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Learning quanta: barriers to stimulating transitions in student understanding of orbital ideas

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Abstract:

This paper reports the results of applying a particular analytical perspective to data from an interview study: a typology of learning impediments informed by research into learning and students' ideas in science. This typology is a heuristic tool that may help diagnose the origins of students' learning difficulties. Here it is applied to data from students interviewed about a problematic curriculum topic – the 'orbital' model of atomic and molecular structure. Several specific features of learners' developing ideas about atomic and molecular structure were identified in published reports of the study. In this paper, interview data is examined 'through' the analytical lens of the typology to explore possible explanations for students' learning difficulties in the topic. It is suggested that the typology provides a useful perspective for exploring some aspects of students' learning difficulties, but that the previously published form of the typology could be modified to include important additional types of learning impediments. The heuristic value of the typology is demonstrated in terms of the way that the analysis can both inform teaching, and suggest a focus for further research.

Introduction: a problematic concept area

According to science, we live in a world that is quantised. Matter, although apparently continuous, is believed to be made-up of myriad tiny particles (be that molecules, atoms, protons, quarks, etc. - perhaps collectively 'quanticles') that behave differently to the particles of everyday experience. Understanding the particle model of matter is a key feature of school science, and one known to be problematic (*e.g.*, Johnson, 1998; Johnston & Driver, 1991; Lijnse *et al.*, 1990; Taber, 2002a). When the structure of matter is considered at the sub-atomic level students are introduced (albeit perhaps often implicitly) to the idea that electrical charge is also quantised. However, it is only when the structure of molecules *etc.* is considered in detail, at college (*i.e.*, 'sixth form' or 'senior high school') level, that some of most difficult aspects of the 'quantum universe' (Hey & Walters, 1987) are considered. The quantisation of angular momentum becomes important (in terms of the quantum-mechanical spin of electrons *etc.*), and the presence of discrete energy levels (and associated transitions) is an important feature of molecular level structure in college level courses.

Although some features of this topic area - the uncertainty principle and wave-particle duality - are staples of popular science, this does not seem to give them enough 'common currency' to support formal learning about quantum phenomena (Olsen, 2002). In particular, research suggests that students are quite resistant to learning about quantum-mechanical models of the atom, with electrons 'located' in orbitals defined in terms of probability and not being subject to well-defined boundaries. Similar findings have been reported at college level (Cros *et al.*, 1986; Fischler & Lichtfeldt, 1992; Ireson, 2000; Mashhadi, 1994; Olsen, 2002; Petri & Niedderer, 1998; Taber, 2002b, c; Tsaparlis and Papaphotis, 2002) and in university courses (Cervellati and Perugini, 1981; Cros *et al.*, 1988).

There have been a number of attempts to explain the nature of the difficulties student face when learning about quantum ideas (Buddle *et al.*, 2002a; Jones, 1991; Justi & Gilbert, 2000; Niaz, 1998; Shiland, 1997; Tsaparlis, 1997), and various suggestions for improving teaching, although these seem to have had limited success (Buddle *et al.*, 2002b; Fischler & Lichtfeldt, 1992).

Two additional complications of discussing this topic are worthy of note. Firstly, the subject matter is 'claimed' by both chemistry and physics, so - perhaps inevitably - the topic may be seen from rather different perspectives from within these two disciplines. (The empirical data discussed in this paper derives from a study of learning in chemistry.)

Secondly, the level of presentation usually given at college level has been the subject of some criticism. So, for example, the model of discrete 'hydrogenic' atomic orbitals used to describe electronic configuration at this level (and sometimes beyond) is, strictly, invalid (Tsaparlis & Papaphotis, 2002). The 'orbital approximation' assumes that the types of orbitals derived from an analysis of one-electron systems can be used to describe more complex atoms. Although the model deriving from the assumption often seems 'to work' (*cf.* Sánchez Gómez & Martín, 2003), it cannot be justified theoretically (Scerri, 1991).

In view of the modest gains made in making recommendations for teaching students about "the 'minefield' of quantum phenomena" (Ireson, 2000, p.20), there is considerable scope for further research into learners' developing understanding of this topic area to inform practice. Research undertaken from a range of perspectives can usefully inform pedagogy in this problematic curriculum area. For example, studies of the (ahistorical) presentation of atomic models in textbooks may help explain why students fail to grasp key aspects of the quantum-mechanical model of the atom (Justi & Gilbert, 2000; Niaz, 1998).

In-depth studies of learners' ideas is another approach able to offer useful insights, and there are now a range of theoretical ideas in the science education literature which can be applied to analysing the data obtained from such research. This present paper explores data from one such study, where data is analysed in terms of a particular analytical tool - a typology of learning impediments.

Learning impediments: a perspective from learning theory

This typology of 'learning impediments' derives from well-accepted ideas from the literature exploring how learning (in science and more widely) takes place, and suggesting why the learning intended to result from teaching often does not occur. For example, Leach and Scott (1995) have used the term 'learning demand' to highlight the importance of the differences between the target science in the curriculum and the present state of the learners' knowledge and understanding of a concept area.

Key assumptions that underpin the typology of learning impediments are the Ausubelian ideas that meaningful learning can only take place when a learner can relate new material to existing knowledge (Ausubel, 2000), and the corollary that a learner's existing 'cognitive structure' (Ausubel & Robinson 1971; White, 1985) is a key determinant of what will be learnt.

From a 'constructivist' perspective (Mintzes, Wanderseee & Novak, 1988; Fensham, Gunstone & White, 1994) the learner builds up their knowledge piecemeal, interpreting what they see and hear through existing frameworks of understanding.

The human cognitive apparatus places significant restraints on learning (Miller, 1968), which restricts the 'complexity' of the new material that can be considered at any moment in time. However, this complexity cannot be measured in absolute terms, as it must be judged in terms of the perception of the particular learner, or 'at the learner's resolution'. This is because related ideas already held in cognitive structure can potentially allow the new materials to be organised and 'chunked' more effectively (Kellog, 1995; Parkin, 1987; Sousa, 2001; Taber, 2002a). This 'chunking' process often takes place at a subconscious level, before the learner is aware of processing any information explaining why it can be so difficult to move beyond well-established ways of thinking (*e.g.*, Kelly, 1963). In the discussion that follows, references to learners recognising existing knowledge as being relevant to new teaching do not necessarily imply that the learner is *always aware* of this process.

Ausubel considered prior knowledge to be the most significant factor in planning teaching, and the constructivist perspective acknowledges how the learners' existing conceptual frameworks are the resources for 'making sense' of new information (*e.g.*, Driver, 1989; Fensham *et al.*, 1994), such that *prior* learning can 'take *priority*' over the teacher's message (Taber, 2003). Teachers are advised that teaching should therefore be planned in the light of a conceptual analysis of the topic to be taught, to determine the necessary pre-requisite knowledge, as well the optimum order of presentation of material, etc. An accurate estimation of the actual 'prior learning' that a learner will bring to bear on new material presented is therefore essential for effective teaching.

The typology of learning impediments (Taber, 2001a), as shown in figure 1, was derived from a consideration of what can go wrong when the prior knowledge 'brought to mind' by a learner does not match the prerequisite learning required to make the intended sense of teaching.

