Taber, Keith S. (2010). Intuitions, Conceptions and Frameworks: Modelling Student Cognition in Science Learning, in M. S. Khine & I. M. Saleh (Eds.), *New Science of Learning: Cognition, Computers and Collaboration in Education*. Dordrecht: Springer, pp.163-182

Intuitions, conceptions and frameworks: modelling student cognition in science learning

Abstract

A great deal is known about student thinking in many scientific topics, as this has been a major focus of educational enquiry over several decades. Much of this research has been undertaken from ethnographic or phenomenological perspectives - where the main concern was developing authentic accounts of how students understood a wide range of concept areas, rather than exploring the cognitive processes involved. The theoretical entities invoked to label findings, such as intuitive theories, alternative conceptions and conceptual frameworks have been the subject of much critical debate. The lack of agreement on how learners' ideas reflect underlying 'cognitive structure' has hindered the application of research findings to informing teaching and developing pedagogy. However, theoretical perspectives from areas of cognitive science are increasingly offering more principled frameworks for thinking about the nature of 'cognitive structures' and learning processes. In particular, approaches which model cognition as being multi-levelled are beginning to make sense of the diverse and seemingly incoherent range of claims about student thinking in science, and to suggest testable hypotheses. A synthesis of cognitive science and science education research has considerable potential to exemplify a new scientific approach to the study of teaching and learning.

Key words: *learning academic concepts*; *modelling cognition*; *learners' alternative conceptions*; *conceptual development*; *understanding science*; *spontaneous and academic concepts*; *folk psychology and educational research*

Modelling student cognition in relation to academic learning

This chapter is about how researchers (and teachers) can model student cognition to make sense of the learning and understanding of school and college subjects. The premise of the chapter is that educational research into student learning has produced a great deal of descriptive material about student ideas: but has been hampered by a lack of understanding of the nature of what is studied. Familiar, but central, terms - such as 'knowledge', 'thinking', 'ideas' - tend to be poorly defined, and the relationships between data elicited in studies and the entities posited by researchers – such as 'alternative conceptual frameworks' and 'intuitive theories' – have not always been convincing. However, it is argued here, that the cognitive sciences (Gardner, 1977) increasingly offer useful conceptual tools to better inform such research. Indeed, progress is leading to strong integration between neuroscience and traditional work in experimental psychology (Goswami, 2008; Pretz & Sternberg, 2005), such that knowledge of brain function and structure may soon significantly inform educational practice (Goswami, 2006).

The context of much of the work discussed here is the learning of science subjects, as there is an immense research base into student thinking and developing understanding of science concepts (Duit, 2007). It seems highly likely, however, that much of what has been found in this area is - at least generally - applicable across other areas of 'academic' learning. Indeed it is worth noting that whilst science education has become established as something of a discrete field within education (Fensham, 2004), the content of science learning is diverse – so that understanding Hooke's law (based on a mathematical relationship), is rather different from understanding the nature of acidity or oxidation (historically shifting concepts that are contingent upon chemists selecting to pay attention to particular patterns in material behaviour which offer particular utility value), and different again from understanding the most widely accepted theories of evolution (a complex argument coordinating a wide range of considerations which together offer a viable explanatory account of the diversity of life on earth) or appreciating the ethical issues involved in pre-natal testing for genetic disease (considering how people with diverse value systems may make different judgements about the social implications of science). Certainly concepts taught in the humanities and social sciences have much in common with at least *some* of what is studied in many natural science classes.

Student learning difficulties in science subjects

There has been a substantial research effort to explore student thinking about topics taught in the sciences (Taber, 2006, 2009). The motivation for this work may be seen as the need to respond to students' difficulties in learning science that have commonly been found.

Science concepts tend to be considered hierarchical in the sense that it is usually possible to identify clear pre-requisite knowledge needed for making sense of any new ideas introduced. This offered a basis for considering students' problems in learning science – clearly it was important for learning to be 'programmed' in the sense of making sure students met concepts in a logical order, so that they were not expected to understand the more advanced concepts before those on which such concepts were built (Herron, Cantu, Ward, & Srinivasan, 1977). So if a perfectly elastic collision is one where kinetic energy is conserved, there is little point attempting to teach the concept of an elastic collision before the students have been introduced to the concept of kinetic energy.

Unfortunately clear and careful concept analysis designed to avoid such problems was found to be insufficient to avoid many of the learning difficulties common among learners. It became clear that understanding the structure of the subject matter was not enough to design effective teaching, and that it was necessary to also understand more about the learning process.

Jean Piaget's (Piaget, 1972) work suggested that abstract concepts could only be effectively learnt once students' brains had matured sufficiently to attain a level of cognitive development that was not found until at least adolescence. Certainly this approach brought useful insights (Shayer & Adey, 1981). However this again did not seem to be the whole story. For one thing, it was found that advanced concepts *did* seem to be within the grasp of younger learners if teaching took into account the need to present the ideas in sufficiently concrete ways (Bruner, 1960). Conversely, older students who had clearly demonstrated the higher levels of cognition, still commonly had difficulties attaining some of the scientific concepts commonly taught in school and college. Levels of cognitive development might be important, but could not explain why so often students failed to learn the concepts they met in science as taught.

