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The mismatch between assumed prior knowledge and the learner's conceptions: a typology of learning impediments.

Abstract

This paper considers some of the reasons why motivated students in suitable learning environments may fail to learn from competent teachers. It draws upon work in the psychology of learning, and the considerable body of research that has been undertaken to explore the nature and origin of learners' alternative conceptions in science. A synthesis of ideas from this previous work suggests a simple typology of 'learning impediments' in terms of the mismatch between the learner's cognitive structure and the teacher's expectations. It is suggested that this classification system may be a useful tool that, alongside techniques to probe prior knowledge, can help teachers diagnose and overcome such impediments to intended learning, and thus make teaching more effective. Although deriving from research into the learning of science, it is suggested that the typology can be applied to conceptual learning across the curriculum.

Introduction

There are many reasons why a teacher may fail to bring about desired learning. A pupil may be unable to see the board or hear the teacher clearly. The 'learner' may not be motivated to learn for various reasons. Perhaps, occasionally at least, a teacher may not be competent in terms of subject knowledge or pedagogic skill, or may not be sufficiently prepared for the class. The literature on learning (for example, in science education) also makes it clear that motivated, able pupils, in appropriate learning environments, may often fail to learn effectively from keen, able, well-organised teachers.

This paper is concerned with this latter type of context. The aim is to help teachers diagnose the reasons why seemingly proficient exposition of accurate content to attentive classes may fail to achieve the intended 'transfer' of knowledge. It provides a simple model for use by practitioners looking to improve their teaching effectiveness. It draws upon well known ideas from psychology, and the research literature on learning in science. The 'scientific' bias reflects the author's own teaching and research background: the principles discussed, however, are general. The ideas that are drawn upon are widely acknowledged, but the present synthesis provides a simple framework which it is believed will be a useful analytical tool when evaluating lessons or teaching sequences.

Learning impediments - the evidence from science education

Research supports a view common among science teachers that pupils *generally* fail to learn *much* of the material presented to them. This is found to be the case even in contexts where the pupils are well motivated and located in apparently suitable, well resourced, learning environments. Science educators have looked to psychology to find the reasons for these failures. A considerable literature now exists examining various aspects of learning in science, and a great deal has been uncovered about the reasons why pupils have difficulties in various topics. It is possible to organise many of the findings by defining a small number of types of possible 'learning impediments' (Taber 1997a). The resulting synthesis provides a simple model for teachers wishing to circumvent such learning impediments, diagnose the causes for 'failures' in learning, and plan effective remedial action.

Meaningful learning, cognitive structure and constructivism

This model derives from the constructivist perspective that learning is a process of knowledge construction in the mind of the learner (Pope 1982; von Glaserfeld 1989, Fensham, Gunstone & White 1994), and assumes that we are concerned with 'meaningful' rather than 'rote' learning (Ausubel 1961). Although it is possible to memorise random strings of letters and numbers, education is intended to produce meaningful learning - where the new information is understood and can be applied. Ausubel pointed out that for learning to be meaningful, the learner had to *make sense* of the materials presented. In other words, the learner had to *recognise* that what was being taught had some connection with existing knowledge.

Therefore, a paramount factor in any meaningful learning is what has previously been learnt. The notion of 'cognitive structure' is useful here, and may be defined as *the facts, concepts, propositions, theories, and raw perceptual data that the learner has available to her at any point in time, and the manner in which it is arranged* (Taber 1997a, after White 1985 and Ausubel and Robinson, 1969). In order for learning to take place, the pupil must understand the new material presented in terms of the existing cognitive structure. And for this to happen it is necessary both for the learner to hold some relevant prior knowledge, and to 'make the connection', i.e., to recognise its relevance. If either of these conditions are not met, then no meaningful learning will take place.

Teachers in any subject area can think of curricular materials that can not be effectively understood and learnt until more basic ideas have been mastered. This is acknowledged in Gagné's approach to analysing subject matter and Bruner's idea of a spiral curriculum (e.g. Child 1986). Practising teachers will also recognise the situation in which 'the penny drops' as a pupil suddenly becomes aware of how some new notion makes sense in terms of her existing knowledge (c.f. Solomon, 1993).