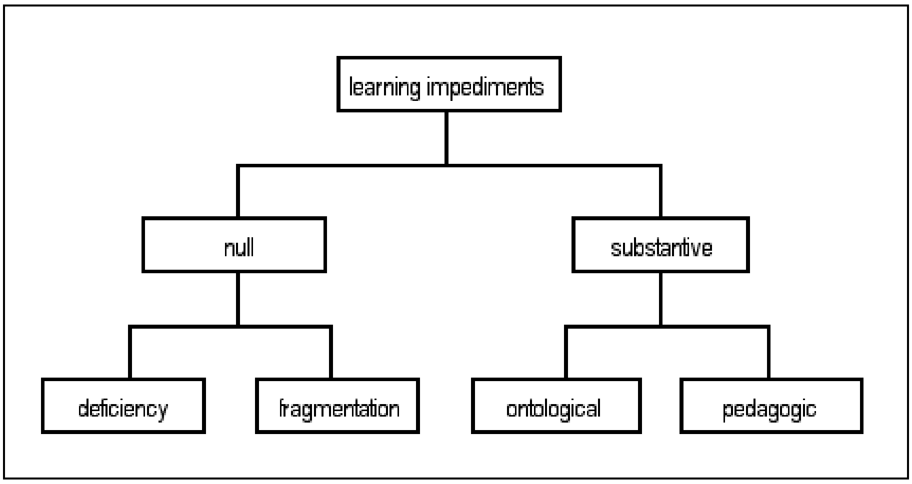

Figure 1: a typology of learning impediments (Taber, 2001a)

The typology is explained in table 1. The major distinction is between 'null learning impediments' (where the learner does not recognise any relevance of new material to existing knowledge) and 'substantive learning impediments' (where the new information becomes distorted in the process of being interpreted through the learners' existing conceptual frameworks).

Null learning impediments are divided into 'deficiency learning impediments' (where the assumed pre-requisite knowledge is absent) and 'fragmentation learning impediments' (where the learner does not recognise how the new material relates to prior learning). The substantive learning impediments are due to existing conceptions that the learner holds. As a matter of practical importance a distinction is made between those alternative conceptions that derive from 'intuitive' or spontaneous interpretations of experience (or from ideas deriving from 'folk science' etc.), and those that derive from teaching.

This division (into 'ontological' and 'pedagogical' learning impediments) is not considered to be absolute, as many alternative conceptions derive form *the interaction* of teaching with knowledge acquired outside the classroom, and the role of language as the medium for learning often bridges the two categories (Lemke, 1982). However, the inclusion of a separate category of 'pedagogic learning impediment' was considered to fulfil a useful *heuristic* role as it does highlight the problem of teaching models which, once learnt, actual impede the learner making further progress.

type of learning impediment	nature of impediment	action required of teacher	example of resulting student conception
deficiency impediment	no relevant material held in existing cognitive structure	remedial teaching of prerequisite learning (if available), or restructuring of material with bridging analogies *etc.*	there is (more of the same, or a different) substance between the molecules of a substance
fragmentation impediment	learner does not see relevance of material held in cognitive structure to presented material	teacher should make connections between existing knowledge and new material explicit	in physics the force *between* two charges depends upon their magnitude and separation; in chemistry the force 'of' a nucleus depends only upon its charge, and is shared between the electrons around it
ontological impediment	presented material inconsistent with intuitive ideas about the world held in cognitive structure	make learner's ideas explicit, and challenge them where appropriate	a force is required to maintain constant velocity - in the absence of a force a moving body will come to rest
pedagogic impediment	presented material inconsistent with ideas in cognitive structure deriving from prior teaching	for individual learner: treat as ontological impediment; for future: re-think teaching of topic - order of presentation of ideas, manner of presentation, *etc.*	reactions occur so that atoms can obtain full shells of electrons

Table 1: A typology of learning impediments (Taber, 2001a).

One of the professional skills of the teacher is in finding ways to make complex ideas seem accessible, but this must be balanced by a need to present material in a way that is scientifically valid, and provides a suitable platform for further learning. In other words, the teacher needs to find the 'optimal level of simplification': *simplifying sufficiently* for the learner's present purposes, but *not over-simplifying* to undermine her future needs. Oversimplifications have the potential to act as significant impediments to further learning.

The application of the typology is illustrated in terms of some examples from the science education literature. Table 1 includes an example of each of the four types of learning impediment.

One of the difficulties with learning about the particle model of matter is the way the molecular level world is so different from the more familiar world that students already know about. So it has been reported that even when students accept that 'everything is made of particles', they often assume that there must be something between the particles - such as the actual substance

(Griffiths & Preston, 1992; Nussbaum & Novick, 1982; Renström *et al.*, 1990). Students have no prior experience that they can use to make the intended sense of the particle model (a deficiency learning impediment).

However, even when students hold relevant prior knowledge in cognitive structure they do not necessarily 'bring it to mind' when new material is met. The ease with which information comes to mind is highly context-dependent (Anderson, 1995; Baddeley, 1990). The degree to which material presented may act as a cue and activate related stored information is an important factor in building up students' knowledge of topics. In formal learning situations learners may compartmentalise material from different subjects, teachers, or topics. The example in table I refers to students who, in chemistry, believed that the charge on a nucleus determined the total amount of force it was able to exert, and that this amount of force would be shared equally between the electrons in the atom or ion. This 'conservation of force' conception was inconsistent with the Coulombic electrostatic principles they had learnt in a different context - *i.e.*, their physics classes (Taber, 1998b).

The compartmentalisation of knowledge acted as a fragmentation learning impediment. Although the relevant conceptual framework was available, it was *not accessed* and so was not used to interpret the chemical context: another null learning impediment as the prior learning which might have been expected to act as the basis for new learning was not 'brought to mind'. Quite the opposite is true in the case of substantive learning impediments, where it is the *presence* of knowledge that *is* perceived (by the learner) to be relevant which distorts learning away from the target knowledge.

Perhaps the best-known example would be learning about force and motion in physics. Students commonly demonstrate a belief that a body's velocity depends upon the force acting on it, even after being taught that it is *acceleration* that is proportional to the net applied force (*e.g.,* Gilbert & Zylbersztajn, 1985; Watts & Zylbersztajn, 1981). This alternative conceptual framework seems to derive from the students' prior knowledge of the behaviour of bodies in the everyday world where objects soon stop moving once we stop pushing them! The student's alternative conceptual framework (sometimes known as the 'impetus' framework) is an example of a substantive learning impediment deriving from 'intuitive', or spontaneously obtained, knowledge of the world.

The final example in table I concerns another common alternative conceptual framework, this time in chemistry - the octet framework (Taber, 1998a). A key feature of this framework is the belief that atoms actively seek to 'fill their shells', and that this is the cause of chemical bonding and chemical reactions. Although it seems unlikely that many teachers explicitly teach such ideas, it has been suggested that the way the topic of bonding is often presented in secondary school provides a basis for such views developing. For example, many books define the ionic bond in terms of electron transfer to form full shells, and illustrate bonding with diagrams (that pupils are often expected to reproduce) of very unlikely 'reactions' between isolated atoms. The octet framework is classed as a pedagogic learning impediment because - to a significant extent - it *derives from* teaching.

Analysis of evidence from an interview study

The typology of learning impediments is an analytical tool which can be used to generate explanations for some of the difficulties learners experience when trying to make sense of, and learn about, curriculum science. In the present paper, this tool will be used to illuminate data from an interview-based study.