The focus in science education shifted to exploring the nature of the ideas students did have. It was soon recognised both that (a) often in science lessons students came to class with existing alternative notions of the topics to be studied, and (b) that often students who failed to acquire target knowledge did learn from their science classes, but developed understanding inconsistent with what the teacher was attempting to teach (Driver & Erickson, 1983; Gilbert & Watts, 1983). A very active research programme developed which explored the nature of the ideas students' presented before, during and after teaching, and which was concerned with how conceptual change occurred and what kind of teaching best facilitated the desired shifts in student thinking (Taber, 2009).

Examples of students' ideas

The literature describing learners' ideas in science (reported as 'misconceptions', 'naive physics', 'intuitive theories', 'alternative conceptions', 'alternative frameworks', etc) is vast, so for readers not familiar with this research I offer a few examples of the kinds of ideas that have been found to be common among learners.

One of the most well established examples that has been widely reported concerns how people (not just children) understand the relationship of force and motion. According to physics, an object will remain in its state of motion unless acted upon by a force. So an object moving in a straight line continues to do so at the same velocity unless subjected to a force. Although this idea is very established in science (since Newton) it is at odds with what most people expect. Students are commonly found to consider that an object will only remain moving if a force is continuously applied in the direction of motion (Taber, 2009: 223-224).

Another example concerns the growth of plants. It is commonly considered that the material in a plant, for example a tree, is incorporated into the tissues after being extracted from the soil through the roots. Whilst this is not entirely contrary to scientific thinking – minerals are accessed in this way, and are incorporated into tissue – it is inconsistent with the scientific model, where photosynthesis allows the plant to acquire carbon that forms the basis of new tissue from the carbon dioxide in the air (Taber, 2009: 224-225).

Chemistry also offers many examples. So learners commonly consider *neutralisation* (the type of reaction that occurs between an acid and a base) to be a process that necessarily leads to *neutral* products (Schmidt, 1991). However, this is only the case when the acid and base are of similar strength. If the weak acid ethanoic acid reacts with the strong base sodium hydroxide, then the product, sodium ethanoate, is not neutral but basic.

Learners also commonly suggest that the reasons chemical reactions occur is because the atoms in the chemicals 'need' to obtain full electron shells, which they do by interacting with other atoms to donate, share or acquire electrons (Taber, 1998). This notion is widespread despite most commonly studied reactions in school science occurring between reactants where the atoms already 'have' full electron shells. The scientific explanations concern how the reactions involve interactions between the charged particles in reactant molecules (or ions) that lead to new configurations that are more stable. Forces act between the charges to bring about lower energy arrangements.

Alternative ideas have been reported across the sciences, so student understanding of the solar system may fare no better than their understanding of the atom. As one example, it is common for youngsters to associate summer and winter with the earth being at its closest and furthest positions from the Sun in its orbit (Hsu, Wu, & Hwang, 2008). If this were the case, both hemispheres should experience seasons in phase. The scientific model is related to the Earth's angle of tilt compared to the plane of its orbit around the Sun. When the Southern hemisphere is leaning towards the Sun it undergoes summer, but it is simultaneously winter in the Northern hemisphere that is leaning away. This offers the possibility of celebrating Christmas with snow in the North and beach barbeques in Australia.

The uncertain nature of students' alternative ideas

Initially the research programme into learners' ideas in science proved very fruitful, as researchers around the world started cataloguing common ideas elicited from students of different ages about various science topics. However the research effort was somewhat undermined by confused notions of what these ideas represented, and how best to describe and label them. References to the objects of enquiry being found in students' conceptual or cognitive structures (White, 1985) offered an impression of a clear ontological basis for the research, but often studies were undertaken with limited thought to the exact nature of what was being elicited.

So some researchers reported intuitive theories that were largely tacit, and only made explicit when students were asked to verbalise their thinking. Other researchers reported alternative conceptions that took the form of explicit propositional knowledge. Some researchers claimed that such alternative conceptions were tenacious and highly resistant to being changed by instruction; where others saw misconceptions that could be readily corrected once identified. Some researchers referred to mini-theories that had very restricted ranges of application; whilst others reported alternative conceptual frameworks that were widely applied. Some researchers saw student thinking as reflecting life-world norms, being more concerned with maintaining social cohesion than reflecting rigorous analysis; where others claimed student thinking was consistent and coherent and deserved to be called theoretical. Such differences had the potential to undermine the research programme, offering very different interpretations of both the significance of learners' ideas for teaching, and of the kinds of pedagogy that might be appropriate (Taber, 2009).

Some of the differences reported could be explained - to a certain extent - by the paradigmatic commitments and methodological choices of different researchers: workers took different fundamental assumptions into their studies about what they were enquiring into, and selected different approaches to their research depending upon the type of knowledge they thought would be possible and useful. So for example, common approaches based on idiographic assumptions (about the uniqueness of individuals) and informed by phenomenology and ethnography found a diversity of student ideas whereas approaches that were informed by more normative assumptions tended to characterise responses into modest typologies (Taber, 2007: 47-51). However, research in any field tends to have an iterative nature, so that even if different camps begin with very different assumptions about a phenomenon and plan their initial enquiries accordingly, over time we might expect a gradual convergence as researchers take on board the 'feedback' provided by their data.