Research in science education has, however, shown that intended learning is also often compromised when there *are* ideas in a student's cognitive structure that *are* recognised as related to the new material (e.g. Driver 1983; Driver, Guesne & Tiberghien 1985; Driver 1989; Gilbert, Osborne & Fensham 1982; Gilbert & Watts 1983). This is because Ausubel's principle - that meaningful learning can take place if the presented material can be related to relevant ideas in cognitive structure - does not specify that the learner's prior knowledge has to be *accurate*. If a learner holds frameworks of understanding that are at odds with accepted knowledge, these alternative frameworks may act as suitable anchors for new knowledge. When the learner makes sense of the presented material in terms of an alternative framework, it will be a *different sense* to that intended.

An extensive research programme has found that it is very common for learners to enter science classrooms already holding ideas relevant to the topic being taught, but at odds with the accepted curriculum knowledge (Driver, Squires, Rushworth & Wood-Robinson 1994; Pfundt & Duit 1991). These alternative conceptions or alternative frameworks [1] have been uncovered across the science curriculum, at a wide range of educational levels, and both before *and after* teaching on the topic has taken place.

Although *some* alternative conceptions may be readily discarded, persuading pupils to give up long-established, and well-integrated, alternative frameworks is a difficult and lengthy process (Taber 1995a, 2000). It should be borne in mind that at school level, at least, pupils seldom have the metacognitive awareness to conceptualise their thinking in terms of which principles and models they apply in explaining phenomena. There is no suggestion that learners are (generally) being deliberately awkward in continuing to apply their alternative schemes.

The research literature shows that even when gains are made, they may be transitory (Selley 1982; Shipstone 1985). So a sequence of lessons that seems to demonstrate to pupils how the scientific model better explains phenomena may produce the desired results in an immediate post-test. However, unless appropriate regular reinforcement of the new scheme is provided, the existing ideas may return to dominance over a period of months. Indeed, it is probably technically incorrect to assume such ideas are ever completely 'erased'. It is probably more realistic to think of certain conceptual schemes falling into disuse (Taber 1995a, 2000, accepted for publication; Taber & Watts, 1997).

'Constructivist' views of learning lead us to expect that individuals may well have alternative ways of seeing the world. The constructivist sees people as actively modelling the world as they try to make sense of their experiences. Kelly (1963) believed that each person develops a unique way of construing the world - their own system of personal constructs. This process starts in the very young child, and once it has begun, later learning is contingent on what is already 'known'. The

[1] I am using the term alternative conceptions to suggest an isolated idea, and alternative framework for a more complex, related set of ideas. Unfortunately, in the literature these terms, and a number of others, are sometimes synonymous, and sometimes given different meanings by various authors (Taber, 1997a)

existing cognitive structure channels subsequent learning as it acts as the framework for interpreting the world (de Bono 1969).

Piaget described how learning takes place through processes of assimilation, equilibration and accommodation (Bliss 1993; 1995). [2] When there is 'cognitive dissonance' between what we are told and what we think we know, a state of dis-equilibrium is established. This may result in accommodation - changing our existing ideas about the world. However, accommodation is not necessary if the new information can be assimilated into the existing frameworks of knowledge. (Again, note that these frameworks may, or may not, match the consensual world view.)

Kuhn (1970, 1977) has reported that scientists on either side of a scientific revolution may interpret the same facts differently. In extreme cases the two camps work within incommensurate 'disciplinary matrixes' or 'paradigms', and do not have a common observational language with which to compare their viewpoints. Similarly, pupils often use key technical terms in science classes, but these have different meanings for the pupils and the teacher (Watts & Gilbert 1983).

Thagard (1992) has pointed out how scientists working within different paradigms are ingenious in fitting the same data within their inconsistent schemes. Although there may not be a perfect match of theory and observation, each scientist believes that their scheme provides the most coherent view overall. As Thagard points out, the familiarity and in-depth knowledge that comes from years of working with one set of theories will often make it seem more consistent than a set of poorly understood novel ideas - even if in retrospect history takes a different view.