The data derive from in-depth study of the developing understanding of chemical bonding of a small group of learners, students c. 16-18 years of age, in one UK college. These students were enrolled on two-year 'A level' courses (*i.e.*, the General Certificate of Education Advanced Level), including the study of chemistry as one of their chosen subjects. Typically, students taking this course were intending to proceed to university, and the A-level course was the standard means of bridging between school and university level study. Fifteen students were interviewed for the study. The interviews were carried out during 1992-4 at various points during the students' studies. The interviews were semi-structured, and were mainly based around a set of line diagrams of chemical species (some of which are reproduced in this paper). The starting points for discussion were asking the students (a) whether they could identify the species represented; (b) whether there was any bonding represented/present in the species represented; and, if so, (c) what type of bonding. Student responses were followed up to explore aspects of their ideas about atomic and molecular structure and related topics.

The 'target' knowledge that students were taught during their college course was a view of bonding based on electrical principles and orbital ideas at a level of treatment appropriate to the 'Advanced level' course (*e.g.*, Hill & Holman, 1995; Clugston & Flemming, 2000). The importance of electrical attractions and repulsions in chemical structures and processes was emphasised.

Students were also taught about (hydrogenic) atomic orbitals; quantum numbers and associated 'rules' (aufbau, Hund's rules); molecular orbitals; and the notions of atomic orbital hybridisation, molecular orbitals being formed by overlap of atomic orbitals, and delocalisation in systems such as the benzene molecule. However, it was found that students commonly already held the alternative conceptual framework for explaining bonding discussed above, i.e. that atoms formed bonds to obtain full electron shells (Taber, 1998a) rather than as the outcome of physical forces. This 'octet' framework was tenacious, and continued to be used even when the more advanced models of college chemistry had been learnt, so that the transition from *tending to* apply the alternative framework to *tending to* apply the new learning was slow (Taber, 2001b). It took time for students to start seeing chemical processes as due to forces acting between charges, instead of being driven by the 'needs' of atoms, and the students did not readily synthesise quantum ideas (*e.g.*, orbitals, electron spin) and Coulombic principles to adopt a model of bonding that closely matched the target knowledge.

This paper considers the published findings from the study regarding the particular difficulties the interviewed students had making sense of aspects of the orbital concept and related ideas. These findings were that students (1) did not appreciate why quantisation 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, 2002b); (6) did not clearly distinguish molecular orbitals from atomic orbitals; and (7) held alternative notions of what resonance structures were meant to represent (Taber, 2002c).

The published accounts use verbatim, and sometimes extended, quotations from a dozen of the students to illustrate the seven reported categories of learning difficulty. The sample is small, and is a 'convenience' sample from one institution The analysis presented in this paper is therefore based upon a qualitative study, lacking any statistical generalisability but offering the authenticity of reports which give prominence to the students' 'voices' (*cf.* Kvale, 1996). Although such research says little about *how common* particular features of student learning may be, it does provide the level of detail needed to explore questions of *how and why* learners' ideas develop (which is the concern of the present paper).

Whereas the previously published studies describe *the range* of ideas elicited from this group of students, the present study draws on this material selectively to explore the extent to which the typology of learning impediments may offer useful interpretations of the data. This paper, then, applies a particular analytical lens - the typology of learning impediments - to the data, and reports how this analysis may (a) help explain learners' difficulties in this problematic curriculum topic, and so (b) inform curriculum planning and teaching. Readers interested in more detail of the original study are referred to the published reports (Taber, 2002b, c).

Results: barriers to learning about the quantum world

Deficit learning impediments

The quantum hypothesis was introduced to 'save the phenomenon' because empirical data did not match theoretical considerations (Petruccioli, 1993). Some of students interviewed in the analysed study could discuss *aspects* of quantisation, but did not relate this to atomic stability.

So one student, referred to as Edward, who described how a photon with energy of "the correct frequency" would allow an electron to "be promoted to another vacant *orbital*", nevertheless explained the continued motion of atomic electrons as being "like the planetary motion", that is that "in creation they were given some initial kinetic energy, and some rotational energy". This student was not aware of the classical analysis that electrons in atoms should act as electrical oscillators, and emit energy, and consequently he did not see the notions of quantisation and of energy levels as a solution to this difficulty. This can be considered as a deficiency learning impediment: the prerequisite knowledge is not present.

Another of the students, Jagdish, explained that the electrons would not fall into the nucleus even though there were "attractions from the nucleus, pulling in the electrons" as "the attraction isn't that strong", whereas "if you could actually physically make those electrons get closer to the nucleus then they would fall in because the attraction would be so strong".

Although, like Edward, she is not aware of the problem that led to the quantum hypothesis, she identifies the "attractions from the nucleus" as a potential cause of an electron falling into the nucleus. She does not recognise that, in a planetary model, the attraction could give rise to *centripetal* acceleration that could maintain the circular motion without orbital decay. So Jagdish does not recognise the classical problem of the stability of the atom (a deficiency learning impediment), but *nor* does she realise that circular motion is *accelerated* motion requiring centripetal force (another deficit learning impediment). For Jagdish the stability of the (planetary) atom *does* need to be explained, but the nature of *her* stability problem is different from that which historically led to the proposal of the quantum hypothesis.

Fragmentation learning impediments

One of the key features of the quantum model of the atom is the possibility of transitions between discrete energy levels: i.e. that electrons can be promoted to give an excited state *if* the correct quantum of energy is available. When Debra was asked about this in an interview she initially seemed unable to recall any relevant knowledge. However, the interviewer was aware that Debra had actually undertaken an experiment to find the wavelengths of spectral lines in her physics classes, as illustrated in the following extract from an interview undertaken for the original study,

> I: Would it be possible to have an excited hydrogen atom? In electrical terms, can you excite a hydrogen atom?
>
> D: No.
>
> I: Can you excite a sodium atom?
>
> D: Don't know.
>
> I: Let me ask you a different question. Have you done an experiment, in physics, not in chemistry, but in physics, where you have to work out spectral wavelengths?
>
> D: Yes.
>
> I: With a spectrometer, and you...measure angles, and work out the wavelengths of colours of light?
>
> D: Yes.
>
> ...
>
> I: Do you think it's possible to excite an atom of sodium? Electrically?
>
> D: Yes.
>
> I: So what does that mean, exciting it electrically, what actually happens to the atom?
>
> D: Well you promote an electron to a higher energy level. And then it falls back and gives out the energy.

I: Interviewer [KST]
D: Student, Debra

Clearly Debra *did* have knowledge of how atoms could be excited represented in her cognitive structure, but this was not activated by the original question, perhaps because she perceived the interview context as 'chemistry'. When specific probing indicated that knowledge Debra considered 'physics' was being sought, *then* her representation of this knowledge was activated. The everyday expression would be that the target knowledge was not initially 'brought to mind': a phrase that emphasises how having a memory stored in the brain is not sufficient for recall, as the mechanism for accessing that memory must be triggered before the memory becomes available for conscious manipulation.

This is an example of a fragmentation learning impediment, as the relevance of prior learning, something assumed by the teacher, is not recognised by the learner. Another example of a fragmentation learning impediment was identified when Carol described how, in the structure of the benzene molecule, there was,

> kind of like a ring [with] like electron thing underneath it, and electron thing on the top…the electron density below and above it…because they're - bonds…*and* then you've got delocalised electrons in the middle, but I don't know what they look like.

