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Of models, mermaids and methods: The role of analytical pluralism in understanding student learning in science

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Abstract:

Research into student ideas and learning difficulties in science education is undertaken to inform developments in pedagogy. Complex phenomena may be best understood by exploring them from a range of viewpoints, and it is argued here that using a battery of 'analytical lenses' to illuminate research data may be an appropriate strategy in researching student learning. The approach is considered methodologically sound provided the 'lenses' derive from perspectives that are congruous with the theoretical framework underpinning the research. The present chapter illustrates such 'analytical pluralism' by applying three 'analytical lenses' ('modelling mentality', 'learning impediments' and 'student ontologies') to illuminate data from research into student understanding of the orbital model of atoms and molecules. The three 'lenses' focus on different features of the data in order to offer possible explanations for student learning difficulties and recommendations for improving teaching.

Key words:

analysing qualitative data; analytical pluralism; analytical lenses; curriculum models; meaningful learning; learning impediments; cognitive structure; student ontologies; orbitals; quantum theory.

Introduction

One key area of research in science education seeks to understand how students learn science. It is recognised that this is a complex phenomenon, such that there are many factors that can influence the course of a students' learning. Research into aspects of learning science has been a particularly active field for the last two decades or so, and so there is a now a considerable literature providing insights for teachers and researchers (Duit 2007). Indeed, it is argued here that there is sufficient maturity in the field (see Taber, 2006a) for research into the learning about any science topic to be informed by quite well developed theoretical perspectives – e.g. conceptual change, learners' ideas, problem-solving etc. Each perspective provides explanations for some of the reasons learning takes the course it does.

The argument explored in this chapter is that data concerning complex phenomena (such as learning) may be sometimes best understood by when examined in the light of a number of 'analytical lenses', i.e. analytical tools deriving from distinct theoretical perspectives. Such 'analytical pluralism' is justified where each theoretical perspective only provides a partial picture of the process being studied, and where the distinct perspectives may be considered to be congruous.

The notion of analytical pluralism will first be compared to two related and well-accepted notions: triangulation and the 'battery-of-tests'. The approach will then be briefly illustrated by examining data from an interview study that explored learners' developing understanding of a recognised 'problem' target concept area, i.e. the orbital model of atomic and molecular structure (Taber, 2004). Three different analytical lenses will be applied to the data to illuminate learners' difficulties. The case being made here is not that this approach necessarily provides *definitive* interpretations of the data (rather, like most such enquiry, it provides recommendations for changes in teaching approach and emphasis that may themselves provide the focus for a further cycle of research) but rather that analytical pluralism provides a more inclusive interpretation of the data than is possible from any single perspective.

It is recognised that not all theoretical perspectives can be considered to be coherent, and therefore it is important that researchers utilising analytical pluralism should be confident that the analytical lenses they select do not derive from perspectives based upon inconsistent assumptions. However, it is argued here that, providing researchers are confident that the analytical lenses applied derive from congruous perspectives, analytical pluralism can lead to a more thorough interpretation of research data.

Methodological triangulation: slices of data and layers of interpretation

The term triangulation derives from the method of locating a beacon by finding its bearing from different locations: the several directions give limited information individually, but collectively establish the source of the signal. By analogy, the term is also used to describe a common approach to data collection in the social sciences (such as education). Triangulation is considered to be one of the criteria that marks out high quality studies in chemical education (Eybe & Schmidt, 2001).

In *methodological triangulation*, different sources of data are collected (Cohen, et al., 2000; Hitchcock & Hughes, 1989; McNiff, 1992; Schwandt, 2001). For example, a teacher may be interviewed about her teaching, but the interview data is compared to that from other interviewees (e.g. her students and colleagues), observations of her teaching, examination of the comments she makes on student work etc (cf. Elliot, 1991). The assumption is that an informant, even an honest informant, will have biases, and will have access to only some of the relevant perspectives, and so sound conclusions can only be drawn from evidence that is corroborated from several data sources.

Triangulation is primarily used, then, due to considerations of validity - for the purpose of raising the ‘trustworthiness’ of interpretations (Ely, et al. 1991). In ‘qualitative’ research ‘trustworthiness’ has been defined as the quality of a study that makes it noteworthy to an audience (Schwandt, 2001).

Similar approaches are used in educational evaluation (e.g. Hopkins et al., 1999). So for example, in the process of inspecting schools in the UK inspectors are required to collect such a range of evidence:

> "A school inspection is a process of evidence gathering in order to provide an assessment of how well a school is performing. This is achieved using data exchange, lesson observation, interviews with teachers, analysis of pupils' work, meetings with parents, pupils and governors" (OFSTED, 2003).

What is suggested in the present chapter is that, just as different 'slices of data' (Glaser & Strauss, 1967) may be useful in providing different perspectives on a research focus, so may *complementary analytical frameworks* be useful in 'interrogating' a specific data set. It is not suggested that this is an alternative to collecting slices of data from several sources: depending upon the study either or both may be appropriate.

It should also be pointed out that the purpose of the *analytical pluralism* proposed here is somewhat different from the use of multiple data sources. Whereas the rationale for triangulation is to see if the same interpretations can be supported from different 'slices' of data, the purpose of analytical pluralism is *to offer alternative insights from the same data set.*

The battery-of-tests principle

The notion of using a battery of tests is certainly familiar from medicine and science. In general medical practice, a family doctor has available a well established set of standard diagnostic tests that can be used to help identify a medical condition (e.g. Pescar & Nelson, 1994)

The principle is also well-established in analytical chemistry, for example, where an unknown sample may be subject to a wide range of distinct tests, including determinations of melting and boiling temperatures, tests for reaction with a range of reagents, and a wide variety of chromatographic and spectroscopic investigations

(Finar, 1973; Wheatley, 1968; Williams & Fleming, 1973). The assumption is that few of these individual tests will provide definitive evidence of the identity of the unknown (especially if it is a mixture), but each test may provide clues.

Some tests will exclude many possibilities; others may suggest the presence of specific features. Given a *sufficient range of tests* it is often possible to make confident identifications of the sample. This is a well-established principle where the different analytical techniques available are seen as “tools [which] give different types of data [and] which are most effectively used in conjunction with each other” (Allinger et al., 1976, p.76).

Although the subject matter of general medical practice or analytical chemistry may seem remote from the central concern of this present study, viz. the learning of science, the ‘battery of tests’ principle is well established in a field cognate to research into student learning. In psychology a number of tests used together (for example when selecting individuals for educational programmes or employment) is known as a ‘test battery’ (Anastasi, 1982). It is an accepted principle in psychological testing and evaluation that “important decisions are seldom made on the basis of one test only. Psychologists frequently rely on a test battery - a selected assortment of tests and assessment procedures” (Cohen, et al., 1996, p.153).

It is suggested here, that when interrogating data from studies into student learning, a similar approach may be useful. Rather than subjecting an individual to a series of tests (as in psychological evaluation), a data set is ‘subjected’ to inspection through a series of analytical ‘lenses’. These analytical lenses will each be suitable for uncovering a particular potential feature of the data set, in an analogous way to how infrared, ultra-violet and mass spectroscopy have the potential for revealing distinct structural features of a chemical unknown.

Clarifying the philosophical basis

It is recognised that the notion of analytical pluralism could be *suspected* of being underpinned by a view that there is no objective basis for knowledge, and that therefore multiple (and potentially inconsistent) interpretations of the data could be presented as valid results of a study. A philosophical basis for such an approach *could* be found in those modern thinkers who reject the notion of the world as a single reality that can be known in an objective sense. As previous science education research (in the constructivist tradition) has incited similar criticisms (e.g. Matthews, 1994; Scerri, 2003 – see Taber, 2006b), it seems appropriate to explore the issue at this point. Whilst recognising the importance of such debates, the type of analytical pluralism espoused here does not rest on the acceptance of such a philosophical basis.

The idea that the world simply 'is' as we perceive and construe it, would be seen as a naïve and child-like notion. It is generally well accepted that our understanding of the world is mediated by the nature of our perceptual and cognitive apparatus (Ellis & Hunt, 1989) and our existing conceptual frameworks (Kelly, 1963). Thus our internal representations of the world are mental models (Johnson-Laird, 1983) that are contingent upon our biological heritage, and our culture and personal life experiences, *as well as* upon any 'external reality' that may be observed.

Some thinkers conceptualise this argument as relating to limitations in the extent to which we *can know* such reality: where others go beyond this to suggest that the notion of there being an objective external reality becomes untenable (cf. Gergen, 1999). Although this debate may seem somewhat esoteric in the context of the present study, it has become important in considering the future direction of research into learning in science (Taber, 2006b), and so is worthy of consideration here.

The exploration of learners' ideas about science topics has been a major research activity for the past two decades. Much of this work has centred about the identification of alternative conceptions and alternative frameworks (Pfundt & Duit, 1994). This research programme has drawn upon a constructivist thesis for much of its justification (Duit, 1991; Taber, 2006a), and the constructivist stance has been the subject of some major criticisms.

The constructivist position taken by many science educators (which I will refer to as 'contingent-constructivism') is based upon work exploring the psychology of learning

(Taber, 2006b). This work suggests that human learning about a topic is necessarily a 'piece-meal' process, which takes place over extended periods of time, and where the meaning of new information (and so how readily and in what way such information is integrated into cognitive structure) is highly contingent on the interpretive frameworks (i.e. prior knowledge) available (e.g. Driver, 1991). In other words what can be learned depends upon what is already 'known' (i.e. thought to be known, whether consistent with accepted formal knowledge structures or not), as existing understanding provides the 'conceptual goggles' (Pope & Watts, 1988) for making sense of new information, and the substrate or bed-rock for anchoring new learning. Within this contingent-constructivist position, existing knowledge is a major determinant of the ease and direction of future learning, and so learners' ideas become a key focus for research.