Pupils entering science classes with their own ideas about a concept area may be considered to be in a similar position. Research has found that learners are very good at interpreting new information to fit their existing ideas (Driver, 1983). Indeed, in practical work they often report *seeing* different phenomena to their teachers: their actual perceptions may be determined by their operative theories! Information that is presented by the teacher as supporting one view may well be interpreted within a different scheme (e.g. Taber, 1995a). Often neither the pupil nor the teacher will realise that they are not sharing common knowledge until later. 'Later' may be when the end-of-topic test is marked, and the teacher is intending to move on to another topic.

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[2] For Piaget, equilibration involved both assimilation and accommodation, and all learning can be considered to involve both additions to cognitive structure and modification of existing elements. However, the terms assimilation and accommodation are often used within the science education literature 'to a first approximation', i.e. to distinguish between learning that takes place without dramatically perturbing existing knowledge, and that which requires significant restructuring of existing schemes.

The influence of the constructivist view in science education has been to encourage teachers to elicit their pupils' ideas about a concept area at the start of the topic (Driver & Oldham 1986). The teacher can then try and explicitly challenge pupils' alternative ideas by focusing on phenomena that are difficult to explain in pupils' existing schemes, and by exploring any logical faults or limitations that can be overcome by adopting the scientific view. This is a challenging task, but is much more likely to be successful than ignoring the pupils' own ideas and hoping they come to see things the way the teacher intends.

The origin of pupils' alternative frameworks

Pupils' alternative conceptions may originate in a number of ways. One of the best established common alternative frameworks concerns the relationship between force and movement (Gilbert, Watts & Osborne 1982; Gilbert & Zylbersztajn 1985). According to physics, an object in motion will *continue* to move with the same velocity indefinitely *unless* it is acted upon by a force. According to many school children (and college students, and even a fair spread of teachers and science graduates) an object will only continue to move if a force is continuously applied. Otherwise, it will come to a stop. The orthodox physics is well established, but the alternative 'impetus framework' view can be seen to derive from common experience. Many other examples of 'children's science' can also be considered to originate in the child's experience of the world.

However, learners are also found to hold alternative ideas about concept areas that are far from everyday experience. For example, chemistry students have been found to commonly hold alternative conceptions about the way atoms and molecules interact (Taber 1998). These ideas are clearly not derived from everyday experience in any direct way.

Some 'unscientific' thinking is simply picked up from the general misinformation circulating in society. Although learning is in one sense something that occurs intrapersonally, within the mind of an individual, this often takes place within an interpersonal context. Learning often involves interaction with others. Indeed, education may be seen as a process of coming to consensual knowledge (Edwards & Mercer 1987), and in classrooms the role of peers may be as significant (Solomon 1993). 'Folklore' is a source of various dubious ideas. Children are told many things by peers, family and the media, and much of this 'lay science' may be wrong or misunderstood

(Claxton 1993). There is, however, another potential source of alternative ideas: teachers themselves.

There is always the possibility that teachers may themselves misunderstand the content they are supposed to teach, and no doubt this sometimes happens. However, even instruction that is accurate in its own terms may be misunderstood by children who do not have the necessary prerequisite knowledge to make the *intended* sense of it. In these cases the learners' ingenious interpretations may become the basis for an alternative framework that will effect subsequent learning.

For example, chemical reactions may be understood in terms of electrical interactions between the molecules of the reacting substances. However, this is usually considered too difficult to teach at an introductory level, and often the issue of why reactions occur is just left in abeyance. Yet pupils have a natural tendency to try and make sense of the chemistry, and to understand 'why'. Pupils are taught early in their course that atoms with certain arrangements of electrons (sub-atomic particles) are more stable, and that in the materials we find around us the atoms usually have these stable structures. This is scientifically accurate. It is very common for pupils to come to think that reactions occur *so that* atoms can obtain these structures. This is not a valid idea, but research has shown that pupils not only adopt the principle, but often make it the basis of quite extensive schemes for understanding various aspects of the subject (Taber 1994a, 1997b, 1998). Unfortunately, much of the chemistry they are expected to learn on more advanced courses is inconsistent with this 'octet framework', and effective learning is inhibited. [3]