At this point in her studies Carol had learnt about the pi-bonding in benzene as two areas of electron density forming rings above and below the framework of carbon-carbon sigma bonds: however, she has not reconciled this with the circle sometimes used to represent the electrons that are not involved in the sigma bond framework. In terms of the typology of learning impediments Carol exhibits a fragmentation learning impediment, having failed to integrate the different modes of representing the pi-bonding in benzene.

Another similar example of students 'failing to connect' ideas being discussed with existing prior learning was that when students discussed electrons in molecules they commonly referred to the bonding electrons being in *atomic* orbitals rather than *molecular* orbitals . Even when there was clear evidence that students appreciated the scheme for forming molecular orbitals used in teaching (as represented in figure 2), they still made this 'error'.

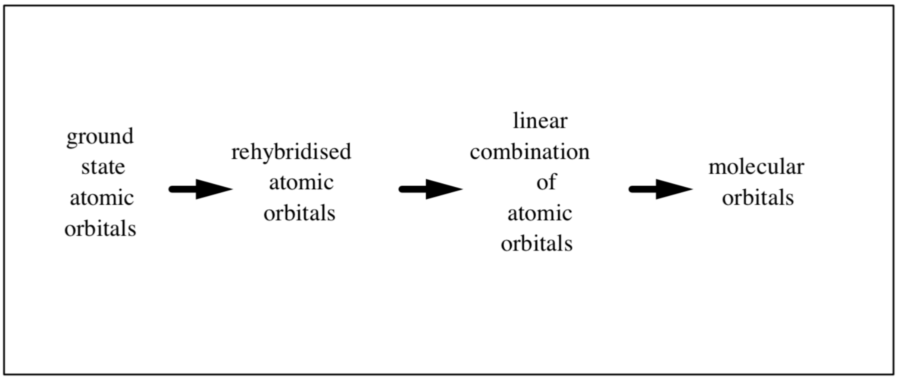

Figure 2: a scheme for forming molecular orbitals

So, Edward was able to explain the rationale for hybridisation in terms of the overall change in stability of the final product, *and* discuss the relative energies of sp^3 hybrid atomic orbitals compared with the ground state orbitals. Yet he explained the bonding in tetrachloromethane in terms of the electrons from chlorine having "left their orbitals, to obtain a more stable structure" and entered the carbon sp^3 "hybridised orbitals".

Another student, Kabul, discussed how the ground state carbon atom would only be able to form two bonds, but hybridisation allowed it to form four, and referred to how hybridisation would occur "in order to get good overlap". He described the energy level of the hybrid orbitals in relation to the ground state orbitals, and considered the possibility of 'low lying d-orbitals' being available for hybridisation in some cases, but not others. Despite this evidence of having appropriate and quite detailed knowledge represented in cognitive structure, it was not 'brought to mind' in an interview where Kabul was asked about the orbitals present in *molecular* systems.

This example provides a clear case of the distinction between knowing something, and 'bringing it to mind' - having knowledge stored in cognitive structure, and actually accessing and retrieving it in response to a particular question - and is worth considering in some detail.

When Kabul was asked about the orbitals present in the hydrogen molecule he did not suggest molecular orbitals, but rather "s orbitals, 1s orbitals...just 1s orbitals". Similarly, when asked about the methane molecule, he initially suggested there would be "1s and p orbitals … like 2p on carbon, and 1s on hydrogen" as well as other orbitals on carbon that "don't take part in bonding". At this point Kabul was thinking in terms of the ground state orbitals on the atoms, and had actually suggested that *four* carbon 2p orbitals were used to form four bonds.

When Kabul was asked to confirm that he thought that the bonding in the methane molecule involves a 1s orbital on hydrogen and four 2p orbitals on the carbon, he initially agreed, but then recognised this could not be correct, and introduced the concept of hybridisation. He made the point that the ground state orbitals "won't have good overlap", and so was clearly aware that the atomic orbitals overlap to "form bonds", yet he then described the orbitals present in a methane *molecule* as "sp^3" hybrid "orbitals from carbon and … s orbitals from hydrogen".

When Kabul was then asked about diamond structure he suggested that the orbitals present in carbon in diamond were "1s, 2s and 2p". Kabul initially suggested there was no hybridisation in carbon atoms in diamond itself, although,

> *when* they are to form bonds, *then* they undergo hybridisation, to get good overlap with one another, and they form bonds

In other words, Kabul was initially conceptualising diamond as comprising of discrete atoms. It has been reported that students commonly think of elements in this way, making an 'assumption of initial atomicity', even when they are asked about diamond with its very high melting temperature (Taber, 2002a).

Then, on direct questioning, Kabul said that there *were* bonds in diamond so it *would* have "hybridised orbitals" and "you can call it sp^3", where, "they've undergone sp^3 hybridisation, because one of [sic] the 2s orbitals and three p orbitals they all … combine together to form orbitals which are the same energy level, so you call them ... sp^3 hybridised orbitals".

So at this point Kabul had talked about their being bonds in the structures discussed, and about hybridisation and overlap of orbitals to form bonds. Yet he was describing hydrogen, methane and diamond as having the electrons in *atomic* orbitals.

Kabul was then challenged, being presented with a hypothetical commentator who might suggest that there were no 1s orbitals in hydrogen, and no sp^3 hybrids in diamond or methane. An extract of interview transcript recording the dialogue is presented in appendix 1. The abstract has been broken up into 8 sections for ease of reference. The dialogue in these sections may be summarised:

1. Kabul initially *disagrees* with the proposition that there are no 1s orbitals in a hydrogen molecule;
2. Kabul *disagrees* with the proposition that there are no sp^3 hybrid orbitals in the methane molecule;

3. Kabul *agrees* that there is a molecular orbital in the hydrogen molecule;
4. Kabul explains that, when two atomic orbitals form a bond, they combine together to form a molecular orbital;
5. Kabul agrees that once the molecular orbital is formed the atomic orbitals are no longer present;
6. *However*, Kabul still argues that sp^3 hybrid orbitals are present in the methane molecule...
7. ...before realising that they've been used to form molecular orbitals;
8. Kabul recognises that diamond would have molecular orbitals rather than sp^3 hybridised atomic orbitals.

So Kabul initially suggests the molecular structures will contain atomic orbitals, but *not* because he does not understand the principle of forming molecular orbitals from atomic orbitals. When he is specifically asked about this point Kabul gives a good answer (at section 4), although he had not spontaneously 'brought this to mind'. Significantly, despite accepting the principle in the hydrogen example, Kabul initially defends his previous response in the case of methane (at section 6). Finally, Kabul then accepts the case in the third example (of diamond) without further argument.

So it seems Kabul 'knew' that atomic orbitals overlapped to give molecular orbitals, and that hybridisation sometimes occurred to give better overlap between atomic orbitals: yet when he was asked about the orbitals present in a molecule he responded in terms of atomic orbitals and *did not bring to mind* the molecular orbitals. It is suggested that this is a fragmentation learning impediment, where prior learning is not accessed in the appropriate context.

Ontological learning impediments

Jagdish, explained that the electrons would not fall into the nucleus even though there were "attractions from the nucleus, pulling in the electrons" as "the attraction isn't that strong", whereas "if you could actually physically make those electrons get closer to the nucleus then they would fall in because the attraction would be so strong". It was suggested above that her comments revealed two deficits in the prerequisite learning needed to make sense of the science (about the classical expectation that atoms with planetary electrons should radiate energy, and an appreciation of the need for a force to maintain circular motion). However, her own explanation for the stability of the atom reveals another discrepancy from the scientific view.

