in research are just *in situ* generations, formed by combining more 'elementary' conceptual resources, then

> Different presentations, problems, task framings and so on are likely to elicit different aspects of students' knowledge and reasoning.
>
> Hammer, 2004b: 8

Then it becomes useful to know *under what conditions* particular 'alternative' ideas are most likely to be generated, so that teachers can avoid some contexts and lines of questioning until students have been channeled towards ways of thinking that are more in line with curriculum science. Neither of these approaches is straightforward, but knowing when each is indicated is a starting point for research to develop pedagogy, and advice to teachers.

It will not be simple to distinguish these alternatives. We might expect 'more' consistency in responses when students are drawing upon well-established conceptual structures. However, the presence of manifold alternative conceptions may provide a range of response options somehow cued by context, and apparently similar questions may not be perceived as such by the learner. Similarly, if a student can *generate* a new mental model of a phenomenon from disparate conceptual resources on one occasion, then clearly there is the potential to reconstruct the same model in response to similar questions (perhaps cued as a response option by having been recently used), or on another occasion (possibly with the previous activation leading to permanent synaptic changes increasing the likelihood of reactivation later).

However, it may be possible to distinguish conceptual complexes that are accessed 'whole' from those generated anew by considering the cognitive load required to apply the ideas (Tsaparlis, 1994). If, as widely believed, an individual's working memory has a limited and fairly fixed 'capacity', then this may provide a means for exploring whether a student's ideas are being accessed as a single 'chunk' of information from memory, or are generated by the *in situ* coordination of several discrete conceptual resources.

The ability to solve problems or complete tasks depends both on task complexity and the number of recalled chunks of information that need to be coordinated. The same individual should be more limited in applying ideas that are generated by coordinating discrete conceptual resources than in applying a conceptual 'complex' already 'stored' in long-term memory. Here we have the basis for devising tests for the presence of thinking in terms of conceptual frameworks or knowledge-in-pieces.

Identifying p-prims

By their nature p-prims operate at a preconscious level, so that they can only be inferred indirectly by the conceptions that may derive from them. So, for example, we can explore with students whether they *really believe* that atoms seek full shells, or that nuclear force is shared between electrons, but we can only speculate about the mechanisms that lead particular students to think in these ways. However, once *candidate* p-prims are nominated, it may then be possible to test out whether other learners do commonly seem to have *predispositions* to see such patterns in sensory data.

For example, if learners who have not studied atomic structure are presented with information about the electronic structures of atoms and ions it might be possible to explore any intuitive responses to the patterns of the structures (and common representations of them) before they have been exposed to any teaching about the stability and significance of noble gas structures. If at this stage learners commonly offer intuitive beliefs that aspects of symmetry or 'completeness' would be more stable, or 'desirable', then there would seem to be a strong perceptual bias that could operate in interpreting teaching. If such beliefs were not elicited at this early stage, then this would suggest the later development of such beliefs could owe more to features of current pedagogy than to a 'p-prim'.

Clearly in the latter case a change in emphasis in teaching might avoid the development of unhelpful ways of thinking. In the former case remediation is likely to be more problematic as alternative ideas develop from very primitive levels of processing, so that bias is introduced before any conscious processing is possible.

However it may be possible over time to catalogue the p-prims that are common to most learners, and identify which p-prims could bias thinking *towards* scientific ideas in particular topics. It may then be possible to develop instruction that uses forms of representation that are more likely to trigger particular p-prims.

Conclusion

Clearly the suggestions made here are somewhat speculative, and significant further research on the specific foci is indicated. This is seen as appropriate in a progressive research programme. A synthetic model is explored, that is considered one 'refutable variant' of the body of theory being developed in the research community to understand learning in science. This model accommodates existing findings, and suggests directions for generating predictions that can be tested by further empirical work.

Neither accounts of learners' alternative scientific ideas reflecting stable conceptual frameworks *nor* accounts of them being generated *in situ* fit all the available research findings. The synthetic model can accommodate the presence of both possibilities, showing that both would be expected depending (for instance) upon the level of familiarity with the perceived context of a research probe. However the model can also lead to new predictions (e.g. about how ideas with different origins may make different demands on working memory; about how p-prims should be detectable by the way they influence initial interpretations when learners are first introduced to new material in the absence of potentially 'leading' teaching), and in this way the model has heuristic power in suggesting possible directions for further research.

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