In principle, the adoption of this common alternative framework could be prevented by a number of strategies. For example, if a more authentic rationale for chemical reactions occurring was provided, then pupils would not need to create their own alternative. Even if this was not done, it would be possible, when introducing ideas about stable atomic structures, to emphasise how both the reactants *and* products in chemical reactions have such structures. This would undermine any tendency to see this as a driving force for the reactions. It has also been pointed out that the way aspects of chemical bonding are commonly introduced leads readily to being misinterpreted as supporting the alternative viewpoint. This is not the place to discuss the details of this particular case (for that see Taber 1994a, 1995, 1997a, 1999), but the point is that *the way the subject is taught*

[3] The term 'octet framework' refers to the fact that in many common molecular structures the atoms may be considered to have eight electrons in their outermost shells, and learners explain reactions occurring because atoms are 'trying' to get such octet structures.

encourages the development of the alternative framework, and therefore *changes* in the way the subject is taught at this point could avoid problems at a later date.

The synthesis: a typology of learning impediments.

The ideas outlined above provide the basis for a simple classification of learning impediments (see figure 1).

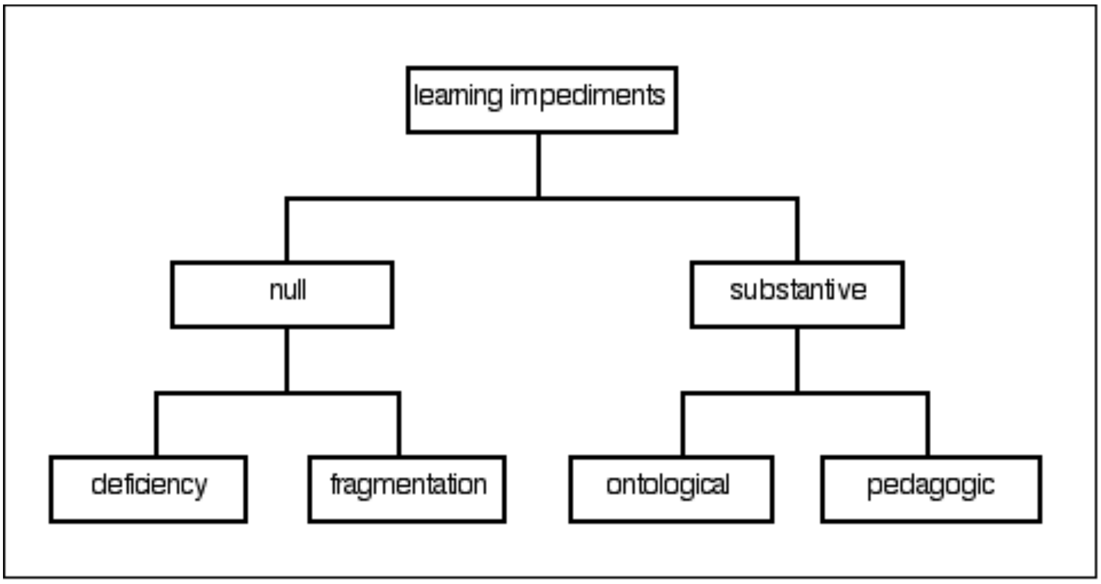

Figure 1: A typology of learning impediments

The primary distinction is between situations when the intended learning does not take place because

(a) the learner can not make sense of the presented material in terms of existing ideas; or

(b) the learner interprets the new material in terms of existing, but alternative, ideas.

The first option encompasses two possible impediments to learning. They are collectively referred to as *null learning impediments*, as the problem is related to the apparent absence of relevant prerequisite knowledge.