However, there is a wider constructivist movement that goes beyond the contingent-constructivism of science education. This view, which may be referred to as 'radical-constructivism' after von Glasersfeld (1989; Nola, 1998), is at least agnostic about external reality (i.e. an objective reality can not be known, and so our constructions are all we can know, and perhaps all there is).

When related to science, and taken to an extreme, this radical-constructivist viewpoint would not see developments in scientific understanding as progress towards greater knowledge, or more accurate models of the universe, but rather as reflections of the prevailing cultural milieu. So Feyerabend argues that "Scientific entities...are projections and thus tied to the theory, the ideology, the culture that postulates and projects them", (1988, p.265). This view, that scientific knowledge is relative to the prevalent culture, is anathema to some commentators, and has led to criticisms of the constructivist movement *in science education* (Matthews, 1994). Yet such criticisms would seem to be misplaced for two reasons.

Firstly, the importance ceded to learners' ideas in science are due to their significance *for learning*, and not because science educators wish to raise the naïve or misconceived notions of pupils to be the equal of established science (Taber, 2006b).

Secondly the raison d'être of science *education* is not directly concerned with developing our species' knowledge and understanding of the world (à la science), but rather concerns developing learners' knowledge and understanding *of curriculum models* (Gilbert, 1998) of science, i.e. of an existing body of knowledge that is formalised, defined and objectified in curricula and syllabuses. Even if some science educators or teachers do have a relativist/radical-constructivist epistemology of science, their pragmatic concern is primarily with helping learners construct versions of curriculum science that match the objectified versions as well as can be. *Science* is about developing reliable public knowledge (Ziman, 1991), where *science education* is about developing personal knowledge (Kind & Taber, 2005).

The present author's position is that of contingent-constructivism, i.e. that individual learners' must construct their own internal representations of scientific knowledge, and that their learning will be channelled and constrained by their existing knowledge and understanding, as well as by the limitations of the perceptual-cognitive apparatus available to them, and by features of the learning environment (e.g. teacher knowledge and pedagogic skills, nature and quality of learning activities including student-student interactions, etc.) Any analytical perspectives applied therefore need to be seen to be consistent with this underlying position.

Understanding multifaceted phenomena

So recommending analytical pluralism is not tied to a relativist view of science or a radical-constructivist epistemology. Even from a naive realist viewpoint (considering the world as objective and fundamentally knowable) analytical pluralism can be justified when researching complex phenomena.

A key area of concern to science education researchers is, naturally enough, student learning in science. By understanding the process by which learning takes place, we are better able to offer pedagogic advice to teachers and curriculum planners. Yet, science learning is a very complex phenomenon, and (as implied above) there are many factors that could be the focus of such studies.

If a student's ideas are elicited at the end of a course of study, it is not sensible to look for '*the* cause' of some particular feature of learning. The factors that contributed to a particular understanding may be legion: the learner's pre-established intuitive ideas about a topic; the degree of match between the learner's preferred learning styles and the teacher's teaching style - including the sequencing and pace of the teacher's presentation; the extent and nature of any peer discussions that accompanied the lesson; any associated informal learning from the media; the idiosyncrasies of the way the teacher and/or the student use certain relevant vocabulary; the way the student recognised connections with other lessons (in the same or other subjects); the frequency and nature of the revision activities undertaken by the student; the extent to which the teacher sought to reinforce learning in later classes etc. It would be possible to extend this list considerably (at the risk of boring the reader), but perhaps a few examples will suffice.

Factors totally beyond the teacher's control, such as the quality of the student's diet and sleep patterns (Sousa, 2001), will influence learning. The time of day of a class, the nature of previous lessons and the weather conditions (not to mention ill health or romantic infatuation) could all influence the student's level of concentration and attention.

Some of these factors are outside the normal focus of research in science education, but they may all be relevant variables in determining the learning that ultimately derived from a teaching episode. Learning (from the contingent-constructivist position established above) is a multivariate and multifaceted phenomenon, highly contingent on features of both the learner's internal 'conceptual ecology' (Hewson, 1985), and the external learning environment, and no single causal explanation of a specific feature of student learning is ever likely to be a complete or sufficient explanation. When dealing with such complex phenomena it is sometimes appropriate to look for different levels of interpretation. A number of parallels can be drawn with other areas of study.

In cognitive psychology, an information processing perspective on cognition often considers three different 'levels' (Dawson, 1998), 'computational' (considering the information processing 'problem' being 'solved' by the system), 'algorithmic' (concerning the method of processing the information) and 'implementational' (the physical properties of the system). Each of these levels of analysis is an accepted focus for research, with its own terminology, techniques of inquiry etc., but ultimately cognitive psychologists would wish to develop an over-arching theory incorporating and relating these levels.

In chemistry we often use several levels of description and explanation to explore reactions: considering the molecular and molar levels for example (Jensen, 1995; Johnstone, 1991) and in an analogous way - exploration of science learning should consider both conceptual factors (e.g. alternative frameworks) and cognitive factors (e.g. limitations due to the capacity of working memory) as complementary levels of interpretation (Taber, 2000c; in preparation). Similar approaches are seen in aspects of biology, where, for example, understanding the functional role of an organ within a system, understanding the structure of the organ, and appreciating the biochemistry of its component cells are complementary in providing an overall understanding of the organ (e.g. Beck, Liem, & Simpson, 1991).

Failure to appreciate such multi-level analyses can also occur. Lovelock's Gaia hypothesis (or 'geophysiology') posits the earth as a single system, *akin to* an organism, with a high level of interdependence among its constituent parts - geology, atmosphere, oceans and all the biota (Lovelock, 1987/1979). The system has evolved a wide range of feedback loops (that may be considered asanalogous to homeostasis within a biological organism) and this perspective can be a fecund way to think about topics such as biodiversity, climate change and pollution.

It is possible to talk about Gaia as being (to some extent) a self-correcting system, in the same way that many organisms are able to adapt to changes in their environment. For example, changes in the sun's radiation output since the formation of life on earth would have made the planet too hot for life, had the ecosystem not evolved in response.

However, some critics have seen this argument as teleological, and consider Gaia as a mystical idea that imbues the earth with its own consciousness and will, because it is able to adapt like an organism (Sattaur, 1987). This is an error of confusing different levels of analysis: the feedback loops that regulate Gaia can all be explained in terms of well-accepted physics and chemistry (e.g. changes in evaporation rates altering cloud formation), but sometimes it is more appropriate to focus on the system level, where the emergent properties may be effectively discussed in terms of the 'geophysiological' model. The Gaia hypothesis provides a perspective for studying the environment that may act as a useful way of thinking and can suggest fruitful research approaches (i.e. a 'positive heuristic' in the sense of Lakatos, 1970).

Modelling complex phenomena

Given that learning (like the biosphere) is a complex phenomenon where research can only be expected to provide partial understandings, it is appropriate that the results of such research should be considered as models. Models can be representations that are simplifications and generalisations. Many of the 'alternative frameworks' reported in the literature should be seen in this way: simplifying complex data to provide models that can be readily communicated, understood and applied; generalising similar features from the distinct ideas of different individual students to provide models of the types of thinking that teachers are likely to encounter (Gilbert & Watts, 1983; Pope & Denicolo, 1986; Taber, 1998a).

Models are recognised in science as often having a heuristic value, as being useful for guiding further research (and in this sense often being of worth even when they are clearly inadequate in some respects). Providing that the users of the models realise that this is their nature - often incomplete, imprecise but useful ways of organising or summarising complex data - then they are appropriate outcomes of scholarly research. As an example, Bohr's model of the atom was recognised as having problematic aspects, yet was still a significant development, having heuristic value to the research community. Bohr's model was known to lack coherence, being 'a kind of mermaid' as a synthesis of classical and quantum principles (Niaz, 1998), but its novel features, and its internal incoherence were both able to stimulate further research.

Theoretical maturity and research into the learning of science

Research into learning science has now been an active field for several decades, and may be considered to have developed some theoretical maturity (Solomon, 1993a; Erickson, 2000; Taber, 2006a). In other words, there are now a number of well-grounded theoretical perspectives that can usefully inform studies into the learning of science. It is suggested that (at least some of) these different perspectives are complementary, and can illuminate different aspects of the phenomenon by 'asking different questions' of the data. A comparison could be made with wave-particle duality: to fully understand the nature of an electron one would need to explore both its particle and wave aspects (Atkins, 1974).

For example, studies of learners' intuitive ideas about the world (e.g. Driver et al., 1994) provide information about one important determinant of later learning pathways; research considering the way learners process information (e.g. Johnstone, 1989) acknowledge another important constraint on the learning process, and ideas about how to judge the status of competing conceptions (e.g. Hewson & Hennessey, 1992) provide insights into how conceptual change occurs. Although each of these perspectives may be distinct, they are all consistent with a contingent-constructivist position.

An example of analytical pluralism

The principle of analytical pluralism will be illustrated here by showing how several different (but compatible) perspectives provide suitable analytical tools to interpret data into student learning. The example discussed is based upon research into student learning in one area of the curriculum - learning about quantum models of atoms and molecules in college chemistry. The findings of this research (summarised below) have been published (Taber, 2002a, b, 2004), and this research will be referred to as the 'source' study.

Three analytical perspectives (modelling mentality; learning impediments; student ontologies) will be briefly considered to show how each illuminate different aspects of the reported data. The present chapter does not set out to provide a comprehensive analysis of the data set but rather to demonstrate the value of the approach. The purpose of *this* present study is to show that different perspectives, each drawing on distinct established literature, but each consistent with the author's underlying position ('contingent-constructivism', as described above), can provide complementary 'analytical lenses' to interrogate data and contribute to the construction of a more thorough (and so more authentic) understanding of the research focus. The topic area, and published research findings will first be briefly reviewed, before the different analytical lenses are introduced, and then employed to illuminate features of the data.

