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Epistemic relevance and learning chemistry in an academic context:

The place of chemistry education in supporting the development of scientific curiosity and intellect

Abstract:

It is often claimed that presenting chemical ideas in the context of learning about topics such as fuels, food production, or clothing and fabrics makes the subject more relevant to our learners. This chapter looks to make the case for a completely different kind of relevance: that students should learn conceptual and theoretical content in the context of appreciating the chemical questions that motivated it. Chemical ideas - constructs, theories, models, and so forth - are intellectual solutions that have been motivated by the challenge of developing satisfactory scientific explanations for chemical phenomena. It is the phenomena that provide the epistemic relevance for teaching the ideas. Context-based approaches may seem less abstract to students who struggle with the theoretical content of 'traditional' courses, yet these approaches may not always offer sufficient intellectual challenge to learners with the greatest potential in the subject. Moreover, a core aim of education is to support the development of the whole person, including their intellectual development. Chemistry as an academic subject, by its very nature, provides considerable opportunity to support learners in developing the kind of sophisticated thinking considered to represent intellectual maturity. For many learners, then, the very things that make chemistry a challenging subject (the abstract nature of its concepts and its dense theoretical content) offer particular relevance in the context of wider educational aims.

Preamble: the challenge of academic chemistry

Many students find chemistry a challenging and difficult subject at school and college levels (Danili & Reid, 2004). A consequence of this is that students may readily lose interest in the subject and be less likely to select it as an option unless they can see good reason to persevere with it. Some students are fascinated by chemistry, and some others recognise its value in relation to entering particular careers and professions. However, the relevance of what we teach in chemistry is not always obvious to students, and when a subject is both hard work and does not seem linked to any personal goals, we can understand why so many students either give up the subject, or at least give up on fully understanding it.

There are several reasons why traditional chemistry courses may seem difficult for many students, and here three key features are considered here: diversity, extent, and abstractness. Chemistry is a varied discipline and whilst academic chemists may specialise the student is expected to demonstrate competence across a range of different kinds of skills. This does not just include different kinds of lab-work as opposed to theory, but indeed the main branches of chemistry have their own characters. Physical chemistry blends into physics in places, where the same could certainly not be said of organic chemistry which in places shifts into biochemistry.

In terms of the extent of chemistry, there is potentially a lot to find out about. Indeed some traditional chemistry courses included surveys within both organic and inorganic chemistry. Students can learn about the chemistry of the alkali metals, the alkaline earths, and so on. This can include physical and chemical properties. They can learn about analytical tests to identify the presence of various ions. They can also learn about alcohols, and ketones, and ethers, and alkenes, and so forth. This can include synthetic routes to, and typical reactions of, different groups of compounds. Reactions can include those that can be used to identify functional groups, and important 'named' reactions. Indeed the amount of chemistry that could potentially be learnt is immense, and is growing all the time.

Modern courses have moved away from the teaching chemistry as an apparently never-ending survey of things to be learnt, to focus on the key ideas and models which have explanatory value within the discipline. This gives a better flavour of chemistry as a modern science, rather than as a form of natural history. However, this requires students to meet and cope with a good many abstract theoretical ideas such as oxidation and oxidation numbers; electronegativity and polarity;

orbital hybridisation and hyperconjugation; adiabatic changes and entropy; 'good' leaving groups and nucleophiles; and so on.

These various concepts have been adopted at different times by chemists because they have been found useful in developing explanations of chemical phenomena, and so to help bring some order to the otherwise unmanageably vast catalogue of chemical knowledge reported in the subject. A historical perspective helps to understand why, for example, there are alternative and not entirely consistent definitions of oxidation or acid presented in chemistry courses: something that many students find unhelpful if not bewildering.

This abstract conceptual material includes many models, and in particular structural models which often relate to a submicroscopic scale that is not directly observable (Johnstone, 1982; Taber, 2013b). Often these models have limited ranges of application, or need to be used in complementary ways to explain the range of data available (de Jong & Taber, Forthcoming), and indeed models used in teaching may be anachronistic historic models or hybrids of models that were originally distinct within the discipline itself (Justi & Gilbert, 2000). Again the impression that they are bering taught one 'wrong' idea only for it to be replaced by another is frustrating to students if they do not appreciate the nature of and motivation for these different models.

Whilst the various abstractions students are taught certainly have relevance to (the current practice of, or at least the historical development of) the discipline of chemistry, many students may struggle to appreciate why they should wish to know about Brønsted-Lowry bases, d-level splitting, or antiaromaticity. The question of the relevance of what is taught is therefore an important one.