If the pupil does not posses any existing ideas relating to the new material then no meaningful learning can occur. This is labelled a *deficiency learning impediment*, as the cause of the learning failure is a deficiency in the match between existing cognitive structure and the necessary prerequisite knowledge. [4] The term 'deficiency' is not intended to imply blame on the part of the pupil. The mismatch could feasibly be due to a previous failure of teaching, or a misjudgement by the teacher either in evaluating the prior knowledge necessary for the new teaching, or in assuming the likely level of prior knowledge in the class.

The teacher's course of action in the case of a deficiency learning impediment is to make good the deficiency. The prerequisite learning needs to be put in place before the new material can be understood. This type of learning impediment is avoided by careful conceptual analysis of the material, and pre-testing of pupils' prior knowledge.

The second class of null impediment, the *fragmentation learning impediment*, would appear to produce the same outcome: that the material presented in class is not understood, and no substantive learning takes place. However, in this case relevant ideas are present, and could *in principle* be accessed. The remedial action needed is less drastic in this situation. The teacher's job is to find ways to help the learner access, and make connections with, their existing ideas. This may involve no more than including a wider range of examples (perhaps including those from more familiar situations). On other occasions it may be necessary to find similarities between disparate topics to act as analogies. Social contexts may often be useful models as points of entry for abstract ideas (Taber & Watts 1996).

The second main category of learning impediment (labelled substantive) is more problematic, as the intended learning is restricted not by the absence of relevant ideas in cognitive structure, but their presence. A pupil suffering from a null learning impediment is likely to be aware that she does not understand the teacher. However, the outcome of a substantive learning impediment is to understand differently.

Although some alternative frameworks can be very tenacious, the types of factors that are considered to encourage pupils to 'change their minds' are well documented (Hewson & Hewson,

[4] It should be pointed out that each learner's cognitive structure is unique, and so technically a common alternative framework represents a model of commonalities in the distinct but similar ideas from many learners (Taber 1997a, 1998).

1984; Strike & Posner, 1992), as are exam- ples of teaching schemes that demonstrate these approaches in practice (Brook & Driver, 1986; Johnston & Driver, 1991).

In general then, substantive learning impediments - as the name perhaps suggest - are more difficult to overcome than null learning impediments. The distinction between those substantive learning impediments which are labelled ontological and those which are judged pedagogic is not absolute. For example, the octet framework, an alternative conceptual framework from chemistry referred to above, is considered to be a pedagogic learning impediment (Taber 1998). There is no way that pupils' everyday experience of their physical environment could directly lead to beliefs about how atoms interact. It has been argued that aspects of teaching provide the raw material from which so many pupils construct this alternative framework to explain chemical processes.

However, it is likely that there are features of this construction process which are better aligned with 'ontological' origins. Pupils seem to very readily accept the (unscientific) model of their world as consisting of isolated atoms which interact (Taber 1995b), and they readily take on the idea of atoms filling their electrons shells as the driving force for reactions to occur. Most pupils are very comfortable with describing these processes anthropomorphically, in terms of the atoms having needs and wants (Taber & Watts 1996). It is quite likely that these features map onto fundamental schemes about the way the world is that are acquired early in life (Watts & Taber 1996).

The extent to which this common alternative framework is taught rather than assimilated into existing schemes is a question for future research. However, this does not undermine the *classification* of this framework as a pedagogic learning impediment. The division between ontological and pedagogic impediments is not intended to be *absolute*, but rather of *utility* to teachers. Whatever predilections pupils may bring to their school science lessons, the construction of the alternative framework uses information provided by the teacher. There seems little doubt that the ordering, emphasis and level of simplification of the teaching conspires to provide pupils with material that they use to build an invalid representation of the subject.

The impetus framework in mechanics derives from early experiences of pushing objects (which soon seem to run out of 'impetus'). When pupils meet Newtonian mechanics in school science a substantive learning impediment is already in place, and the teacher must act accordingly. The octet framework in chemistry only develops *in response* to teaching, and it could in principle be avoided by changing the teaching (Taber 1999).

Using the typology

The typology presented in this paper derives from a model of teaching and learning informed by psychological theory and educational practice. The *components* of the model are well established, but this synthesis can be a useful way for teachers to organise aspects of learning theory from disparate sources.