Learning about quantum models of atoms and molecules

It is recognised that students find the particle model of matter as problematic during school science (e.g. Johnson, 1998; Johnston & Driver, 1991; Lijnse et al. 1990; Taber, 2002c), even though at this level the quanta of matter - atoms, molecules etc. - are treated as if 'classical' particles. At college (senior high) level students are taught about an even more counterintuitive model of matter, where 'particles' - perhaps better labelled as 'quantum objects' (Ponomarev, 1993) or 'quanticles' (Taber, 2004) - such as electrons are considered to be wave-particle hybrids with non-classical properties. The structure of the atom, usually taught at the previous educational stage as a planetary-type system with electrons arranged in shells, is now explained in terms of electron orbitals which can technically stretch to infinity - although with infinitesimal probability of finding electrons there! There is little in students' experience of the perceptible world that can be used as a starting point for making sense of such ideas.

Studies into college and university students' understanding of the curriculum models of atoms and molecules presented at this level have revealed that learners commonly have difficulty adopting key features of the ideas presented to them (e.g. Cervellati & Perugini, 1981; Cros et al., 1986, 1988; Mashhadi, 1994; Petri & Niedderer, 1998; Tsaparlis and Papaphotis, 2002). In view of the abstract and unfamiliar nature of the subject matter (Feynman, 1985; Petruccioli, 1993) it is not surprising that attempts to explain and counter students' learning difficulties have met with limited success (Buddle et al. 2002a, 2002b; Fischler & Lichtfeldt, 1992; Jones, 1991; Niaz, 1998; Shiland, 1997; Tsaparlis, 1997). *This is a topic area where illumination from a range of perspectives can fruitfully contribute to directing further research and informing pedagogy.*

This present chapter draws upon evidence from the source study of UK college students' understanding of the quanta/orbital model of atoms and molecules. That study derived from a research project that explored the developing understanding of chemical bonding among students taking the 'A level' chemistry course in a Further Education college in England (Taber, 1998a). This course is at 'university-entrance' level, and is typically studied by 16-18 year olds. The principle informants in the research were 15 students who were interviewed in depth during their studies. The specific (source) study of learners' understanding of the quanta/orbital model drew upon the interview comments of 12 of the students, and detailed findings have been published (Taber, 2002a, b).

It was found that the learners had *particular* difficulties in making sense of aspects of the orbital concept and related ideas. These college level students (1) did not appreciate why quantization was introduced into the atomic model; (2) had difficulty forming an adequate concept of electron orbitals; (3) confused related concepts such as shells, sub-shells, orbitals, energy levels, etc.; (4) did not appreciate what was meant by electronic spin; (5) found the designations of orbitals confusing (Taber, 2002a); (6) did not clearly distinguish molecular orbitals from atomic orbitals; and (7) held alternative notions of what resonance structures were meant to represent (Taber, 2002b). Some of these features will be briefly considered in this present chapter, which draws upon the previously published results.

Introducing the analytical lenses.

The three 'analytical lenses' that are applied in this study are:

- modelling mentality
- learning impediments
- student ontologies

These lenses draw on perspectives that are discussed in the science education literature:

1) modelling mentality: student understanding of the roles of models and representations;

2) learning impediments: the role of prerequisite knowledge in channelling and supporting new learning;

3) student ontologies: the arrangement of concepts within a learner's cognitive structure, and the nature of conceptual change.

Each of these distinct perspectives is consistent with the contingent-constructivist position, and so it is argued that each perspective, *inter alia*, can help illuminate aspects of the data.

Analytical lens: modelling mentality

Understanding the role of scientific and teaching models

As alluded to above, modelling is a central aspect of the scientific process (Gilbert, 1998). Scientific models are constructed to explain or organise existing data, to allow prediction in areas where empirical data is not yet available, and so to suggest fruitful directions for further research and theory development. Scientific theories must be open to falsification (Popper, 1989), and so they should never be considered final or proven (cf. the position of radical constructivists, see above); and the status of our models of the world should reflect this. Although, *in practice*, well-established models do become accepted as part of the description of nature, *in principle* they are our constructions, our exploratory and explanatory tools, and should be considered as partial and fallible representations of the world.

Scientific models of the atom provide a case in point. The historical progression in proposed models demonstrates their heuristic value (Justi & Gilbert, 2000; Niaz, 1998). Ideas for modelling atomic systems were introduced because they seemed to work - they helped develop theory that fitted exiting data, and to suggest fruitful directions for future research (Petruccioli, 1993). However, had these ideas come to be viewed as conceptual cul-de-sacs (like phlogiston or caloric) then they could *still* have played a useful role in *the development* of science.

Models are mind-toys that help us explore: a model that does not match new data is still informative, even though it may fall into disuse. And some models which are found *not* to match new data may still retain their usefulness in limited contexts: so Newtonian mechanics is still very widely taught and used even though it leads to increasingly inaccurate predictions as velocities approach the speed of light. An orbital model of atoms is taught in college level chemistry even though it is only theoretically valid for hydrogenic systems (atoms and ions with a single electron), and the extrapolation to apply the ‘orbital approximation’ to more complex systems seems to be justified by the extent to which it ‘works’ (Scerri, 1989, 1991; cf. Sánchez Gómez & Martín, 2003).

The nature of curriculum models (Gilbert, Boutler and Rutherford, 1998) is similar to that of scientific models with an important distinction alluded to earlier in this chapter. Scientists develop models to help them come to know more about the world. Teachers use models to help learners come to know more *about the scientific models* that are accepted and represented in curricula. In teaching, the target is usually defined in curriculum documents and is already known to the teacher, who has the 'problem' of moving student understanding towards the known 'target' knowledge (Kind & Taber, 2005).

It is worth stressing these points because it is important for science teachers to appreciate the role of the models they use in teaching (cf. Justi & Gilbert, 2002), i.e. as tools for helping students come to understand aspects of scientific models and theories. The two key points here are that (a) as models are tools they are not intended to be represent absolute replicas of scientific knowledge; and (b) that the target knowledge *is itself a set of models*, which may sometimes only map onto the available data in a limited way. What the literature does suggest is that school *students* may often have quite limited appreciation for the provisional nature of theory and the role of models in science (Driver, Leach, Millar & Scott, 1996; Grosslight, Unger, Jay & Smith, 1991; Harrison & Treagust, 1996, cf. Treagust, Chittleborough & Mamialia, 2002).

Certainly if teachers rely upon the models of the atom found in many textbooks then they might well be presenting hybrid models that have dubious scientific or historical validity, and so limited educational value (Justi & Gilbert, 2000). For example, the atom is often modelled as a tiny solar system, but this analogy is inherently problematic both in terms of the need to explore the negative aspects of the analogy, and indeed, in terms of the 'classical' picture of the atom presented (Harrison & Treagust, 2000a; Taber, 2001c): students need to appreciate that they are being taught about one partial scientific model with limited application. This particular example is even more questionable as a teaching tool when it is realised that pupils often hold alternative conceptions of both the target concept and the supposedly familiar analogue (Taber, 2002c).

The role of multiple models

A perspective on models that sees them as tools - which are partial representations with limited ranges of application - allows the modeller (or model user) to accept that several different, and apparently incoherent, models may collectively give greater insight than an approach that relies on a single model. Given, then, that research suggests that pupils often have naïve appreciation of the role of models in science, it is likely that they will not readily accept that they should use several clearly inconsistent models of the same phenomenon. Rather, this can be a source of confusion (Carr, 1984).

Research into students' ideas often apparently reveals the presence of 'multiple frameworks' for concepts such as energy or force (Pope and Denicolo, 1986), and there is some evidence that - at least at college level - students who hold manifold conceptions of a concept area *can* learn to see them as alternative explanatory 'stories' which may all potentially apply, but which have different strengths and limitations (Taber, 2000a cf. Harrison & Treagust, 2000b; Petri & Niedderer, 1998; Treagust et al., 2002). This would seem to be an attitude that science teachers would do well to encourage.

Interpreting chemical representations

This may be particularly important in chemistry where students typically meet a wide range of graphic representations of atoms, molecules and other structures. These representations vary along at least two separate dimensions. For one thing they may be based upon different underlying scientific models (Platts, 1968). So a figure of an atom may show electrons on shells as in a Bohr-type orbital model (ignoring the notion of orbitals), or may show the shapes of orbital lobes. In addition, the way in which the same type of model is *represented* varies considerably.

At a relatively trivial level, electrons may be shown as e, e^-, •, ×, ○, etc. *Most* college level learners seem to 'see past' such differences, although this is not true of some weaker students (Taber, 2002c). More significantly, representations of atoms modelled with orbitals may show orbital lobes with sharp cut-offs, or alternatively may attempt to show the gradual change in electron density. Some figures show overall electron density for a species (molecule, atom, ion), others show the distinct orbitals, and it is quite common for students to meet hybrid figures (which may reflect most of the electron density in terms of lines for bonds, but explicitly show certain atomic or molecular orbitals). Such a range of representations for molecules and related species is quite common in textbooks used by students at the level in the UK system where the source study was undertaken (e.g. Andrew & Rispoli, 1999; Clugston & Flemming, 2000; Lewis & Berry, 2000).

There may often be good reason why particular types of representations are used to illustrate specific points in texts. However, authors and teachers may not recognise the extent to which this increases the 'cognitive load' on the students (cf. Johnstone, 1989). Whereas interpreting the multitude of representations used in college level chemistry is largely a subconscious process for the expert chemist or teacher it can provide a major challenge when seen 'at the resolution' of the novice student.