The notion(s) of relevance

It seems unlikely that there was ever a time when relevance was not *in some sense* a consideration in curriculum planning. Curriculum should start from aims - what the curriculum is intended to achieve. The curriculum programme is then designed accordingly, and teaching schemes should also be planned with those aims in mind. Teaching and learning activities should then be designed to be relevant to the curricular aims.

The aims of science education have shifted over time - or at least the priorities among multiple aims change. Certainly at school level, vocational purposes - preparing learners for further education and workplace needs - have come to be seen as no more important than supporting the development of scientific literacy or civic engagement (Millar & Osborne, 1998). 'Science for all' has become a common slogan. The question of what science, or more specifically what chemistry, will be useful to the future citizen-as-consumer; citizen-as-activist; citizen-as-voter; etc. becomes just as important as asking what chemistry it is useful to teach at one level (say high school) to prepare those students who may aspire to study the subject at some higher level (e.g., as an undergraduate).

Chemistry as a curriculum subject

We might consider why we teach chemistry in school and university. There are a range of possible reasons. One type of rationale is economic. Chemistry has undoubtedly been of great importance in the development of modern societies in supporting the production of materials for a wide range of purposes. No area of modern life is untouched by the products of the chemical industry and ultimately the research chemist - and we are surrounded by materials that have either been processed to extract and purify them from their 'natural' state or indeed have been manufactured from other materials. This often involves the production of new chemical substances, including many that probably only exist as a result of the synthetic work of chemists and would not otherwise be found in the Universe.

Increasing environmental and ecological awareness has led to chemistry being considered, *inter alia*, as one cause of extensive pollution and environmental damage. Yet this only leads to a greater impetus for chemical research and development - to find more efficient production processes that have better yields and require less fuel stocks; to replace toxic or harmful ingredients and components; to provide more effective fuel cells; to develop materials with longer useful lives, and shorter afterlives as junk before decomposing harmfully; to find materials that can be used to remove or neutralise existing pollution, and so on. Chemistry as a school and college subject remains highly relevant to societal needs (Eilks & Rauch, 2012).

However there is a less pragmatic way to understand the curriculum which looks less to societal needs than to the development and formation of the person (Hansen & Olson, 1996). Two somewhat different perspectives may be considered here. One approach is to consider first what skills and qualities we desire in fully formed people, and then how education can support personal growth towards that ideal. Curriculum subjects can contribute by providing opportunities to develop in different ways. The study of sciences, for example, has been considered to contribute to the development of logical patterns of thought and of creative problem-solving skills.

A somewhat different starting point considers the nature of what it is to be human in terms of forms of our culture. Human culture encompasses arts and sports and sciences and politics and so forth - and so a liberal education should provide the learner with access to these important aspects of the culture. The sciences are among the greatest achievements of human culture and every learner should be given the opportunity to understand and appreciate something of key scientific achievements (Snow, 1998). To be a cultured person in the twenty-first century, one needs to understand something of the nature of science.

These different perspectives can be seen as complementary: a person can be educated for enculturation *and* personal growth *and* still develop knowledge and skills that equip them to take up a valued place in the economic system of their society. However, these different perspectives have different emphases and priorities - and so there are tensions between them when making choices about the specific subjects and topics that are included in a curriculum, and in the kinds of learning activities that are most educative.

Changing priorities for structuring chemistry teaching

The organisation of chemistry teaching has been influenced by various perspectives from different strands of educational thinking. Figure 1 caricatures some of the changes that have been seen in thinking about the chemistry curriculum over a period of some decades.

One area of academic focus on chemistry teaching has concerned the nature and structure of the disciplinary material itself. In particular, researchers considered the internal structure of the concepts that might be taught in chemistry with a view to offering a logical analysis. Concept analysis included identifying pre-requisite concepts that needed to be taught earlier in the curriculum before other concepts that (according to the internal logic of the subject) necessarily drew upon them (Herron, Cantu, Ward, & Srinivasan, 1977). This approach puts a focus on the hierarchical structure of concepts. So the concept of covalent bonding can be subsumed under the overarching concept of chemical bonding, and ketones can be classed under carbonyl compounds, etc. Chemistry presents particular challenges in the way that some of its most core concepts - substance, reaction/chemical change - are difficult for students to fully appreciate, and tend to be acquired over extended periods (Taber, 2012). Therefore, although conceptual analysis informs a 'logical' presentation of material, this often has to be taught through a spiral curriculum where ideas are revisited over time (Bruner, 1960). Despite this need for some 'boot-strapping' between key concepts, conceptual structure undoubtedly remains an important consideration when selecting and organising material to be taught in chemistry. *For material to be relevant to learners it has to be sequenced in terms of necessary prior learning.*