The immediate value of using the typology is the diagnosis of the type(s) of learning impediment present, leading to an indication of the type of action needed to bring about the desired learning (see Table 1). Deficiencies that may be uncovered suggest prerequisite knowledge can not be assumed. When knowledge is fragmentary, extra emphasis on making connections explicit will aid learning. If substantive learning impediments are in place, the teacher is warned that the material presented may easily be misconstrued, and that learners have to be convinced that a new way of organising their knowledge is more coherent that their existing frameworks.

Table 1: Pedagogic consequences of the four types of learning impediments

Type of learning impediment	Nature of impediment	Action required
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.*
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
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
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.*

Regular use of this scheme should help teachers think about *potential* learning impediments *before* they happen. The key idea is the need to arrange the content presented to match the learners' own cognitive structures. The teacher must therefore be familiar with the learners' prior knowledge in order to plan effective lessons There are many techniques available to do this (White & Gunstone 1992), but concept mapping can be recommended as an approach which has the advantages of being especially useful in evaluating the degree of knowledge integration, and being an approach that learners themselves find helpful in organising and articulating their knowledge (Taber 1994b). Routine pre-testing of classes paired with careful analysis of curricular content will inform more effective teaching.

Conclusion

Clearly there are many reasons why pupils fail to learn the intended curriculum, and the typology presented in the present paper only addresses one aspect of the context of formal learning. Teachers have to be enthusiastic, knowledgeable in their subject specialisms and have developed effective pedagogic skills. Indeed, it is only recently that ideas from Vygotsky's work (1978, 1986) have been incorporated into our understanding of how to support conceptual change in the classroom (e.g. Howe 1986), leading to new insights about the types of 'pedagogic interventions' that teachers can use to scaffold the pupil's learning (Scott 1998).

Pupils have to be motivated to learn, and be provided with an appropriate curriculum and a suitable learning environment. As Watts and Bentley (1987) have pointed out, this needs to be perceived as a non-threatening learning environment if pupils are to risk exposing their existing conceptions to public (teacher and peer) challenge, as part of the process of reconstructing knowledge in the classroom.

The present paper addresses the needs of those teachers who are already in the position of having achieved these basic conditions for learning (motivated pupils, comfortable and supportive learning environment, well prepared lessons with varied, logically sequenced activities etc.), but are disappointed with the learning outcomes achieved. The simple typology presented here provides a way of thinking about the possible sources of mismatch between the assumed pre-requisite knowledge for a teaching episode, and pupils' actual conceptual structures. The typology is a framework to help the teacher conceptualise the 'system failures' in communication that occur when people do not share the assumed common ground. Although, like all classification systems, it over-simplifies potentially complex phenomena (learners' actual knowledge structures are likely to be multifaceted, highly responsive to idiosyncratic aspects of context, and somewhat fluid), it provides a starting point for diagnosing and 'debugging' learning blocks.

References

Ausubel, David P., In defense of verbal learning, *Educational Theory*, 11, 1961, pp.15-25.

Ausubel, David P., & Floyd G. Robinson (1971) *School Learning: An Introduction to Educational Psychology*, London: Holt International Edition (first published by Holt, Rinehart and Winston, 1969.)

Bliss, Joan (1993) The relevance of Piaget to research into children's conceptions, Chapter 2 of Black, Paul J., & Lucas, Arthur M. (Eds.), *Children's Informal Ideas in Science*, London: Routledge, 1993, pp.20-44.

Bliss, Joan (1995) Piaget and after: the case of learning science, *Studies in Science Education*, 25, pp.139-172.

Brook, Angela & Driver Rosalind (1986) in collaboration with Anderson, Michael & Davidson, John, *The Construction of Meaning and Conceptual Change in Classroom Settings: Case Studies on Energy*, Children's Learning in Science Project, Leeds: Centre for Studies in Science and Mathematics Education, University of Leeds.

Child, Dennis (1986) *Psychology and the Teacher* (4th Edition) London: Cassell.

de Bono, Edward (1969), *The Mechanism of Mind*, London: Penguin Books (first published by Jonathan Cape).