Jagdish explains the stability of the electron orbit in terms of her personal understanding of how forces act: that the electrons are too far from the nucleus for the attraction to have an effect. This seems to be an *ontological learning impediment* as she applies her own intuitive conceptual framework for forces. Although she has been taught from a curriculum perspective that a smaller force will have a smaller effect, her everyday experience of a world where significant frictional forces are ubiquitous (but often covert) is that forces can be too small to have *any* effect.

Another area of learning difficulty highlighted in the study was understanding what was meant by electron 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'). Students tended to transfer associations of movement to the term spin.

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, and that the electrons were always spinning "because they're all going to be repelling each other and circling, always trying [sic] to get as far apart". Umar conceptualised 'spin' in terms of the exclusion principle, and reported that "it doesn't actually spin, it's not really spinning itself", but he still related the notion of spin to a 'direction', suggesting that the two electrons "in the same orbital ... might be in *opposite directions*".

These students associated the term 'spin' with the macroscopic, everyday, 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, present author's emphasis). It is likely that some of these students had little knowledge of the scientific concept of angular momentum (which would act as a *deficit learning impediment*), but in any case they applied their 'life-world' (Solomon, 1992) understanding of spin to the context of the 'spin' of an electron (an *ontological learning impediment*). The familiar term suggested the familiar meaning (*cf.* Schmidt, 1991).

Pedagogic learning impediments

As well as failing to make expected connections with *assumed* prerequisite learning, students may also make unexpected (and 'inappropriate') connections with their prior learning. One of the student misconceptions reported was that after a molecule had absorbed light and was "excited" having "more energy", then *all* of the electrons would "probably move faster". Although one should be wary of over-interpretation, this appears to be a *pedagogic learning impediment* where the student has related new learning about electronic transitions with prior learning about kinetic theory - where heating causes an increase in temperature, that is explained as a general increase in particle motion.

A clearer case occurred when Kabul confused thermionic emission *of electrons* with the emission *of photons* from a luminous body,

> when we heat the metal, the electrons will rise from a lower energy level to a higher energy level, as it's a vacuum the electrons will just jump off ... the metal, if you heat it quite sufficiently, the electrons will rise from a lower energy to a higher level and, just be emitted outside…[for] example if you take iron, if you heat it you will see it turns red, it turns red because it starts emitting electrons, but once it cools down the electrons go back to the electron shells and it regains its shiny colour. While you're heating the electrons are being emitted, so it gives off colours of different wavelength when you cool down the electrons go back to their original energy levels.

The thermionic emission of electrons, and the emission of (visible) thermal radiation, are both effects obtained when heating a metal, and both involve electrons and energy changes. It seems the two sets of ideas were not sufficiently distinct in Kabul's cognitive structure, so that discussion of one activated ('brought to mind') his knowledge of the other - an example of a *pedagogic learning impediment.*

It was reported above that Edward explained the continued motion of atomic electrons as being "like the planetary motion", that is that "in creation they were given some initial kinetic energy, and some rotational energy". Edward was not aware of the classical analysis that electrons in atoms should act as electrical oscillators, and emit energy, and this was considered above as a *deficit learning impediment*. However, this student *had* learnt somewhere about the rotational energy *of the planets* being due to inertia after the formation of the solar system. This information was 'brought to mind', and he made *an analogy* to apply the same principle to the atomic case. His knowledge of theories of solar system evolution, and of the 'atom as a tiny solar system' model acted as a pedagogic learning impediment.

One of the key aspects of the introduction of quantum ideas in college level chemistry is the adoption of the orbital concept to describe the electronic structure of atoms and molecules. At the secondary school level the model of the atom presented is of electrons being arranged in shells, often represented as circles around the nucleus on which the electrons are located. This representation is often compared to planets orbiting the sun (Taber, 2001c). College level students are expected to move beyond this simple model to adopt the orbital approximation (see figure 3).

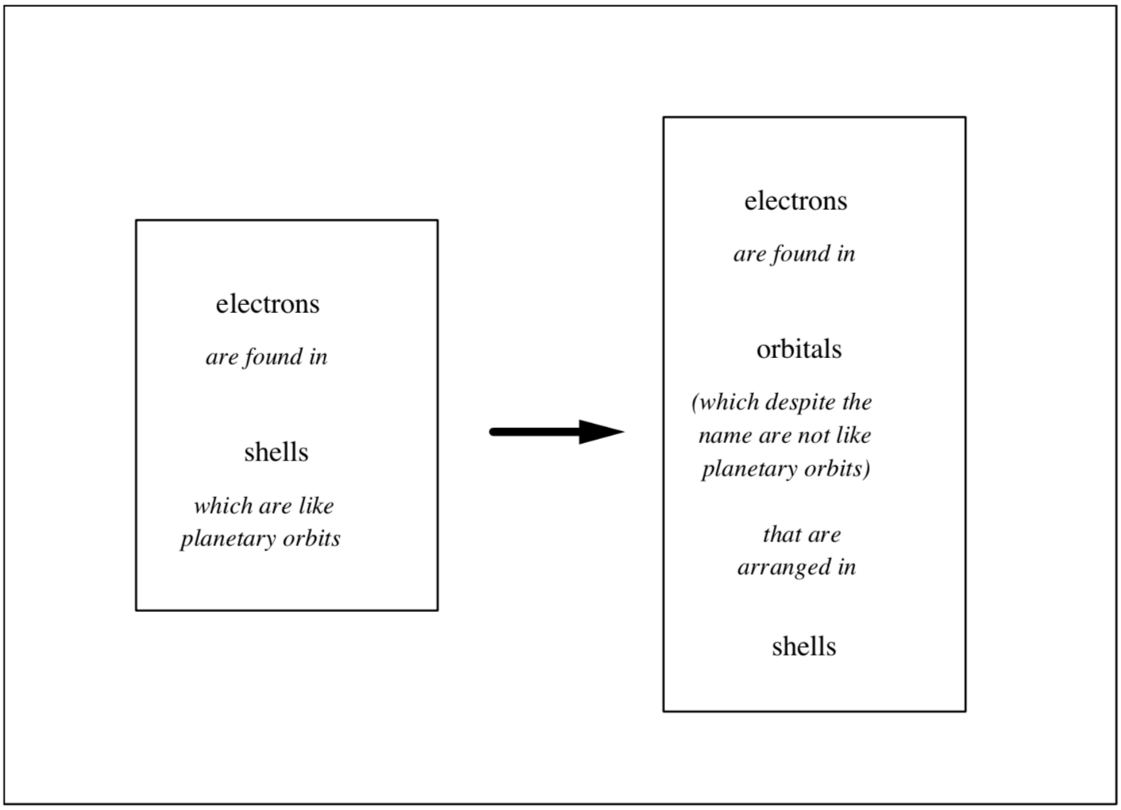

Figure 3: intended meaning of 'orbital' concept

The research suggested that students adopted *the term* 'orbital' readily, but often tended to use it to re-label their existing conceptions of electron shells (see figure 4). Orbitals were referred to as 'round', or the "*path* the electron takes" as it "*circles* the nucleus", and diagrams which did represent electrons in shells were said by students to show the orbitals.