Modelling the molecular structure of benzene

In the source study of students' understanding of orbital and related ideas, it was found that some of the college students had particular difficulties making sense of the structure of molecules such as benzene that are considered to have 'delocalised' electrical structures. Students may meet various types of textbook illustrations of the structure of the benzene molecule (including a common approach that represents *part* of the bonding in terms of lines, and *part* in terms of the overlap of atomic orbital lobes, e.g. Sykes, 1986).

Two types of structural formula are commonly used to represent the benzene structure, either showing a resonance between several canonical forms (figure 1) or using a circle (figure 2) to symbolise the delocalised electrons (the pi-system of molecular orbitals).

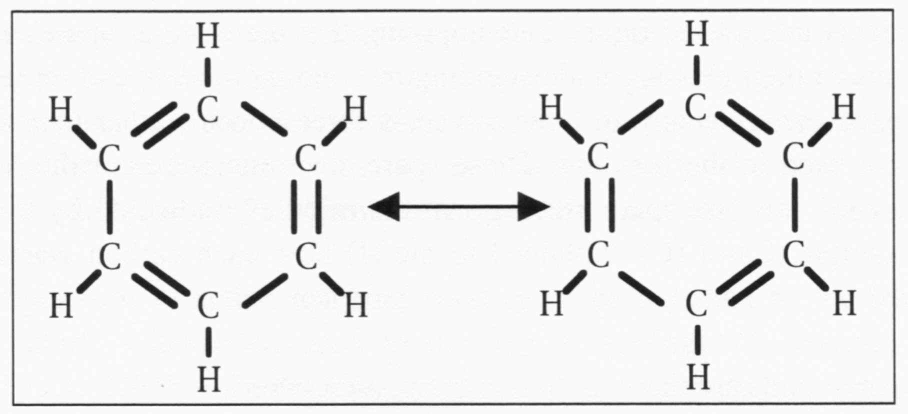

Figure 1: Representing the structure of the benzene molecule as a 'resonance'.

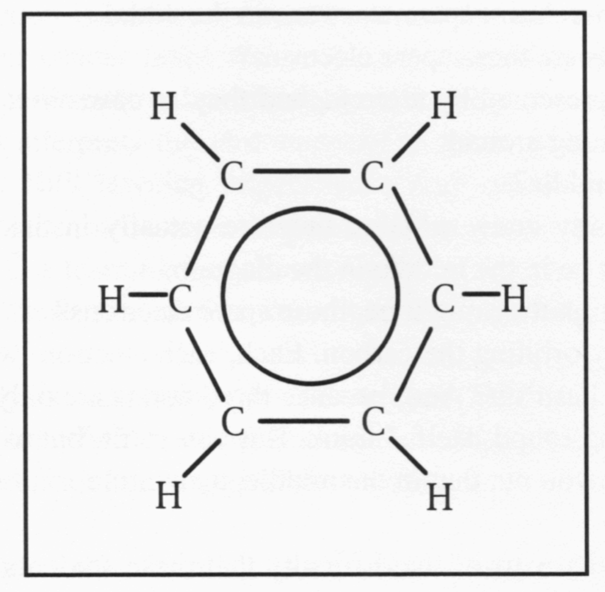

Figure 2: A representation of *the* benzene molecule

Some students (Taber, 2002b) misinterpreted diagrams of resonance between canonical forms as showing an actual alternation between discrete alternative structures ("you can either have a double bond, or a single bond", "and where there was a double bond in one diagram there would be a single bond"). The students recognised the symbols for single and double bonds, and interpreted the figure as showing that the single and double forms swapped positions: "it can change from one to the other". This is clearly a reasonable inference in terms of the students' *existing* models of molecular structure and how such structures are usually represented. So one student (Carol) described how,

> "It will be double bond, single bond, double bond, single bond, double bond, single… and where there was a double bond in one diagram there would be a single bond in the other one...you can either have a double bond, or a single bond, … sometimes single, sometimes double"

Another student, Quorat, who was able to talk of "resonance structures" and "canonical forms" construed these notions as devices *for overcoming ignorance* about *which* bonds were double and which were single, "since the actual positions are not known, it is better shown as a delocalised system".

Several students interpreted figure 2 as implying that there were 'spare' electrons in the molecule. In terms of their existing understanding of bonding models and representations this figure showed each carbon centre to be involved in three bonds (rather than four) leaving a spare electron not used in the bonding. These spare electrons were considered to occupy a *reservoir* in the ring, the "six spare electrons in the middle", indicated by the circle on the diagram. For example, Carol (C) explained to me (I) how each carbon was only shown to have three bonds:

> I: How many bonds are there in that diagram, altogether?
> C: Twelve.
> I: Twelve. What kinds of bond are they?
> C: Covalent. And there's six spare electrons in the middle.
> I: Ah - whereabouts are these spare electrons?
> C: Well, they're represented by a circle, and they're dawn in a like diagram form. And they're just spinning around.
> I: You say in the middle?
> C: Well, I don't really know whether they are actually in the middle,

> in real life, but they're shown to be in the middle in the diagram.
>
> I: Where do you think they might be, these spare electrons?
>
> C: They're probably orbiting the carbon. Each, each electron, well the carbon, it's got a valency of four, hasn't it? And, because three bonds are only shown, it's got to have one still whizzing round itself. I think. But you can't, but to show that on a diagram it'd be messy, so you put that in the middle, by a circle.

It is suggested here that part of the difficulty that these students had of making sense of the figures was related to their rigid interpretations of the representations. These students had learnt models of single and double bonds, and of how to represent them, but they did not think of them as models - as *partial*, as *provisional*, as *tools* to aid thinking. When they met examples of structures that did not fit their existing models they found it difficult to develop beyond them.

It is part of the role of teachers and textbooks to present scientific ideas *as models*, but as the research literature suggests teachers are often not communicating this perspective to their students (Grosslight et al. 1991), even when they do hold such a view themselves (Justi & Gilbert, 2002a, b; van Driel & Verloop, 2002).

Analytical lens: learning impediments

Meaningful learning, chunking and scaffolding

The second perspective that will be presented as an example is developed in part from Ausubel's well known and widely accepted idea of 'meaningful' learning which highlights the role of the students' existing knowledge as a key interpreter and organiser of new learning (Ausubel & Robinson, 1971; Ausubel, 2000).

This perspective on learning implies that successful teaching needs to be designed so that it builds effectively on prior learning. This is a key principle of 'constructivist' approaches to teaching and learning (e.g. Driver & Oldham, 1986). In effect, the teacher needs to plan the presentation of new material with the students' current knowledge structures in mind. From this perspective, many 'failures' of teaching can be explained in terms of the relationship between the hypothetical cognitive structure, assumed by the teacher, that *would* make sense of new material, and the way students interpret the new material through their *actual* cognitive structure.

This principle – of effective teaching needing to be matched to the learners' existing conceptual structure – has been used to develop a typology of 'learning impediments' (described in Taber, 2001b – for the latest versions of the typology, see the website 'Science Learning Doctors - using diagnostic assessment in the science classroom', at http://people.pwf.cam.ac.uk/kst24/ScienceLearningDoctors.html).

The primary distinction is between situations when the intended learning does not take place because the learner cannot make sense of the presented material in terms of existing ideas ('null learning impediments'); and situations where the learner inappropriately (from a curriculum perspective) interprets the new material in terms of existing ideas ('substantive learning impediments'). Null learning impediments may occur because the assumed prior learning has not taken place, or because the learner does not bring it to mind when the new material is met. Substantive learning impediments may be acquired from various sources (but for pragmatic reasons those that derive from previous teaching are put into a separate category).

In the present analysis this typology was applied, and students' learning difficulties (Taber, 2002a, b) were identified in terms of a number of types of 'mismatches' between the teaching and the assumed prior knowledge (Taber, 2004):

- deficits in assumed prior learning (such as not being aware of the classical physics which would make 'planetary' atoms unstable);
- failures to make expected connections with prior learning (such as not recognising the relevance of work on spectral lines undertaken in physics);
- interpreting new information in terms of alternative conceptions (such as considering that a force can be too small to have any effect);

- interpreting new information in terms of oversimplified models from prior teaching (such as adopting the term 'orbital' as a synonym for electron shells).

These and other examples (see Table 1) suggest that mismatches between the material presented in teaching and the learners' prior knowledge structures may contribute significantly to the 'learning demand' (Leach & Scott, 1995) of this topic. It is important to point out that this approach does not imply that learners are 'to blame' for the mismatches – it is the teacher's responsibility to plan teaching to connect with the students' actual prior knowledge, and to undertake the necessary diagnostic assessment and any 'remedial' instruction that may be needed (Taber, 2002c),

This perspective draws upon ideas about the conceptual (i.e. content) *and* cognitive (i.e. process) aspects of learning: where prior learning includes 'alternative frameworks' then new material may be interpreted accordingly, but not all 'faults in the system' are due to missing prerequisite knowledge or the presence of alternative conceptions (cf. Taber, in preparation).