Claxton, Guy (1993) Minitheories: a preliminary model for learning science, Chapter 3 of Black, Paul J., & Arthur M. Lucas (Eds.), *Children's Informal Ideas in Science*, London: Routledge, pp.45-61.

Driver, Rosalind (1983) *The Pupil as Scientist?*, Milton Keynes: Open University Press.

Driver, Rosalind, Guesne, Edith, & Tiberghien, Andrée (Eds.) (1985) *Children's Ideas in Science*, Milton Keynes: Open University Press.

Driver, Rosalind & Oldham, Valerie (1986) A constructivist approach to curriculum development in science, *Studies in Science Education*, 13, pp.105-122.

Driver, Rosalind (1989) Students' conceptions and the learning of science, *International Journal of Science Education*, 11 (special issue), pp.481-490.

Driver, Rosalind, Ann Squires, Peter Rushworth and Valerie Wood-Robinson (1994) *Making Sense of Secondary Science: research into children's ideas*, London: Routledge, 1994.

Edwards, Derek & Mercer, Neil (1987) *Common Knowledge: The development of understanding in the classroom*, London: Routledge.

Fensham, Peter J., Gunstone, R. F., & White, R. T. (Eds.) (1994) *The Content of Science: a constructivist approach to its teaching and learning*, London: Falmer Press.

Gilbert, John K., Osborne, Roger J. & Fensham, Peter J. (1982) Children's Science and its Consequences for Teaching, *Science Education*, 66 (4), pp.623-633.

Gilbert, John K., Watts, D. Michael, & Osborne, Roger J. (1982) Students' conceptions of ideas in mechanics, *Physics Education*, 17, pp.62-66.

Gilbert, John K., and Watts, D. M. (1983) Concepts, misconceptions and alternative conceptions: changing perspectives in science education, *Studies in Science Education,* 10, pp.61-98

Gilbert, John K., & Zylbersztajn, Arden (1985) A conceptual framework for science education: The case study of force and movement, *European Journal of Science Education*, 7 (2), pp.107-120.

Glasersfeld, Ernst von (1989) Cognition, construction of knowledge, and teaching, *Synthese*, 80, pp.121-140.

Hewson, P. & Hewson, M. (1984) The role of conceptual conflict in conceptual change and the design of science instruction, *Instructional Science*, 13, pp.1-13.

Howe, Anne C. (1996) Development of science concepts within a Vygotskian framework, *Science Education*, 80 (1), pp. 35-51.

Johnston, Kate, & Driver, Rosalind (1991) *A Case Study of Teaching and Learning about Particle Theory: a constructivist reaching scheme in action*, Children's Learning in Science Project, Leeds: Centre for Studies in Science and Mathematics Education, University of Leeds.

Kelly, George (1963) *A Theory of Personality: The Psychology of Personal Constructs*, New York: W. W. Norton & Company (taken from *The Psychology of Personal Constructs*, first published 1955).

Kuhn, Thomas S. (1970) *The Structure of Scientific Revolutions (2nd edition),* Chicago: University of Chicago. (First edition published in 1962.)

Kuhn, Thomas S. (1977) *The Essential Tension: selected studies in scientific tradition and change*, Chicago: University of Chicago Press.

Pfundt, H., and Duit, R. (1991) *Bibliography: Students' alternative frameworks and science education*, IPN Reports in Brief, Germany: University of Kiel.

Pope, M. L. (1982) Personal construction of formal knowledge, *Interchange*, 13 (4), pp.3-14.

Scott, Philip (1998) Teacher talk and meaning making in science classrooms: a review of studies from a Vygotskian perspective, *Studies in Science Education*, 32, pp.45-80.

Selley, Nicholas J. (1982) Children's understanding of atoms and molecules, *Chemical Education Research and its Implications for Teaching*, Royal Society of Chemistry, pp.70-78.