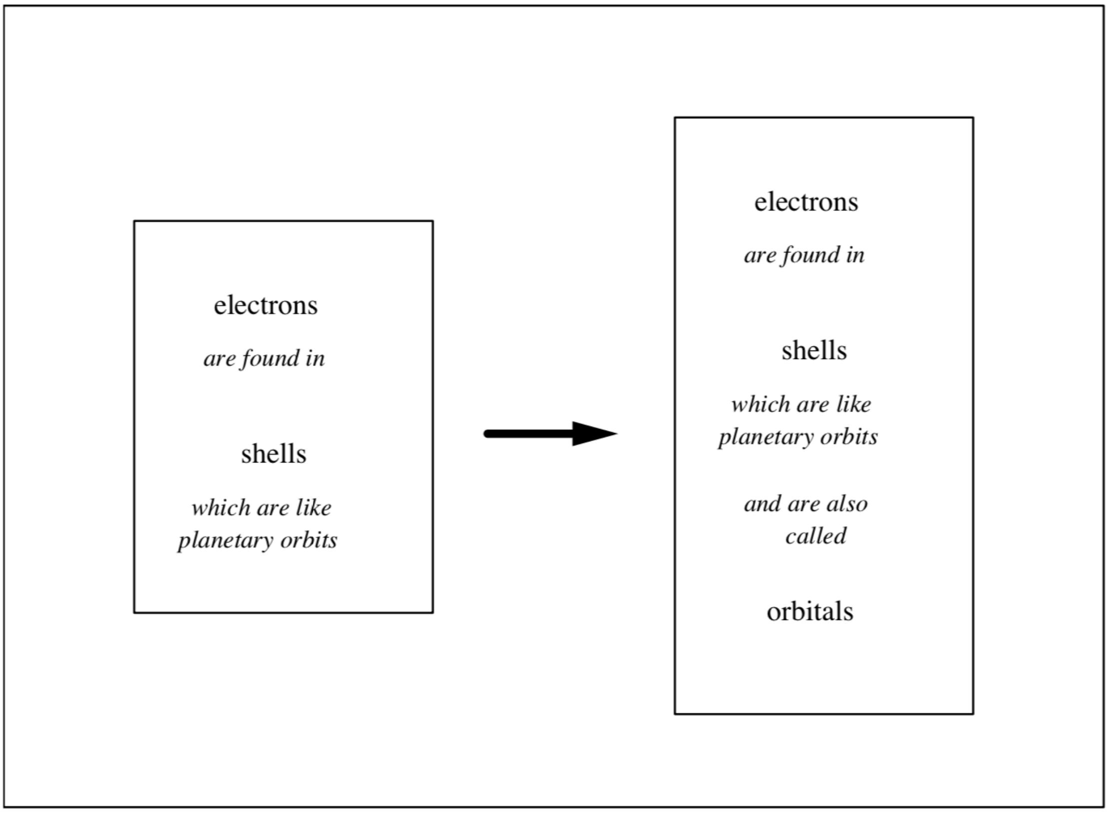

Figure 4 Adopted meaning for 'orbital' concept

Here we see how prior teaching about the structure of atoms seems to interfere with new learning. Students enter college courses having been taught a model of the atom where electrons exhibit planetary orbits, in concentric shells, around nuclei. At college level, then, the atomic model learnt at school acts as a *pedagogic learning impediment*: when students are told about *orbitals*, they may interpret the new concept in terms of the familiar shells model.

Another example of prior knowledge interfering with intended learning was found with the representation of molecules with bonding that could not be explained in terms of 2-centre-2-electron bonds. The structure of the benzene molecule is said to be a resonance of several canonical forms, usually limited to the two Kekulé structures (see figure 5) at college level (although the three Dewar structures may be included at more advanced levels).

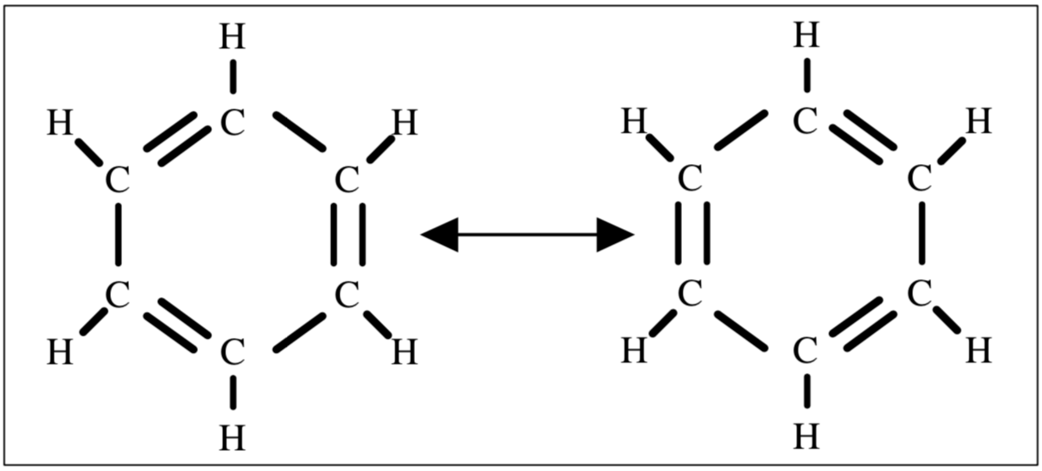

Figure 5: representing 'resonance' in the benzene molecule

The research found that students had difficulty constructing the intended meaning of resonance. So Brian referred to how "the double bonds aren't…in specific places on every benzene…molecule". This was one of several descriptions of *resonance as an alternation* between double and single bonds. Carol described how

> it will be double bond, single bond, double bond, single bond, double bond, single… and, to make the resonance, you draw a little two way arrow, and where there was a double bond in one diagram there would be a single bond in the other one...[the circle] shows that you can either have a double bond, or a single bond, and it happens so quickly that you might as well just have a single bond…[the bond was] sometimes single, sometimes double.

Even a student, Quorat, who referred to "resonance structures" and "canonical forms" construed these notions as a device *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".

Similar comments were made in the context of other figures representing resonance in terms of canonical forms (such as in the ethandioate ion). The actual species being represented was thought to "alter between the two states". So for some students the arrow conventionally drawn between canonical forms (such as in figure 5) "represents that it can change from one to the other", because "the electrons that are in [one] double bond move over to form a double bond [in a different position]".

It seems that some students, having previously learnt the formalism of a straight line representing a bond (conceptualised as a permanent feature of molecular structure), tend to misconstrue canonical figures as molecular structures between which the molecules actually "just flick around".