This did not happen in science education, suggesting that here the phenomenon was complex and multi-facetted, allowing different researchers to find evidence to support very different characterisations of student thinking about science (Taber, 2009). So science teachers work with students who come to class with ideas which are at variance with the target knowledge in the curriculum to different degrees: and which may sometimes be labile, but sometimes inert; sometimes fragmentary and sometimes coherent; sometimes similar to those of many other students, but sometimes idiosyncratic; sometimes a useful intermediate conception that can lead to target knowledge, and sometimes a substantial impediment to the desired learning. This makes life more interesting for researchers and teachers, but clearly such a complex picture is not helpful in informing pedagogy.

Without understanding the origins of this variety found within learners' ideas about science, there is no reason not to suspect that much the same pattern (or perhaps lack of apparent pattern) could be found when students are taught new concepts in other academic areas such as history, economics, literary criticism or theory of music.

This fascinating but challenging variety in the apparent nature of conceptions students bring to class confuses attempts to use research into learners' ideas to inform teaching – which is after all a key rationale for educational research. Advising teachers how to respond to students' ideas depends upon being able to systematise the research findings, so as to start to know how and when learners ideas have certain characteristics, and so when it might be best to ignore, mould or discredit their ideas.

Whereas eliciting and characterising students' ideas can be undertaken from 'within' education, the programme to build a systematic and inclusive model from the disparate research findings needs to draw upon ideas from the cognitive sciences. In particular, science educators (and their colleagues exploring teaching and learning in other subject disciplines) need to understand better the nature of the objects of research (learners' ideas), and especially the origins and development of students' thinking. This is not a new idea. Researchers in the field have for example recommended drawing upon information processing models, either instead of focussing on students' ideas (Johnstone, 1991), or as a means for understanding their origins and development (Osborne & Wittrock, 1983). Despite this, much research has reported findings in what are largely phenomenological terms, without seeking to interpret what is reported in terms of a cognitive science framework.

Considering cognitive development and conceptual learning

The Soviet psychologist Lev Vygotsky (Vygotsky, 1934/1986) drew the distinction between two types of concepts – those that an individual develops spontaneously without formal instruction, and those that are acquired only through formal teaching of some kind. Whilst something of a simplification, this proves to be a useful distinction when thinking about student learning. Vygotsky's class of taught concepts may be labelled as 'academic', although interestingly the common translation is 'scientific'.

Whereas 'spontaneous' concepts are considered to derive from the individual's inherent 'sense-making' of the environment, Vygotsky's 'scientific' or 'academic' concepts are considered to be part of the cultural capital of the society in which an individual is raised, and to be culturally 'transmitted' – often intergenerationally. This may of course be seen as one function of formal educational institutions (schools, colleges, universities): i.e. to impart that knowledge valued by a society and considered suitable and appropriate to pass on to the young.

Spontaneous learning

Before considering some issues surrounding the learning of academic or scientific concepts, it is useful to consider how concepts may be learnt spontaneously. This discussion will be largely framed in terms of the learning of individuals, an important point to which I will return.

The learning of 'spontaneous' concepts can be understood in terms of the principles discussed by such thinkers as Piaget and Dewey. John Dewey had a notion of people as learning through experience in terms of how their expectations were or were not met in particular interactions with the world (Biesta & Burbules, 2003). In effect, people are naive scientists who form models of the world that allow them to act intelligently by predicting the effect of various behaviours. When expectations are not met, that experience leads us to modify the models that we hold and apply. That is, we act as scientists with an instrumentalist epistemology: our knowledge of the world is tentative, acts as the best currently available basis for action, and (in principle at least) is always open to revision when new evidence suggests this is indicated (Glasersfeld, 1988). In practice, of course, people are well known to often fail to shift their thinking even when acknowledging the lack of match between predictions based upon their existing models of the world and new experiences. Indeed this issue is at the basis of personal construct theory, an approach to therapy developed by George Kelly (1963) to help clients 'shift' ways of construing the world that were considered to be counterproductive and acting as barriers to personal happiness and growth.

A clear problem for Dewey's approach (which was primarily philosophical) is the issue of a starting point: how do we get to the point where we make sense of the world enough to have those initial models that can guide our actions? To borrow William James's phrase – how do we get past the point where our perception of the world is just a 'blooming, buzzing confusion'?

Piaget (Piaget, 1979) had a scientific background and considered cognition accordingly. Humans have evolved over a very long period, and natural selection has equipped modern humans with apparatus to allow intelligent behaviour in the world, i.e. to modify behaviour patterns in the light of experience as Dewey had noted. A human being does not enter the world *ex nihilo* but as the outcome of a long-term selection process that provides genetic instructions that offer the organism some compatibility with the environment. Those genetic instructions support the development of a brain that has structures similar to those that have allowed previous generations to survive and procreate in the world: we might say our brains are structured to 'fit' the world. This is especially so for humans who despite lacking any exceptional qualities in terms of strength or speed or visual acuity or sense of smell or tolerance of hot and arid or cold conditions etc., are however endowed with facilities to make enough sense of the world to have a good chance of surviving in it. One aspect of this is that the newly born infant's brain is 'programmed' to learn (as this is something that has been selected for): to learn new behaviours, and - in particular - to learn to 're-programme' itself to some extent.