It is not enough for a learner to hold relevant prior knowledge in memory, this relevance needs to be recognised and the prior learning brought to mind if prerequisite knowledge is to act as a substrate for new learning. There are at least two good reasons why this may not occur. Sometimes the new learning does not act as a sufficient cue to trigger the prior learning. This was seen in one of the examples listed above, where the student did not bring to mind the experiment she had undertaken in *physics* to measure the wavelengths of spectral lines. When the student was first asked whether it was possible for an atom to be 'excited' in electrical terms, she did not think it was. However, after being reminded of an experiment she had undertaken in her physics class "with a spectrometer, and you...measure angles, and work out the wavelengths of colours of light?" she changed her mind and was then able to explain an atom could be excited, when "you promote an electron to a higher energy level. And then it falls back and gives out the energy". Memory research suggests that recall is often context specific (Baddeley, 1990; Anderson, 1995; Parkin, 1987) and an interview *about chemistry* may have not been an ideal context to activate knowledge seen as *physics* (Taber, 1998b).

type of learning impediment	learning difficulty
deficiency impediment (no relevant material held in existing cognitive structure)	D1. no knowledge of radiation of energy by electrical oscillators D2. no knowledge of centripetal acceleration and centripetal force D3. no direct experience available to understand wave-particle duality D4. no knowledge of the scientific concept of angular momentum
fragmentation impediment (learner does not see relevance of material held in cognitive structure to presented material)	F1. work on spectral lines stored as physics knowledge F2. areas of electron density above and below the benzene carbon skeleton not related to the 'spare' electrons not used in σ-bonding
ontological impediment (presented material inconsistent with intuitive ideas about the world held in cognitive structure)	O1. forces can be too small to have an effect O2. spin is a property of rotating bodies
pedagogic impediment (presented material inconsistent with ideas in cognitive structure deriving from prior teaching)	P1. electrons are found in concentric shells P2. electrons move around nuclei in planetary orbits P3. inertia is sufficient to explain planetary motion P4. energy input leads to (all) particles in system moving faster P5. heating the cathode in thermionic emission leads to electrons being emitted P6. bonds are between two atomic centres and are represented as lines

Table 1: Classification of some student learning difficulties

Another potential factor concerns the capacity of what is normally termed working memory, where “temporary holding and manipulation of information during the performance of a range of cognitive tasks such as comprehension, learning and reasoning” takes place (Baddeley, 1986, p.34). For new information to be considered alongside prior learning it is necessary to bring both to mind at once. Studies show that working memory has a very limited capacity, so that most people can only ‘juggle’ with about seven ‘items’ at once (Miller, 1968). Now it appears that these ‘items of thought’ are not fixed quanta. Rather it is possible that a single ‘item’ can sometimes be a rather complex entity, because people are able to ‘chunk’, that is, to see *familiar* complexes as single items of information, i.e. as gestalts (Calvin, 1997; Kellogg, 1995; Parkin, 1987; Sousa, 2001).

However this level of familiarity depends upon having already consolidated the information into long-term memory. In the context of science classes it is possible to suggest a wide range of symbolic information that can be recognised *by experienced teachers* as a single familiar pattern, but which may seem to be very complex information *to the novice*.

So a biology teacher will recognise, for example, a schematic of a typical insect body plan in terms of well-consolidated prior learning, but the detail may be too much for a student to take in all at once. In physics the teacher may recognise a graph as showing an exponential decay, and knowing the key characteristics of such a function, be able to take in all the essential information to reproduce the graph: but the student may not recognise the general form or identify the critical features needed to reproduce the graph.

In chemistry the teacher may recognise a formula, even a quite complex structural formula, or a familiar reaction scheme as single item of information. However, from the students’ resolution these schemes may be too complex to take in at once (Taber, 2002c).

When relating new information to prior learning the situation is compounded. Not only will new information likely seem much more complicated to the student than to the teacher, but if prior knowledge is not yet fully consolidated it may be stored in a form that can not yet be effectively chunked. This is a significant issue when studies of memory suggest that this process of consolidation typically takes place over months and even years (Carter, 1998; Greenfield, 1997; Sousa, 2001). This limitation was considered to contribute to some of the learning difficulties identified in the source study of college students' understanding of quantum models of matter.

The research found that students readily adopted *terms* such as sub-shell and energy level, and the general pattern of orbital labels (Taber, 2002a). However, the students made a variety of errors in conflating or confusing this range of distinct concepts (referring to sub-shells as orbitals; shells as sub-shells; sub-shells as shells; shells as energy levels and so forth) and talked of electrons in orbitals that they gave invalid designations such as 1p and 1d.

From a *learning impediments* perspective these types of learning difficulties, perhaps best considered as 'confusing' similar ideas, can be understood when the information that students were being expected to learn in a relative short period is considered from 'the resolution' of the learner. Students begin their college course having a model of the atom with concentric shells of electrons, but the quantum model of electronic configuration, and the relationship of this to energy levels (important to match the atomic model to the periodic system) introduce significant complications.

electrons	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓
orbitals	1s	2s	$2p_x$	$2p_y$	$2p_z$	3s	$3p_x$	$3p_y$	$3p_z$	$3d_{z^2}$	$3d_{x^2-y^2}$	$3d_{yz}$	$3d_{xy}$	$3d_{xz}$
subshells	1s	2s	2p			3s	3p			3d				
shells	1	2				3								

Figure 3: orbitals, sub-shells and shells for n=1 to n=3

Some characteristics of the electronic orbitals present in the hydrogen atom (and used as a model for other atoms) may be deduced from some simple mathematical relationships between the quantum numbers, and the pattern for the first three electron shells are shown in figure 3. However the energy level associated with an electron is not determined in any straightforward way from the combination of quantum numbers alone (Scerri, 1998), so that a range of considerations apply, as shown in figure 4. (This figure applies to comparisons within a single atomic system. Comparisons between orbitals in atoms with *different* nuclear charge provide an additional complication).

principal quantum number, n	n=1<n=2<n=3…			
azimuthal quantum number, l	if more than one electron present, then	s<p<d<f…	if only one electron present, then	s=p=d=f…
magnetic quantum number, m_l	if in uniform magnetic field *and* if same occupancy (all singly or all doubly occupied):	then degenerate	otherwise:	degeneracy razed (various permutations possible)
spin quantum number, m_s	(parallel in same orbital excluded)	spin-paired (anti-parallel) > singly occupied	parallel with electrons in *other* orbitals < antiparallel	

Figure 4: relationship between quantum numbers and electronic energy levels for a specific atomic system

(key: < lower energy than; = same energy as; > higher energy than)

Clearly this material is both abstract and complex, although to the teacher, to whom it is well consolidated and the basis of understanding electronic configurations and the periodic table, it will be meaningful, ordered and readily applied.

When these ideas are introduced by experienced teachers many students *will* understand the scheme, because the skilful teacher will in effect work as an ‘add-on-memory unit' - or what Bruner calls acting as a vicarious form of consciousness (Hennessy, 1993, p.13) - whilst the student is mastering a new skill or concept. Experienced teachers become skilled at facilitating the construction of knowledge in the classroom (Edwards & Mercer, 1987; Ogborn, Kress, Martins, & McGillicuddy, 1996).

The teacher manages the information being considered at any moment so that the learner's working memory is not overloaded (Gallimore & Tharp, 1990). This is *analogous* to the process by which we are able to successfully undertake calculations that are too complex to 'do in our head'. We use paper to plan out, and keep track of, the stages of the calculation, and focus on each step in turn. In introducing complex conceptual material, the teacher manages the process so that the learner only has to be concerned with understanding each individual step, whilst the teacher monitors the process and navigates through the overall scheme. In this way the learning process will be scaffolded for the learner through the teacher's exposition (Scott, 1998).

However, consolidation of memory is a long-term process, so even if the material is initially understood, and can be recalled, it does not immediately become 'chunked' in long-term memory, and cannot be accessed alongside other information without overloading working memory.

It was also found that when students discussed electrons in molecules they commonly referred to the bonding electrons being in *atomic* orbitals rather than *molecular* orbitals (Taber, 2002a). Even when there was clear evidence that students appreciated the scheme they had been taught about for forming molecular orbitals from atomic orbitals ('linear combination of atomic orbitals'), so they 'knew' that the bonds were formed by combining atomic orbitals to form molecular orbitals, they still made this 'error'.

The scheme for labelling ground state atomic orbitals acts as pre-requisite knowledge for understanding the hybridisation model (which gives alternative sets of orbitals with energetic and geometric properties more suitable for forming bonds), and the geometry of the hybrid atomic orbitals is prerequisite knowledge for appreciating the schemes for forming molecular orbitals that are introduced to students. Even if the learner is able to understand the *components* of the scheme for forming bonds by orbital overlap (as presented at this level, i.e. see figure 5), they may still be unable to keep the whole scheme clearly in mind.

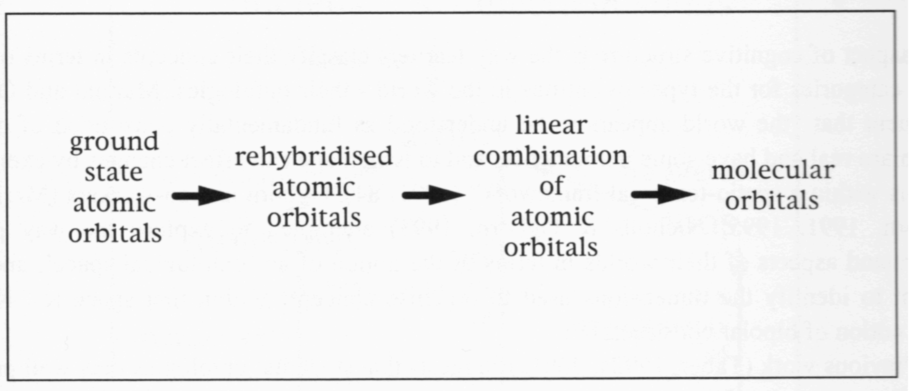

Figure 5: a scheme for conceptualising the formation of molecular orbitals

Chemistry teachers are well aware that these aspects of college chemistry are abstract, and difficult for students to understand. What perhaps is less obvious, but is highlighted in the study considered here, is that even when students *understand* the ideas, and are able to *recall* them correctly in response to a direct question, they may still demonstrate difficulties applying the ideas in appropriate contexts (cf. Bloom, 1964/1968).