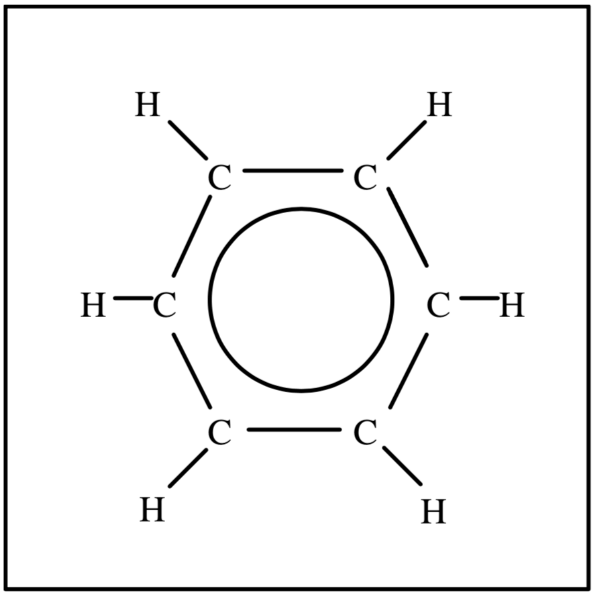

Figure 6: An alternative representation of *the* benzene molecule

Benzene is also commonly represented as a hexagon with a circle inside it (figure 6): the circle standing for the delocalised electrons in the 6-centre molecular orbital system. However, students who have learnt that covalent bonding is a pair of electrons shared between two atoms represented by straight lines, may not readily link the new symbol to bonding, but rather interpret it as standing for 'spare' electrons *not* used in the bonding. Carbon is (in this interpretation) only explicitly shown as having three bonds, and so, students argue, there should also be "spare electrons". These are considered to be located "within the ring" or "left in the middle", and "you show that by the circle". So the circle was considered to represent the "six spare electrons in the middle". The definitions and modes of presenting bonds learnt at an earlier educational stage act as barrier to learning the new material: i.e. pedagogic learning impediments.

Discussion

The analysis presented above shows how one particular analytical tool suggests interpretations of the learning difficulties identified in the source study (Taber, 2002b, c). The findings from this analysis will now be discussed from three specific perspectives: in terms of the implications for teaching of the topic area, suggestions for further research into learning about the topic, and an appraisal of the analytical tool itself.

Implications for teaching about atomic and molecular structure

The role of the science teacher is to facilitate learning that is meaningful (rather than rote), and which increasingly matches the target knowledge presented in the curriculum. Meaningful learning occurs when the learner is able to relate novel information to existing knowledge structures (Ausubel, 2000). When the appropriate pre-requisite knowledge is not present then there may be no meaningful learning, or else the creative student may anchor the new information to something else that is construed as relevant. Studies into student learning such as that analysed above, can highlight particular areas of difficulty and 'sticking points' -the nature of the 'learning impediments' - and so inform teaching.

This paper discusses a topic area where it is known that students' direct experiences of the world do not provide appropriate background knowledge, so that aspects of the science seem 'crazy' (Feynman, 1985): the wave-particle nature of 'quanticles' such as electrons; the quantum numbers and their consequences; the way minute atoms have orbitals that technically extend to infinity. Teachers will be aware that they must find approaches to teach the abstract and unfamiliar ideas for a topic with such a high 'learning demand' (Leach and Scott, 1995).

The analysis above is able to highlight some particular features of the learners' existing ideas, and the way they accessed them, which acted as particular 'sticking points' in their learning. Teachers may wish to consider the identified learning impediments when planning their own teaching of the topic. Among *this particular group* of students it was found that:

- not knowing about the *classical* physics that predicted that atoms with 'planetary' electrons could not be stable may prevent students appreciating *why* the quantisation of energy was introduced;
- holding an intuitive 'life-world' physics perspective that small forces have no effect (rather than a small effect) may lead to a student considering the nuclear attraction as too weak to influence the electron;
- a student who does not know that centripetal force is needed to maintain a circular orbit, or who does not recognise the relevance of physics learning about circular motion may

expect the electron to be attracted into the nucleus even when holding a planetary model of the atom;

- conversely, a student who does not understand the nature of circular motion may see inertia as sufficient reason for electrons to 'orbit' atoms;
- students who have studied spectral lines in physics may not spontaneously bring these ideas to mind in a chemistry context;
- students may adopt their existing 'life-world' meaning for 'spin' for the (quantum-mechanical) spin of the electron, and so imagine that electrons have spin *because* they are rotating (either on their axis, or around an atomic nucleus);
- if angular momentum is not a concept that is itself referred to in the chemistry syllabus then students may lack the prerequisite knowledge to adopt a new meaning of spin as integral angular momemtum;
- students may expect energy absorbed from radiation to be distributed across the electrons in the system (similar to how heat absorbed by a material is distributed among molecules);
- a student who has previously learnt about thermionic emission, may activate (bring to mind) this prior learning when emission of light due to the 'movement' (between energy levels) of electrons is studied, confusing the two similar ideas;
- having previously learnt that electrons in atoms are found in 'shells', some students may understand the new term 'orbital' as synonymous;
- students used to representing bonds as lines, in fixed positions, may not recognise other representations as showing bonds.

Clearly this list derives from the analysis of one interview study, and it should not be assumed that this small group of students can be considered to be typical of all learners at this level. Nevertheless, these findings can provide useful indications for the teacher: suggesting areas

- where the teacher may find pre-requisite knowledge lacking; or
- where the teacher needs to explicitly relate the teaching to the prior knowledge that some students may not otherwise bring to mind; or
- where the teacher might helpfully emphasise the distinctions between a concept being introduced and similar familiar ideas that could readily be confused.

Clearly the teacher can only use the present analysis as a *starting point* for identifying the *particular* learning impediments at work in her own class. For example, failure to apply notions about centripetal force to the planetary model of the atom could be a *deficiency learning impediment* (if the topic of circular motion has not been studied), but could also be a *fragmentation learning* *impediment*, where relevant material that has been studied in physics, was not 'brought to mind' in the context of a chemistry class. Distinguishing between these two situations would be important in a particular case, as different remedial action by the teacher is different is indicated (see table 1).

Implications for research: developing the analytical tool

A typology, by its nature, is a scheme for classifying phenomena, and so will be useful to the extent that its categories reflect regularities in the phenomena being explored. In this interview-based study it has been possible to identify difficulties due to each of the four types of learning impediment in the scheme: missing pre-requisite knowledge; failures to make required connections; and interpreting new knowledge inappropriately in terms of both intuitive notions of the world and in terms of previously learnt teaching models. This indicates that the typology has some heuristic value as an analytical lens for interpreting research data from studies into student learning. Consideration of the findings of the present study suggest ways in which the typology might be refined for future research.

The main distinction in the typology of learning impediments is between where the intended learning does not occur because expected 'links' are not made, or because 'inappropriate' links are made by the learner. The 'substantial learning impediments' were categorised into 'ontological' and 'pedagogic' to reflect the *practical* significance of the difference between the learners' intuitive ideas and prior learning from science. This is a first-order distinction, as classroom learning is both determined by, and modifies, existing ideas.

The choice of the term 'ontological', for what has variably been called children's science, life-world knowledge, intuitive theories, preconceptions and the like, was chosen as a blanket term for how the learner understood the world to be composed and structured. Chi (1992, Chi et al. 1994) has suggested that when a learner who has an ontology at odds with that of science (categorising something on the wrong major ontological branch - a process such as heating as a type of substance for example), may misconceive phenomena in ways that are difficult to correct. This may have particular relevance in the topic discussed - where orbitals are fundamentally different in nature to orbits for example.

It could also be suggested that it might be useful to consider additional separate categories of substantive learning impediment that may be at work. Clearly some links that students make are largely due to linguistic cues (orbital = orbit may be one example). Schmidt (1991) refers to how labels may act as 'hidden persuaders' (cf. 'spin').