It was in this context that Piaget developed his highly influential model of cognitive development (Bliss, 1995). The newly born baby is equipped to interact with the environment, and to modify its actions on that environment through feedback. This pre-supposes the existence of mental structures, schema, that have plasticity. These schema are sensori-motor: according to Piaget, 'thinking' at this stage is through moving, pushing, touching, sucking, etc. However, Piaget's argument was that the developing apparatus could not only refine its sensori-motor schema through feedback processes, but that the ongoing maturation of the brain allowed this level of cognition to provide the foundations for the development of qualitatively different new structures to appear which supported a more abstract form of cognition (Sugarman, 1987). In Piaget's model there were four main 'stages' of cognitive development that occurred through this interaction of brain development (maturation) with feedback from experience – learning. The most advanced of the stages in Piaget's system is formal operations, which supports the use of logical operations in such areas as science and mathematics.

Many of the details of Piaget's scheme have come under criticism, but some of the key elements remain highly pertinent. Piaget offered us the modern view of the brain as an organ which has evolved to *both* develop according to a common general pattern through childhood and adolescence, and to retain plasticity throughout the life-span.

The cognitive and the conceptual

Here then we have the basis of another example of a very useful if over-simplistic distinction. All human brains tend to have strong similarities in terms of the basic cognitive apparatus and how this developments as we mature. Yet each brain is unique, not only because of the specific generic instructions in a person's genome, but also because unique experience of the world leads to unique learning.

It is useful to consider the development of *cognitive* abilities as largely under genetic control, if conditional upon suitable triggers from experience. Here we might consider that life experience has some effect on the rate of development, and the degree to which potential is met.

However, the specific '*conceptual*' knowledge an individual develops is primarily the result of particular learning experiences, *albeit* noting that those experiences are filtered and channelled by the available cognitive apparatus. A new born baby will not develop abstract knowledge regardless of the richness of the learning environment, because it has not yet developed the apparatus to do so.

The nature of concepts is – like so many constructs in education and the cognitive sciences – not universally agreed (Gilbert & Watts, 1983). However, here I would adopt a common notion that an individual 'has' conceptual knowledge[1] if they are able to make discriminations on the basis of that knowledge. So a young child who is able to reliably distinguish between cats and dogs, or between the cat that lives next door, and a stray, is demonstrating conceptual knowledge: i.e. previously experienced patterns in the perceptual field have been somehow been modelled and then represented in the brain in a form that allows the individual to guide responses to current patterns in the perceptual field that are judged as related.

Of course such a description becomes problematic in practice. In everyday life we seldom have sufficient data to be quite sure whether others are making reliable discriminations – and even in clinical studies such judgements rely on agreed protocols that at best offer statistical likelihood. The absence of such behaviour does not *imply* absence of the conceptual knowledge that could *potentially* enable the behaviour. Moreover, evidence of a desired discrimination offers no assurance that the conceptual knowledge being applied matches anyone else's version of the concept. These are not merely inconveniences in research, but fundamental issues that teachers have to work with in their professional lives.

So, just to offer one example, consider a learner in an elementary class learning about the concept 'animal'. Imagine that the learner was able to classify living things as animals or not animals as below:

[1] The term 'knowledge' is not here used in the sense of certain, justified belief (the meaning of the term preferred by some philosophers) but rather in the sense of what we think we know about the world. The latter sense better described how the term is widely used in cognitive science and in education.

animal	**not animal**
cow	moss
dog	maple tree
hamster	rose
horse	mushroom
dolphin	grass

The teacher might feel that the learner had grasped what scientists mean by the concept label animal. However given a different set of examples, the same learner may well have excluded from the category 'animals': humans (considered people not animals); whale (considered a big fish – which it is not of course - not an animal); a butterfly (considered an insect, or in the USA a 'bug', not an animal); pigeon (considered a bird not an animal) and so forth. In this particular case it is well established that the common taxonomic class of animal applied by most people in everyday life does not fit with the scientific version. A teacher who was aware of this would chose their examples accordingly, but no matter how many examples we might use to test out a learners' application of a general concept, and no matter how good the match between their discriminations and ours, we can never be certain that the learner has 'the same' concept that we do. This is of course just a specific example of the fallacy of induction (Driver, 1983).

Conceptual development

If *cognitive* development is primarily a matter of the unfolding of biological potential triggered by interactions with the environment, then *conceptual* development is basically due to learning which is contingent upon particular experiences. Conceptual learning in science is considered a largely iterative process: where available mental structures are used to interpret experience, and are modified according to that experience. This reflects the comments about Dewey's ideas above, and indeed common thinking about learning in science education tends to be considered 'constructivist' in the sense that Dewey, Piaget, Kelly and Vygotsky (among others) are widely considered to be constructivist (Taber, 2009). That is, they see the development of personal knowledge as basically a building process: using existing knowledge as tools for forming new knowledge. This links too to the ideas of Gagné (1970), but with the important difference that where Gagné encouraged teachers to consider how the formal public knowledge structures of science are built up into coherent networks of ideas, constructivists in science education have been concerned with how learners tend to build up their own, often alternative, knowledge structures.

Such knowledge is considered to *complement* conceptual analysis of scientific knowledge in informing pedagogy.