The importance of *understanding* concepts is usually well recognised by science teachers, but the research considered here highlights the need for students to be given time to consolidate new learning before it can be accessed and applied effectively (Taber, 2004). In Piagetian nomenclature, assimilation is not enough - accommodation is also needed (cf. Caravita & Halldén, 1994). Only after the new knowledge is well integrated into conceptual schemes (i.e. after equilibration has occurred), and can be conceived as a single pattern (or gestalt), can the material be processed as a single chunk of information.

The principle of memory consolidation over time is well established (Parkin, 1987; Greenfield, 1997; Carter, 1998), and is reflected in the common teaching principle of regular review of important concepts. Yet, this aspect of learning in science has received relatively little research attention (but see Gauld, 1989; Taber, 2003a), perhaps because of the logistics of collecting the necessary data. The analysis presented here offers one explanation for some of the learning difficulties uncovered in the source study (Taber, 2004). This leads to the testable hypothesis that restructuring the teaching scheme to allow more time between the introductions of new concepts that build upon each other may help students achieve the intended learning.

This perspective focuses on aspects of learners' cognitive structures such as 'missing' pre-requisite learning, or alternative frameworks. However, the approach also emphasises that it is not sufficient to know 'what' a student knows, it is also important to know how that information is organised and integrated within cognitive *structure* as this determines how readily it may be accessed, which contexts encourage it being activated, and the extent to which bringing it to mind will load working memory.

Analytical lens: student ontologies

Exploring student ontologies

One aspect of cognitive structure is the way learners classify their concepts in terms of their basic categories for the types of entities in the world - their ontologies. Mariani and Ogborn comment that "the world appears to be understood as fundamentally constituted of objects which are real and have some permanence, and to which one can effect changes by exercising actions within a spatio-temporal framework" (1991: 84). Ogborn and co-workers (Mariani & Ogborn, 1991, 1995; Nicholls & Ogborn, 1993) attempted to explore the way people understand aspects of their worlds in terms of the notion of an 'ontological space', and they sought to identify the dimensions used to organise concepts within that space (cf. Kelly's 1963 notion of bipolar constructs).

Previous work (Taber, 1998a, 2001a) suggests that students' ontologies may well provide a fertile perspective for exploring their learning difficulties when studying structure concepts in chemistry. One example concerns the way that secondary (junior high school) students commonly conceptualise chemical bonding as a dichotomy of two distinct bonding types (see Table 2).

Type of bond	Covalent	Ionic
Formed between	Non-metal & non-metal	Metal & non-metal
Formed by	Electron sharing	Electron transfer

Table 2: A dichotomous bonding ontology

Students seem to strongly adopt this dichotomy and see bonding as *either* covalent *or* ionic (Taber, 2002c). One consequence of this is that when polar bonding is introduced at college (senior high school) level (i.e. Table 3) students do not readily appreciate how it can be an intermediate form of bonding, and tend to see it as *a type of* covalent bonding (i.e. Table 4).

Type of bond	Covalent……..….polar……..…….Ionic
Formed when…electronegativity difference	none……………………………..………..high
Formed by	electrical interactions

Table 3: A continuous bonding ontology

Type of bond	Covalent		Ionic
(sub-type)	pure covalent	polar covalent	
Formed by	equal electron sharing	unequal electron sharing	electron transfer

Table 4: A modified bonding dichotomy

The previous research also shows that students at secondary (junior high) level commonly learn about the molecular world in terms of an 'atomic ontology', i.e. that the basic units of matter are atoms (Taber, 2003b), and other entities are constituent part of atoms (e.g. electrons), altered atoms (i.e. ions), or combinations of atoms (e.g. molecules). This is shown in figure 6:

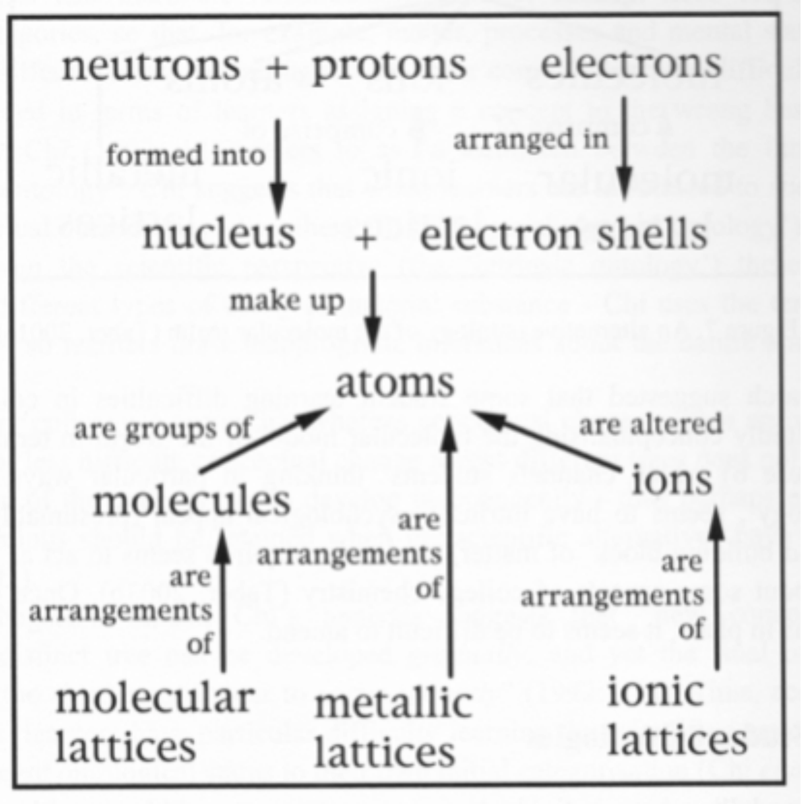

Figure 6: an atomic ontology (Taber, 2001a)

Whilst this approach certainly represents one way of conceptualising the molecular world, it is not the only possibility. So figure 7 represent an alternative way of thinking about matter at this scale that is more consistent with the range of concepts introduced at college (senior high) level study.

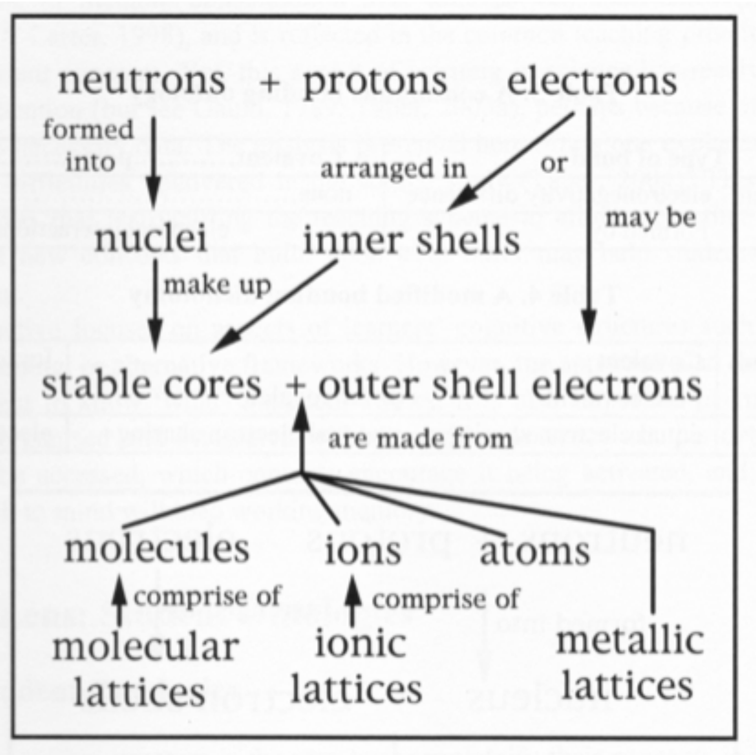

Figure 7: an alternative ontology of the molecular realm (Taber, 2001a)

This research suggested that some student learning difficulties in college chemistry derive from rigidly conceptualising the molecular model of the world in terms of an atomic ontology (figure 6) which channels students' thinking in particular ways. However, the 'atomic ontology', seems to have intrinsic psychological appeal (presumably because it is able to offer '*a* building block' of matter), and once acquired seems to act as an impediment to learning about some aspects of college chemistry (Taber, 2003b). Once the ontological classification is in place, it seems to be difficult to amend.

Modelling student ontologies

One way of modelling how individuals represent concepts within cognitive structure is in terms of tree diagrams, where subordinate concepts are shown as branches of superordinate concepts. Within such a model changes in cognitive structure may be represented as additions or deletions to a tree, or branches moving from one tree to another.

Thagard (1992) has used a computer model of this type, where the evolution of conceptual structures is governed by increases in explanatory coherence. Thagard suggested that major reorganisations of cognitive structure, conceptual revolutions, could not take place by a sudden radical restructuring, but rather that alternative structures may develop in parallel, so that a revolution involved the point where the habitually used conceptual framework no longer had as much explanatory coherence as an alternative which had been developing ‘in the background’.

Although storing multiple versions of reality may initially seem inefficient, there are good reasons to think otherwise. Much of human cognition is based upon developing knowledge by metaphor and analogy (Lakoff & Johnson, 1980) and Karmiloff-Smith (1994) has argued that a major advance in human mental evolution took place when our ancestors developed the ability to make copies of mental representations from one domain and apply them elsewhere (‘representational redescription’). Calvin’s (1997) notion of cognition involving the cloning of spatio-temporal patterns of brain activity across the ‘patchwork quilt’ of the cortex also makes use of a similar principle.

Thagard’s model uses a branching tree model of conceptual structure. The work of Chi and co-workers (1992, 1994) uses this type of branching representation within distinct conceptual trees to explore the idea that some of the alternative conceptions elicited from learners may be considered as categorisation errors. For Chi conceptual change means a change in categorical status - i.e. a change in the branching of cognitive structure.