Another important area is the nature of the students' epistemological assumptions. For example, prior learning of atomic models is less likely to act as a substantive learning impediment if the learner appreciates the nature of models (as partial representations, as tools for thinking) and accepts the potential value of manifold models in understanding complex phenomena (e.g. Taber, 2000). A planetary model of the atom is more likely to block new learning if it is thought to be a precise, accurate and 'true' representation of the atom, and if the learner sees scientific models and theories as established facts (Driver, *et al.*, 1996; Grosslight, et al., 1991; Justi & Gilbert, 2000).

The pedagogic learning impediments identified in this study are of two types: the expected influence of prior learning about the topic (e.g. knowledge of the planetary model of the atom with electron orbits can act as an impediment to learning about more sophisticated models), but also examples of learners drawing inappropriate comparisons with pre-existing knowledge from *other areas* of science learning. So, prior learning about thermionic emission was activated ('brought to mind') when emission of light due to the 'movement' (between energy levels) of electrons was studied. Seeing inertia as a sufficient reason for electrons to 'orbit' atoms, and assuming that all electrons in an atom move faster after energy is absorbed, appear to be the outcome of a *creative* act of making an analogy with prior learning. This is something that teachers would generally wish to encourage, although the present analysis shows the importance of monitoring students' developing understanding, as students' spontaneous analogies can act as substantive learning impediments.

These considerations would suggest that the typology could be modified to include substantive learning impediments categorised as analogical, epistemological, linguistic, pedagogical or ontological.

Implications for research: further exploration of student learning

One way in which qualitative and quantitative studies can complement each other is when learning difficulties identified from an interview study are used to design probes to survey larger, more representative, populations (e.g., Taber, 2000).

The present study also suggests a direction for further qualitative enquiry. When the notion of a fragmentation learning impediment was proposed it was assumed that this type of impediment derives from the compartmentalisation of knowledge taught in another subject, or even under another topic-heading in the same subject, so that relevant material held in cognitive structure was not accessed by the learner (Taber, 2001a). This certainly seems to apply to some of the examples discussed here, such as when an experiment carried out in physics is *not* 'brought to mind' when studying chemistry.

The identification of fragmentation learning impediments *within* the topic area is worthy of further investigation. Here we see students failing to 'make connections' between concepts that we know they have available, and which would seem to be very closely and clearly related. It is not clear why Carol failed to link the delocalised electrons in the benzene structure with her existing knowledge of the rings of electron-density making up the pi-bonding; or why Kabul spontaneously located electrons in molecules in atomic orbitals, *although* he believed that the atomic orbitals were no longer present once they had been used to form molecular orbitals.

These failures to make the link with such closely related knowledge seem to be a different kind of fragmentation of learning to, say, Debra failing to recognise the significance of a physics experiment when asked a question that she considered to be about chemistry. Kabul could provide all the relevant knowledge when scaffolded (Scott, 1998) through specific direct questioning, but was not yet able to spontaneously construct chains of explanation in this concept area (*cf.* Taber & Watts, 2000, p.346).

It could be *hypothesised* that these *fragmentation* learning impediments occur in such 'within-topic' contexts when the students had not integrated aspects of recent learning, i.e. that the new ideas are present in cognitive structure, but not yet consolidated (*cf.* Dykstra, et al. 1992; Hashweh, 1986). This is a conjecture, but one that is consistent with accepted ideas about learning and memory.

Consolidation of learning is a long-term (subconscious) process (Carter, 1998; Greenfield, 1997; Parkin, 1987; Sousa, 2001; see Taber, 2001b for an example from science education) that gradually strengthens links between, and rationalises the organisation of, conceptual knowledge (*cf.* Thagard, 1992), so that knowledge is more readily accessed, and can be processed more efficiently within the limited capacity of a person's working memory (Miller, 1968; Sousa, 2001; *cf.* Johnstone, 2000).

It is conjectured here that recently acquired knowledge – though accessible in response to direct questioning - may not always be available in a form suitable to act as the foundations for new learning, not having yet been fully integrated into conceptual schemes. From this perspective the new learning is present, but 'fragile' (Carter, 1998), whereas prior learning has to be well established ('robust') before it can effectively support new learning. This would mean that simply checking that students have access to prerequisite knowledge does not guarantee that they are able to use it as the foundations for new learning. This interpretation would clearly have significance far beyond the topic discussed here, and so could be a fruitful avenue for further research into the learning of science.

Concluding comments

In this paper the findings from an interview study have been explored through the 'analytical lens' of a typology of learning impediments. Like all such schemes, the typology has limitations. The same apparent failure of learning may have different origins in different learners, or may be due to a combination of factors. It is also suggested that the categories in the original typology could be refined to admit more 'types' of learning impediment: providing a 'repertoire' of potential learning impediments. Learning difficulties may not always have a single identifiable cause, and the 'repertoire' notion may remind the teacher or researcher that the categories as not mutually exclusive.

The typology was, nevertheless, found to be a useful heuristic tool, providing interpretations of learning difficulties that can inform the teaching of the topic. The analysis also highlighted an area where learning impediments were not expected – fragmentation learning impediments within closely related learning. This outcome leads to a hypothesis (about the nature of prior learning suitable to act as foundations for constructing new knowledge) that can inform future research.

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Appendix 1: Dialogue from an interview

1.

I: So if someone came along and 'well actually no, I don't think there are any 1s orbitals present there'?

K: Hm. [Sounding unconvinced]

I: You'd disagree with that, would you?

K: Yeah.

2.

I: Yeah? And if someone said 'well here, there aren't any 2s orbitals on carbon or 2p orbitals on carbon', would you agree with that?

K: Yeah.

I: You'd agree with that?

K: Yeah.

I: And they said 'well there aren't any sp^3 hybrid orbitals there either?'

K: No, then I would disagree.

I: You'd disagree with that?

K: Yeah.

I: Okay. Right, okay.

3.

I: What about if someone said 'there's a molecular orbital present in there, [hydrogen]'?

K: Yeah.

I: You agree with that?

K: Yep.

4.

I: Yeah. And they said ‘well’, all right what do you think a molecular orbital is?

K: It’s made up of, for example, two atomic orbitals, when they form a bond, the orbitals, you know, combine together to form a molecular orbital.

I: Right, so how many molecular orbitals do you think are present there?

K: One.

I: Just one, and that’s made up form?

K: The two 1s orbitals.

I: Okay.

5.

I: And someone says to you ‘right, aren’t any 1s orbitals present in this [hydrogen] molecule, because the 1s orbitals were used to make the molecular orbital’.

[pause, c.2s]

K: Yeah, true.

I: You’d agree with that?

K: Yeah.

I: So are there any 1s orbitals present in that molecule?

K: No, no longer.

I: There aren’t any more?

K: No.

6.

I: Same person comes along, and says, ‘there aren’t any sp^3 hybrid orbitals in this methane’ What do you think?

K: I disagree.

I: You disagree?

K: Yeah, there are sp^3 hybrids.

I: You think there are?

K: Yeah.

7.

I: sp^3 hybridised *atomic* orbitals?

K: No but they've combined with hydrogen,

I: Mm.

K: actually, to form molecular orbitals,

I: Mm.

K: so, yeah there aren't any sp^3.

I: There aren't any?

K: No.

8.

I: Okay, what about in [diamond structure], are there any sp^3 hybridised orbitals there?

K: No, all molecular orbitals.

I: Interviewer
K: Student, Kabul

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