Drawing upon cognitive science

Whilst science education researchers are in a strong position to explore and characterise student thinking, many of the constructs used in the field are ambiguous. Terms such as 'alternative conception' are sometimes used to refer to a hypothetical mental structure, and are sometimes used to label the models researchers form to summarise findings from different informants (Taber, 2009: 188). Where conceptions (or intuitive theories or alternative frameworks or minitheories etc) are posited as being located in learners' minds, it is often unclear what form they are understood to take. Indeed it might be suggested that just as students often operate with alternative technically dubious versions of science concepts, science education researchers have been exploring students' ideas using conceptual tools that are in their own way just as vague and imprecise as those of the students they are exploring.

Folk psychology and educational research

In other words, educational research has often been based on a good understanding of the science concepts students are asked to learn, and a strong familiarity with the classroom context in which school and college learning takes place – but an *impoverished conceptual framework for interpreting cognition*. It may be ironic that science educators have worked hard to shift teachers away from operating with a 'folk psychology' model of teaching (as the transfer of knowledge from teacher to student), whilst carrying out their own research from a similar folk psychology base (Taber, 2009).

For example such constructs as 'ideas', 'beliefs', 'learning', 'understanding', 'thinking', 'memory' have often been taken for granted in studies, rather than seen as problematic to define and so recognise. This is not true of all studies, and it is clearly recognised that in any research certain starting points have to be taken as accepted givens. However, such implicit 'taken-for-grantedness' may commonly lead to confusing what a researcher interpreted as the meaning of a students' speech utterance with what the student thought, and indeed then what they remembered and so what they may be considered to know. That is not to suggest that such distinctions are ever likely to be unproblematic in practice (Taber, 2009), but lack of clarity in researchers' accounts only increases the potential for confusion.

Such confusions have characterised the debate about the nature of students' scientific thinking when difference research evidence is drawn upon to argue that learners' ideas are coherent or piecemeal; or are stable or labile, etc. Whilst it would be naive to assume that this area of research can be significantly advanced by a simple clarification of terminology and tightening of language, the cognitive sciences, the 'new science of mind' is now sufficiently developed to offer a good deal of valuable guidance (Gardner, 1977). The rest of this chapter will explain this position with some examples.

Thinking, knowing and ideas

One central feature of any model of student cognition drawing upon the cognitive sciences is the distinction between what a learner thinks (at any one time) and what they can be considered to 'know'. Thinking is a process, and the ideas that learners have (and may then express) are products of that process. Thoughts are transient, and draw upon both memory and immediately available perceptual information.

So, to take an extreme example, if a student locked in an isolated sensory derivation chamber thinks that uranium is the heaviest naturally occurring element, then we might feel that justifies assuming the student 'knows' that information. (This ignores the issue of *how we know* what the student thinks: not a trivial consideration, especially in this set of circumstances!) However, we might have less confidence in thinking another student 'knows' this same fact when they tell us this whilst reading a chemistry book. Indeed, if the student is Chinese and is just learning to read English, but has minimal English language comprehension, we might infer that any 'thinking' is at the level of converting text to verbal output, and does not justify us assuming the student even 'held the idea' during processing. My computer can convert text into 'speech' in a similar way, but I do not consider it to think.

Often, as educators, we are less concerned with what ideas might be expressed in a specific unique context (such as when reading a pertinent text), but what ideas are likely to be reproduced reliably in a variety of contexts with limited environmental support. By the latter, I mean that educators traditionally judge student knowledge in formal education by what they express under test conditions where they have no access to reference materials and are not allowed to confer with others. We want to know what they remember: what they have 'held in memory'. Whilst such test conditions are seldom authentic reflections of how knowledge is applied in real life contexts, there seems to be widespread tacit acknowledgement that what is produced working alone in a test can be considered to offer a pragmatic assessment of what someone can remember with limited support - and so reflects what is 'known'.

Memory

However, memory is an area where folk-psychology notions may seem seductive (Claxton, 2005). Memory, on such an account, is a kind of storage space where we place things we may want to take out again later. When we remember, we take those same things back out of memory, and metaphorically blow off the dust as we re-examine them.

Here cognitive science has much to offer. For one thing, studies of memory have sharpened the distinction between working memory (where currently considered material is processed) and long-term memory. The rather severe limits of working memory have been used to explain some student learning difficulties in terms of tasks being beyond the capacity of working memory, although it has also been argued that this severe limitation is an adaptation to prevent our thinking becoming too labile for our own good (Sweller, 2007).

However, more significantly, cognitive science shows that long-term memory is based upon making structural changes in a substrate that can later channel thinking. The important point here is that the memory traces are different in nature to the ideas. This should perhaps be obvious to all, but the influence of the metaphors of everyday life should not be underestimated (Lakoff & Johnson, 1980). We do not put ideas into storage, *we code them in a very different format.*

Remembering is a reconstructive process whereby we use the memory traces to help build new thoughts that (we trust) are close to those we had that triggered the original trace. The process does not give perfect fidelity, so remembering is creative: it involves making sense of the available trace as best as possible. This explains, of course, why the same student seems to know something one day, but have forgotten it the next: the same memory trace will be sufficient to generate thinking similar enough to the original thoughts under some conditions, but not others. It also explains how students can remember a teaching episode, but manage to recall it as supporting their own alternative conceptions, even when the teaching was specifically designed to challenge those very conceptions. Recalling (correctly) that the teacher showed us electrical circuits and measured the current flow at different points can be the basis of a (reconstructed) narrative where the real details are interpreted in terms of the students' understanding: so the student remembers (incorrectly) how the teacher showed that current decreases around the circuit (Gauld, 1989) – and has no awareness that only parts of the memory are based on the original events.