Chi suggests that there are fundamentally distinct concept trees for different basic ontological categories, so that, for example, matter, processes and mental states need to be considered as different trees. According to Chi some common learning difficulties in science may be explained in terms of learners assigning a concept to the wrong basic ontological category, what Chi (1992: 133) refers to as “a mismatch between the intrinsic and the psychological ontology”. Chi suggests that when learners are introduced to such concepts as heat and electrical current they class them (in their 'psychological ontology') with material substances. From the scientific perspective (the 'intrinsic ontology') these concepts are actually very different types of entity to material substance - Chi uses the term 'constraint-based events' – so learners draw inappropriate inferences about the nature and properties of the entities.

Chi and her colleagues argue that whereas conceptual change *within* an ontological tree may be more or less difficult, conceptual change across different trees does not occur. Rather, another version of the concept has to develop independently - thus perhaps explaining why 'life-world' notions should be retained when the scientific alternatives have been acquired (Solomon, 1993).

As in Thagard's model, Chi's analysis suggests that "new conceptions on an ontologically distinct tree can be developed *gradually*, and yet the final outcome of the development (the shift) may appear to occur *abruptly*" (1992: 134). Thus, according to Chi and colleagues, learners have particular difficulty learning the scientific version of a concept if it has a different ontological status to their own initial categorisation (Chi *et al*., 1994).

Forming an orbital concept from the existing ontology

In the research discussed here it was found that learners readily acquired the concept label of 'orbital' although they initially saw this as an electron trajectory (Taber, 2002a). Students entered study at this level with an existing concept of electron shells, and developing the notion that shells are divided into sub-shells, which are divided into orbitals, can be modelled as adding branching to the existing concept tree. However, where a students' existing concept of electron shell consisted of a set of electrons orbiting the nucleus, then any notion of 'orbital' understood as a branch from the existing 'shell' concept would be a very different sort of entity to the 'orbital' target concept. (This example is discussed in more detail below.)

The analogy of spin

One of the ways that quanticles such as electrons are different from the particles of everyday experience is that they can have *intrinsic* angular momentum, a property which is known as quantum-mechanical spin (or just 'spin'). This property of spin is important at college level chemistry, so - according to the Pauli exclusion principle - two electrons can only occupy the same orbital if they are 'spin-paired' (i.e. have 'opposite' spin).

It was found in the source research that students tended to transfer associations of movement to the term spin (Taber, 2002a). So that one of the students, Edward had read that electrons were "spinning on their axes", and he *assumed* that the electron spin direction meant,

> "that an electron moves about this volume of space that's called an orbital in *one particular direction*, whereas the other moves in *the opposite direction*"

Another student, Quorat, explained that she thought that the spin was caused by the electrical repulsion,

> "because they're all going to be repelling each other and circling, always trying [sic] to get as far apart, 'cause that's why they're always spinning."

These students associated the term 'spin' with the macroscopic phenomenon of that name, of which a key feature is movement, rather than recognising spin as "the intrinsic angular momentum of a subatomic particle, nucleus, atom, or molecule, which continues to exist even when the particle comes to rest" (Lafferty and Rowe, 1994, p.556).

This finding may be represented in terms of ontological trees, for the scientist sees the spin of an electron as an *inherent property* (like mass), whereas the students see it, more akin to velocity, a *contingent property*, as the consequence of a process the electron is currently undergoing.

So figure 8 shows how the electron is presented in the curriculum, where the (rest) mass, charge and spin are fundamental properties of an electron, and where the energy assigned to an electron is contingent upon the location of the electron (i.e. the energy does not reside in the electron itself, but is associated with the configuration).

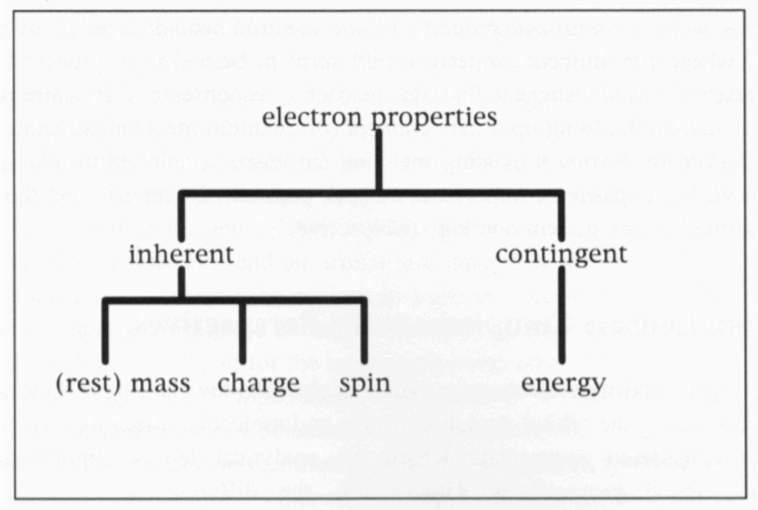

Figure 8: properties of electrons

However, students may conceptualise spin as something that is contingent upon the electron's motion in an orbital, rather than being a fundamental property of the electron itself (see figure 9).

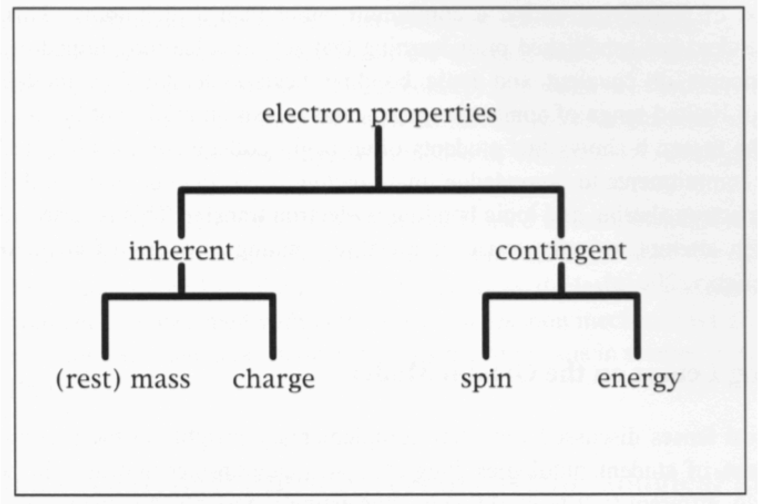

Figure 9: student perception of properties of electrons

This misclassification would seem to be similar (albeit in an inverse sense) to the situation where students identify potential energy as located in an object, seeing it as a inherent property of the object rather than better associated with a system configuration. So, for example, fuels are often thought to 'contain' energy (e.g. Brook, 1985).

The shift required here (moving 'spin' from the *contingent* to the *inherent* branch of the figure) does not seem very drastic when represented in simple diagrams, but, if these different types of property are ontologically very different, conceptual change may be very difficult. In terms of Chi's work, an intrinsic property of the electron would seem to be part of the 'matter' tree, where a contingent property would seem to be tied to a 'process'. Chi's (and Thagard's) research would suggest that the teacher's response to this learning difficulty would need to involve building up a new concept (of quantum-mechanical spin), rather than attempting to *shift* the learner's existing meaning for electron spin. More classroom-based research is needed to explore the importance of such 'mis-classifications', and the efficacy of strategies informed by the student ontology perspective.

Converging lenses: complementary perspectives

The three perspectives discussed above provide insights into the learning difficulties faced by students when meeting the orbital model of atomic and molecular structure. Such 'analytical pluralism' is considered appropriate where the analytical lenses applied derive from consistent theoretical perspectives. Given this, the different perspectives can offer *complementary* ways of understanding research data. For example, the three analytical lenses applied here would all suggest reasons why students might have difficulty developing an appropriate understanding of polar bonding (an example from previous research discussed above).

To appreciate polar bonding as an intermediate form of bonding between pure covalent and pure ionic bonding the student has to understand the covalent—ionic distinction as a different sort of classifying entity: a continuum rather than a dichotomy. This is difficult where the student has established prior learning that acts as a learning impediment. Had the existing concepts of covalent and ionic boning been understood as models – partial, simplified, of limited range of application, etc. – this transition might not be too challenging. However, the research shows that students often begin college (senior high) level studying with strong commitments to 'knowledge' that *bonding is covalent or ionic*, and that covalent bonding *is* electron sharing and ionic bonding *is* electron transfer. This is reflected in the way learners often attempt to make sense of metallic bonding in terms of covalent and ionic prototypes (Taber, 2003c).

Converging lenses on the orbital model

The analytical lenses discussed can offer complementary insights in the present study. The analytical lens of student ontologies suggests that quantum-mechanical spin is something *fundamentally* different to 'life-world' spin, suggesting a possible explanation for the finding that students did indeed struggle to acquire the scientific concept, and so suggests a specific focus for future research into improving teaching practise.

This is not the only area where the notion of student ontologies might illuminate learning difficulties in this topic. Just as the shift in the atom concept (from an immutable, fundamental and indivisible particle of matter, to a system of particles that can be changed in interactions with other particles) is potentially problematic (Taber, 2003b), so is the transition from electron orbits, to orbitals.

In the model learnt in school a discrete particle moves around the nucleus along a particular trajectory. With the introduction of the quantum model of the atom, the electrons cease to be particles in the familiar sense, and can no longer even be considered to have a definite position at any moment in time. The quantum model of the electron in an atom describes a very *different sort of entity* to the notion of an electron that is familiar to students from their secondary education.