Shipstone, David (1985) Electricity in simple circuits, Chapter 3 in Driver, Rosalind, Guesne, Edith, & Tiberghien, Andrée (Eds.) (1985) *Children's Ideas in Science*, Milton Keynes: Open University Press, pp.33-54.

Solomon, Joan (1993) The social construction of children's scientific knowledge, Chapter 5, in Black P. J. & Lucas, A. M. (eds.), *Children's Informal Ideas in Science*, London: Routledge, pp.85-101.

Strike, Kenneth A. & Posner, George J. (1992) A revisionist theory of conceptual change, Chapter 5 of Duschl, Richard A. & Hamilton, Richard J. (1992) Philosophy of Science, Cognitive Psychology, and Educational Theory and Practice, Albany, N.Y.: State University of New York Press.

Taber, Keith S. (1994a) Misunderstanding the Ionic Bond, *Education in Chemistry*, 31 (4), July 1994, pp.100-103.

Taber, Keith S. (1994b) Student reaction on being introduced to concept mapping, *Physics Education*, 29 (5), September 1994, pp.276-281.

Taber, Keith S. (1995a) Development of Student Understanding: A Case Study of Stability and Lability in Cognitive Structure, *Research in Science & Technological Education*, 13 (1), pp.87-97.

Taber, Keith S. (1995b) The octet rule: a pint in a quart pot?, *Education in Chemistry*, 32 (3), May 1995.

Taber, Keith S. (1997a) Understanding Chemical Bonding - the development of A level students' understanding of the concept of chemical bonding, Ph.D. thesis, University of Surrey.

Taber, Keith S. (1997b) Student understanding of ionic bonding: molecular versus electrostatic thinking?, *School Science Review*, 78 (285), June 1997, pp.85-95.

Taber, Keith S. (1998) An alternative conceptual framework from chemistry education, *International Journal of Science Education*, 20 (5), pp.597-608.

Taber, Keith S. (1999) Alternative conceptual frameworks in chemistry, *Education in Chemistry*, 36 (5) pp.135-137.

Taber, Keith S. (2000) Multiple frameworks?: Evidence of manifold conceptions in individual cognitive structure, *International Journal of Science Education*, 22 (4), pp.399-417.

Taber, Keith S. Shifting sands: a case study of conceptual development as competition between alternative conceptions, accepted for publication in *International Journal of Science Education*.

Taber, Keith S. & Watts, M. (1996) The secret life of the chemical bond: students' anthropomorphic and animistic references to bonding, *International Journal of Science Education*, 18 (5), pp.557-568.

Taber, Keith S. and Watts, Mike (1997) Constructivism and concept learning in chemistry - perspectives from a case study, *Research in Education*, 58, pp.10-20.

Thagard, Paul. (1992) *Conceptual Revolutions*, Oxford: Princeton University Press.

Vygotsky, L. S. (1978) *Mind in Society: The development of higher psychological processes*, edited by Cole, Michael, John-Steiner, Vera, Scribner, Sylvia & Souberman, Ellen, Cambridge, Massachusetts: Harvard University Press.

Vygotsky, Lev (ed. Alex Kozulin) (1986) *Thought and Language*, London: MIT Press (first published in Russian in 1934).

Watts, D. M. & Gilbert, J. (1983) Enigmas in school science: students' conceptions for scientifically associated words, *Research in Science and Technological Education*, 1 (2), 1983, pp.161-171.

Watts, Mike, & Bentley, Di (1987) Constructivism in the classroom: enabling conceptual change by words and deeds, *British Educational Research Journal*, 13 (2), 1987, pp.121-135.

Watts, Mike, and Taber, Keith S. (1996) An explanatory gestalt of essence: students' conceptions of the 'natural' in physical phenomena, *International Journal of Science Education*, 18 (8), pp.939-954.

White, Richard T,. (1985) Interview protocols and dimensions of cognitive structure, chapter 4 of West, Leo H. T., & Pines, A. Leon (eds.), *Cognitive Structure and Conceptual Change*, London: Academic Press, pp.51-59.

White, Richard, & Gunstone, Richard (1992) *Probing Understanding*, London, The Falmer Press.