The important point here is that any simplistic notion of whether someone 'knows' something or not will not do justice to human cognition. People will give reports of thinking that seem to indicate certain knowledge under some conditions when perceptual cues, and preceding thoughts, allow memory traces to generate ideas that will not be 'recalled' under other conditions. This explains some of the variation sometimes found in research into students' scientific thinking.

Situated knowledge and distributed cognition

There has been a good deal of work exploring 'situated' knowledge, where a person can apparently demonstrate knowledge only in particular situations, such that the knowledge cannot be considered to reside in the individual as such, as in other contexts it is apparently not demonstrated (Hennessy, 1993). This again relates to what we mean by 'having' or 'holding' knowledge. Here we need to consider how a person's cognitive apparatus accesses both memory traces and perceptual cues in the environment when processing (thinking).

If familiar environments cue activation of particular memories, leading to behaviour (e.g. talking or writing) that we interpret as demonstrating knowledge and understanding, then we will find that the context-dependence of performance varies between individuals – i.e. some will demonstrate knowledge at most times and places; others only when conditions closely match those of the learning episodes. This raises issues for assessing student learning.

Indeed the distinction between only being able to offer accounts we judge as demonstrating knowledge in certain contexts, and the ability of an individual to produce similar reports through reading information directly from a reference source may need to be seen as separate points on a continuum. When teachers adopt 'scaffolding' approaches to support student learning in their 'zones of next development' (Scott, 1998) they are in effect facilitating intermediate states between these points.

A related issue concerns the social aspects of learning. One major area of contention in research into learners' ideas in science has been the acceptability of studies that treat learners as if effectively isolated thinkers who develop knowledge individually without regard to the social context (Taber, 2009: pp.191). There are indeed two issues here. One concerns the admissibility of treating the social context of learning as a complication that needs to be initially ignored to develop first order models of student learning. This is something of argument about degree: both sides acknowledge the importance of the social dimension – but disagree about whether it should be a core focus of research, or a complexity best addressed later in the research programme.

However, there is also a school of thought, the construct*ionist* view, that questions whether it is ever sensible to consider that the individual is the locus of knowledge: believing that knowledge is always distributed across a social network. To those working in the personal constructivist tradition – exploring what *individuals* think, know and understand – such a position seems quite bizarre. Indeed it suggests that the objects of their research are a kind of epiphenomena, and are not sensible foci for study. That both sides tend to talk across each other in such debates may again be related to the common practice of researchers operating with common-sense folk psychology definitions of knowledge, knowing, understanding etc.

Perception and conception

Another useful area of cognitive science that can inform our understanding of student thinking and understanding is work on perception. An important feature of studies in this area is to erode another simplistic distinction – that between 'pure' perception and thought. A simple model considers that perception is a process by which information from the environment is captured and presented to mind, where it can become the subject of thought. Work in cognitive science has demonstrated that perception involves multi-stage processing, so that the conscious mind seldom experiences anything close to 'raw perceptual' data. As Gregory (Gregory, 1998: 9) reports in the case of sight: "the indirectness of vision and its complexity are evident in its physiology". As the Gestalt psychologies first suggested, what is presented to consciousness as the object of perception is usually a pattern that has *already been interpreted* (Koffka, 1967): we see a bird or a snake or a tiger: not just patches of moving colour and shadow.

A cognitive science perspective suggests that in modelling thinking, remembering is much like perceiving – in both cases the available 'data' (electrical signals from sensory organs; electrical patterns modulated through memory 'circuits') undergoes various processing ('interpretation') before being presented to consciousness. The evolutionary advantage of this is clear: quick responses – we can run or duck or attack before it is 'too late'. The cost is that we have to accept a fairly high rate of false positives – leading to people commonly seeing images of figures in toast or rock formations, or sending in photographs of their 'rude' vegetables to television shows. This also leads to people seeing potential attackers in the dark and children seeing evil characters in wallpaper patterns at night. This is relevant to science learning, as it start to explain some of the common ways that people interpret phenomena that are at odds with scientific understanding.

Research is starting to explore where these effects are operating in the cognitive system. Some aspects of pattern recognition may actually be genetically determined. For example, humans appear to have evolved to be 'hard-wired' to readily detect face like patterns – and sure enough we see faces readily: not only the 'man in the Moon', but even on a crater on Mars. We are able to effectively communicate the face with a simple emoticon, i.e. :-)

Other pattern recognition systems may develop in response to environmental stimuli. For example, Andrea diSessa (1993) has undertaken work to explore how what he terms *phenomenological primitives* channel student understanding and explanations according to common patterns that are abstracted, and has used this approach to offer explanations of many conceptions elicited from college students. This work has mainly been carried out in physics, but certainly has potential to inform learning in other sciences (García Franco & Taber, 2008) and probably beyond. It suggests that research that is able to identify the types of patterns that are readily abstracted from the perceptual field could help teachers design teaching to use, rather than be thwarted, by such mechanisms (Taber, 2008).