In the source study being considered here it was found that some of the students readily adopted the term 'orbital', but initially applied this to their existing notion of electrons in shells around the atomic nucleus (Taber, 2002a). Electrons were said to "go round, like in orbitals, or in spherical things" and an orbital was described as "the *path* the electron takes around the nucleus" as it "*circles* the nucleus in a sphere". Acquiring the new vocabulary did not necessarily imply acquiring the intended new meaning. That the term *orbital* is so similar to *orbit* could well be significant for the meaning learners adopt (Schmidt, 1991) – i.e. a type of substantive learning impediment grounded in a linguistic cue (see http://people.pwf.cam.ac.uk/kst24/ScienceLearningDoctors.html).

The tendency for students to continue to think about atoms in terms of a 'planetary-type' orbit model has also been found in other studies (e.g. Cros et al. 1986, 1988; Mashhadi, 1994; Petri & Niedderer, 1998). That this is a common difficulty is not surprising in view of the analytical perspectives considered in this chapter. All three of the analytical lenses discussed would suggest reasons for this phenomenon.

Prior learning ('e.g. electron orbits') can act as an impediment to new learning (cf. Tsaparlis 1997). Students are asked to adopt a new model of the atom, which in many ways is inconsistent with the model they have already learnt, and which includes features that are ontologically very different from the familiar model. If the orbital concept is acquired as a subdivision of an existing simplistic notion of the electron shell then the acquired concept will be ontologically unlike the intended target concept (i.e. electrons should no longer to be seen as particles in orbit, but should be seen as having wave characteristics, and being considered either in terms of probability, or modelled as smeared-out into clouds of charge density).

Not only this, but this new very different model is used to complement the existing one: i.e. even after they have been taught about the quantum model of the atom there will be many contexts when electrons will continue to be discussed as if classical particles (e.g. where electron movement is represented with curly arrows in reaction mechanisms). Clearly, this is an area where a sophisticated appreciation of the nature of models in science would be helpful (cf. Jones, 1991).

Discussion - analytical plurality versus methodological purity

At the outset of this chapter it was suggested that the analysis of data relating to complex phenomena, such as learning in science, might benefit from the apparently eclectic approach of applying a range of analytical lenses as perspectives to interrogate the data. The science education research literature offers a range of potential insightful perspectives, and appropriate analytical frameworks may even be selected *in the light of* the research data, as long as the approaches used are congruous with the philosophical assumptions underlying the research, and with each other.

'Qualitative research', that is, interpretive research based upon the collection and analysis of primarily qualitative forms of data (Taber, 2007), is judged upon different criteria to 'quantitative research' (Eybe & Schmidt, 2001). In quantitative research it is normally considered good practice to design a research study so that features of data collection (sampling procedure, sample size) are chosen on the basis of the particular statistical tests to be applied: and specific hypotheses, and confidence levels (e.g. $p \leq 0.05$ for statistical significance) are part of the research design. Qualitative research often follows a more iterative procedure, where some methodological decisions may justifiably be made as the research progresses (e.g. Taber, 2000b).

As a narrative and rhetorical device, the term 'battery of tests' was introduced - a notion that was familiar from science, medicine and psychology, and might be considered by readers to signify an approach that is methodologically sound. However, this begs the question of whether the different tests said to work together in a battery *can* be considered to be part of a consistent approach in this sense. Within analytical chemistry, for example, it is clear that the techniques commonly used *are* congruous, as they are all underpinned by a coherent and consistent framework of theory. So, for example, there is no inconsistency between the theory that links aspects of chemical structure to (a) chromatographic properties and (b) spectroscopic properties.

If the approach discussed in the present chapter is to be seen as justified in the same way, then it is necessary for it to meet the same type of criteria. In others words it is important that any analytical tools applied to data are seen to be consistent with the methodological assumptions guiding the study.

In this chapter three different tools have been selected from the expanding repertoire of analytical frameworks that have been adopted or developed for use within science education research. Data from a published research study (Taber 2002a, b) were subjected to inspection from each of these perspectives, and the present chapter presents examples of how these different approaches can illuminate the nature and origins of some of the students' learning difficulties reported in the source research.

It is argued that these three approaches are consistent, both among themselves and also with the conceptual framework unpinning the study. The research was undertaken within the 'constructivist' tradition (Taber, 2006a), informed by notions such as the importance to learning of existing cognitive structure; the unique and personal nature of each individual's conceptual frameworks; and the potential significance of learners' alternative conceptions.

Although an information-processing perspective, drawing upon research from cognitive science, would normally be seen as a separate tradition, there is a clear link between notions of working memory capacity, and of consolidation of learning allowing chunking, with Ausubel's theory of meaningful learning (e.g. Ausubel, 2000), and this has informed the typology of learning impediments (Taber, 2001b, 2005). The link between these ideas and Piagetian notions of accommodation and equilibration was also noted above.

Part of the research into learners' ideas deriving from the constructivist tradition has led to studies into conceptual change and the status of learners' ideas (e.g. Hewson & Hennessey, 1992; Strike & Posner, 1992; Taber, 2001d), and that may be seen as one source of the current interest in students' understanding of models. In science we are looking for intelligible and feasible ideas - rather than articles of faith. Yet learners often take teaching models as facts. There is a connection here with neoPiagetian ideas about post-formal thinking which enables people to accept views of the world as incomplete - as partial models that can be complemented by alternative perspectives

(Arlin, 1975; Castro & Fernández, 1987), and in particular Perry's (1970) scheme of intellectual development among college students.

The work on students' understanding of models also links with Chi's ideas about ontological category errors. Just as students may mis-classify processes (e.g. heating) as objects, or intrinsic properties as contingent properties - as in the example of electron spin discussed here - they may also mis-classify scientific models as realistic representations.

Of course the types of representation of cognitive structure, as a hierarchical system, used by some workers, such as Chi and Thagard, may not be an ideal model (cf. Taber, in preparation). Ogborn's approach also offers useful insights, as does Kelly's (1963) personal construct system. Seeing cognitive structure as a kind of semantic network (diSessa & Sherin, 1998) also has advantages. Each of these ways of conceptualising aspects of learners' ideas may present difficulties when we wish to accommodate certain reported phenomena that we might consider of significance: phenomena such as alternative frameworks; Vygotsky's (1986/1934) notion of the interaction of spontaneous and scientific concepts; gestalts (Andersson, 1986); phenomenological primitives (Hammer, 1996), etc.

This brings the argument full circle. Phenomena such as cognitive structure and student learning are obviously much too complex, too multifaceted, to be comprehensively described by simple models. Research into *students'* understanding of scientific models provides a limited perspective on student difficulties in learning. A typology of learning impediments will include gross simplifications and may force complex learning difficulties into a straightjacket of a limited system of categories. Hierarchical branching trees cannot surely *fully reflec*t the way concepts are represented in our minds.

Yet this is not a reason to dismiss these perspectives. When faced with complex phenomena we turn to complementary partial models that can illuminate aspects of the phenomena being studied. The key question is not whether these particular tools provide a *complete explanation* - for example of student difficulties in learning about quantum models of matter - they clearly do not. The important questions are (a) whether these perspectives are congruous in the sense of being consistent with the theoretical position underlying the research, and (b) whether they have useful heuristic value.

The curriculum focus discussed - quantum models of atoms and molecules - is known to be a problematic one that would benefit from a better informed pedagogy. It is recognised that this topic is highly abstract, divorced from life-world experience (Knight, 2002), and this clearly makes it difficult for many students. Such an observation is, however, just a starting point for informing specific teaching approaches designed for helping students understand the topic. A more detailed investigation of exactly where and why student learning 'breaks-down', or 'goes astray', is needed to advise teachers how to respond to the inherent difficulty of the topic.

The present chapter provides interpretations that can contribute to such a programme:

- *A better understanding of the nature and role of models in science* might help students develop more flexible conceptualisations that are more readily modified or augmented. In particular, teachers could put more emphasis on the partial and provisional nature of the models and representations used (Taber, 2006c).
- *The typology of learning impediments* has been used to identify some specific aspects of the topic where learners interpret teaching through alternative conceptual frameworks; and where the students do not have, or do not recognise the relevance of, prerequisite knowledge (or where prior learning is not sufficiently well consolidated to be applied in new contexts without overloading working memory). One possible response is to reorganise teaching schemes to provide students with the time needed to reinforce and consolidate each new concept before it is to act as the basis of further learning.
- *The 'ontological discontinuities' that can restrict progression in developing understanding* - i.e. the way that concepts such as electronic orbital and electron

spin are different kinds of entities to those already represented in the learner's cognitive structure that are most likely to be used as the anchoring prior knowledge (e.g. electron 'orbits', life-world spin that *entails* movement). The work of Chi (1992) and Thagard (1992) would suggest that here teachers may sometimes need to build-up new understandings rather than allow students to develop their existing ideas.

Conclusion

This chapter does not claim to present a comprehensive account of learning difficulties in this topic. I have drawn upon a single source study that provided suitable data to demonstrate how analytical pluralism might be applied in science education. The source study provided the in-depth data needed for this type of analysis, but only reported findings from a specific group of students in a particular educational context. Any attempt to provide a more definitive analysis of students' difficulties in the topic would certainly need to draw upon a larger and more representative sample, and could surely benefit from the application of a broader battery of analytical lenses. Nevertheless, the present chapter demonstrates how a range of complementary analytical lenses that draw upon congruous theoretical perspectives can be applied to interrogate a data set, leading to recommendations for developing pedagogy at the level of a science topic.

These recommendations are specific enough to inform teaching. They should, of course, be seen as hypotheses to be tested in practice – as the source of research questions for a further cycle of research. The ability to draw such conclusions demonstrates the heuristic value of the analytical tools used in this study. Just as Bohr's mermaid, his model of the atom, was open to criticism and refinement, the qualitative analytical tools currently available to science education researchers (such as the examples selected for this study) are not able to provide a complete and incontrovertible analysis of students' learning difficulties. They provide limited and provisional perspectives, but - like Bohr's mermaid - they provide avenues that can be tested and explored in further research.

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