Constructing knowledge

When thinking about the learning of complex conceptual material, work such as that of diSessa offers very useful insights, suggesting that processing elements in the pre-conscious part of the cognitive system may be highly significant for how learners come to understand science concepts (or those of other subject areas). In particular it implies that we need to recognise that our brains hold some 'knowledge' at intuitive levels: that is, that we make systematic discriminations based on processing elements that are well 'below' conscious awareness. DiSessa believes that conceptual knowledge may be built upon networks of such intuitive knowledge elements.

A model developed by Annette Karmiloff-Smith (Karmiloff-Smith, 1996) posits at least four discrete levels of the cognitive system: one purely implicit level to which we have no access through introspection, and three more explicit levels. The highest of these levels allows us to access knowledge in verbal propositional forms: an elephant is a mammal; transitions metals can demonstrate a range of oxidation states in their compounds, and so forth. The intermediate levels do not reflect knowledge elements that are themselves 'in' verbal, propositional form. This again links to science education research: for example about the role of visualisation in learning science (Gilbert, 2005).

Karmiloff-Smith's model (which informs Figure 1) assumes that knowledge held in each level of the system can be (but is not necessarily) re-represented at the next level. Conceptual development involves this type of re-representation making knowledge more explicit over time. The student who replies to a question about the seasons by suggesting the Earth is nearer the Sun in summer could on diSessa's model be activating (at an intuitive level) a primitive knowledge element that (we can verbalise as) 'effects are greater closer to the source', and applying this intuition to the specific question. However, it is also possible that such an intuition has over time been re-represented such that the learner actually has developed an explicit conception that the Earth is nearer the Sun, which is accessed as propositional knowledge. Such distinctions are not purely academic: in the latter case answers on this topic are likely to be consistent, whereas in the former case, modifying the question may sometimes lead to a different primitive intuition being activated and a different answer generated. This model offers some explanatory value in making sense of the disparate characteristics reported for students' ideas in science.

Karmiloff-Smith also offers another possibility: that under some circumstances it is possible to short-cut the process by which we build implicit intuitions of the world which through successive re-representation can become converted to directly accessible representations of propositional knowledge. She suggested that we are able to sometimes directly acquire knowledge at this level by interactions with others. This is of course reassuring to those working in school systems where much of teaching concerns presenting the concepts to be learned by verbalising propositional knowledge. However, the mechanism is not limited to true information: a student could through this mechanism learn the Earth is nearer the Sun during the summer if this is suggested by a classmate.

Here Vygotsky's distinction between spontaneous and scientific/academic concepts becomes very relevant. Vygotsky recognised the limitations of spontaneous concepts that could not be directly verbalised and applied in principled ways; but also that academic concepts would be rote learnt and meaningless unless related to existing knowledge grounded in personal experience. For Vygotsky (Vygotsky, 1934/1994), conceptual development was a process of developing linkage between these two types of concepts so that spontaneous concepts become available to operate on in principled ways, and academic concepts are understood not just regurgitated. Vygotsky put great stress on the way those with access to cultural tools such as language could support the learning of the young during this process.

Conceptual change

This brings us back to a pre-occupation of science education – how to bring about conceptual change (Taber, 2009: pp.280). The natural process of conceptual development may well involve the slow building of explicit knowledge structures by re-representing more intuitive cognitive elements: but what when this leads to conceptions at odds with what teachers are asked to teach? Some approaches to cognitive change are based on persuasion, but seem to suggest that the learner is able to undergo conceptual change as a deliberate rational choice. It seems likely that teaching that encourages metacognitive sophistication may indeed support such processes in some cases. However, for those student conceptions that have been found to be most tenacious, persuasion has limited effect.

Sometimes this can actually be explained on rational grounds – from the students' perspective their own understanding is more coherent and has greater explanatory power (Thagard, 1992). In other cases research suggests that fundamental ontological category errors have been made: so that the type of *process* the teacher means by 'heat' or 'light' is just totally incompatible with the type of *stuff* the student understands 'heat' or 'light' to be (Chi, 1992). Research suggests in these cases the teacher really needs to start again and help build an alternative understanding from scratch, rather than challenge the students' ideas: i.e. the teacher needs to help the student acquire a totally new concept.

The knowledge-in-pieces approach based on diSessa's work suggests that at least with some concept areas a better knowledge of students' repertoires of intuitive knowledge elements will allow teachers to deliberately channel learning by building - and sometimes rebuilding – conceptual knowledge upon the most helpful intuitions in terms of match desired target knowledge (Hammer, 2000). So thinking about the seasons in terms of throwing balls at targets at different angles to the direction of throw might activate suitable intuitions, rather than thinking in terms of getting closer to a fire.

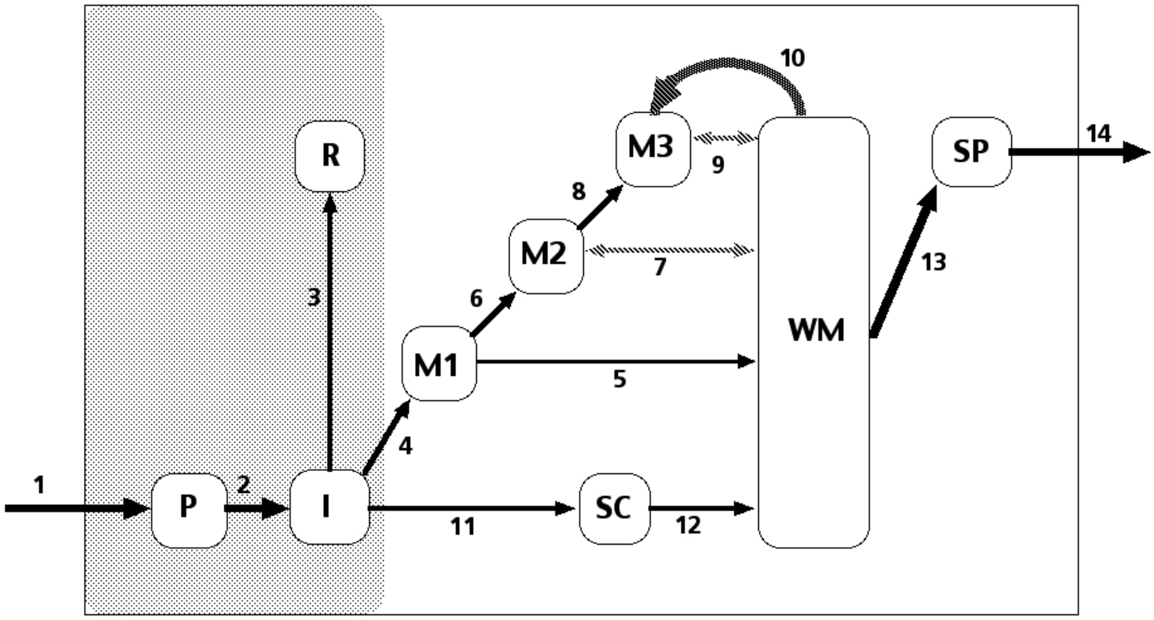
Towards a model of cognition that supports research into student learning

This chapter has done little more than offer an overview of an interesting research issue in education, and a glimpse of how cognitive science can support our research into classroom learning and teaching.

The issue - deriving from science education but likely equally relevant in other subject areas – was the nature of learners' ideas in science. In particular, how several decades of work exploring student thinking and understanding of science concepts has led to an eclectic range of findings. Research has characterised learners' ideas along a range of dimensions (Taber, 2009), so that they:

- may reflect or contradict target knowledge in the curriculum;
- may be recognised as fanciful or conjectural, or may be the basis of strong commitments;
- may be labile and readily 'corrected' or tenacious and resistant to teaching;
- may be highly integrated into complex frameworks or may be isolated notions with limited ranges of convenience
- may be inconsistent, or show high levels of coherence across broad domains;
- may be unitary or manifold.

For a time, this led to much debate about *which* characterisations were actually correct. However, as research in science education has increasingly drawn upon ideas from cognitive science, it has become much clearer why thinking elicited from science students has such variety. A cognitive system with different types of knowledge elements at different levels of explicit access; a limited working memory; a long-term memory system that necessarily has to represent ideas in a physical substrate; etc, starts to explain why students sometimes offer inconsistent and changeable answers, but other times reliably offer accounts of complex well-integrated frameworks of conceptions. This is illustrated in figure 1.



A highly simplified model of the cognitive system illustrating how ideas from cognitive science can inform thinking about student learning and thinking (drawing particularly on the ideas of Annette Karmiloff-Smith). 1. Sensory input is processed in hardwired perceptual elements (P) before … 2. being interpreted by implicit pattern-recognition elements (I) that are not open to conscious awareness, but are able to… 3. signal other implicit units (R), e.g. to initiate the blink reflex. 4. Implicit 'knowledge' may be re-represented at an explicit level (M1) that is not open to conscious interrogation, but that can… 5. inform conscious thought (WM) without conscious awareness of the source. This leads to 'intuitive' knowledge. Implicit knowledge in this form can also be… 6, 8. re-represented at more explicit levels (M2, M3). Knowledge represented at level M2, is… 7. open to conscious introspection, but is not presented to consciousness in verbal form - e.g. running a mental simulation through imagery - and has to be verbalised before being reported. Knowledge represented at level M3 can be… 9. directly accessed in propositional form and is presented to consciousness verbally, i.e. as conceptions. 10. The outcome of thinking can be deliberately integrated in this representational form, allowing the development of extended conceptual frameworks of propositional knowledge. Patterns of sensory input recognised as carrying linguistic information can be… 11. processed in the brain's speech comprehension areas (SC), and then… 12. directly presented as language. The outcomes of processing in working memory (WM) can be… 13. processed in the brain's speech production centres (SP), which… 14. produce utterances that are interpreted by researchers as demonstrating intuitive theories, conceptions, conceptual frameworks etc.

Figure 1: A scheme to explain the origins of different types of learner knowledge.

A single chapter can only offer a brief taster of how ideas from the cognitive sciences are supporting research into science education (and many of the ideas mentioned in this chapter are explored in more depth in (Taber, 2009). It is certainly not the case that science educators now have a clear understanding of cognition that explains all we wish to know about learning in science, and how to support that learning more effectively. However, the adoption of a range of notions from the learning science is certainly offering the means to start clarifying some of the vague taken-for-granted ideas that have been common in the field, and is offering useful models of cognition that are helping us make much better sense of the disparate findings of research in this field.

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