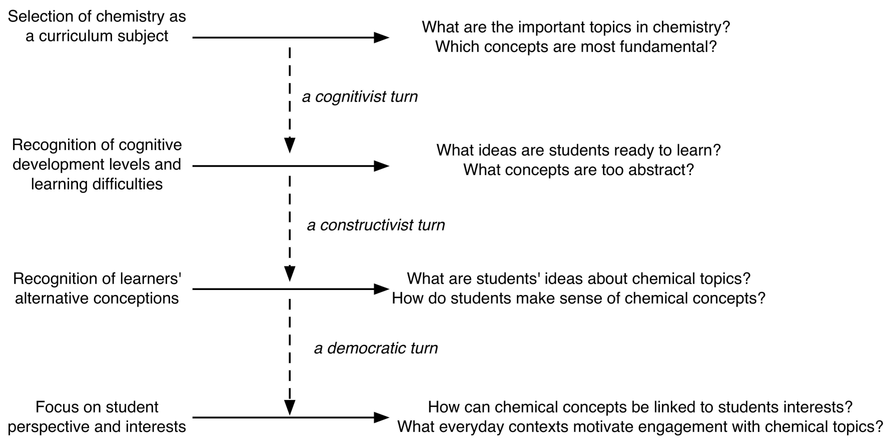

Figure 1. Shifts in focus on course design

Learning difficulties experienced by many students when taught chemistry suggest that content analysis to determine a logical order of presentation might be a necessary, but not a sufficient, condition for effective instruction. In particular the influence of work in the Piagetian tradition suggested that there were inherent limitations in children's and young people's cognition (Bliss, 1995; Piaget, 1970/1972). According to Piaget's model of cognitive development people normally only become able to undertake the kind of thinking needed for much scientific work - being able to mentipulate abstract ideas in mind, operating on them as mental objects - during adolescence. This research programme suggested that much of the science included in secondary level school curriculum was likely to be inaccessible to many of the students being taught as they would not have fully acquired (what is termed) the level of 'formal operations' (Shayer & Adey, 1981).

Of course neither the Piagetian model, nor its consequences, were universally accepted. Followers of Jerome Bruner (who claimed that any child of any age could be taught any topic in an intellectually honest manner) would argue that the findings from Piagetian research should not exclude abstract science concepts, but rather illustrated the pedagogic challenge of presenting such concepts in sufficiently concrete ways for learners to make sense of them. Whichever view was taken, there was something of a 'cognitivist turn' in considering curriculum design that reminded planners that the nature of cognition was as important as the nature of subject matter in thinking about setting out target knowledge for students. This offers a new slant on relevance: *for material to be relevant to learners it has to be accessible to them through their existing cognitive apparatus*. So, for example, lasers in everyday devices (CD players, DVD players, computer drives) may offer a context for teaching about quantum theory that might interest many primary school children, but arguably it may not be relevant in terms of what they are in a position to make good sense of.

Consideration of the cognitive 'architecture' supporting learning and the nature of learning processes supported the increasing influence of 'constructivist' thinking about learning (R. J. Osborne & Wittrock, 1985), and with it work to explore students' thinking in science topics (Driver, 1989; Gilbert, Osborne, & Fensham, 1982). If learning is understood as an active process of interpretation and making sense of sensory input in terms of existing conceptual resources, then effective teaching has to engage with existing understanding. There was something of an explosion of interest in exploring student understanding of various phenomena and concepts relevant to science learning. The research literature offers many accounts of children's and other learners' ideas, misunderstanding, conceptions, mental models and intuitive theories (and various other descriptors are also used) related to acids, the behaviour of gases, chemical bonding, rates of reactions, orbitals, and so forth (Duit, 2009). So there was something of a constructivist turn in thinking about curriculum and pedagogy. For subject matter to be relevant it not only had to be scheduled into teaching schemes in accord with its logical structural relationship with other subject matter; and had to be presented in a form accessible to learners at that stage of development; but also has to be interpretable in turns of the learners' existing knowledge and understanding. The term 'knowledge' is not used here in its limited philosophical sense of necessarily being 'true justified belief' but rather in a wider sense of what someone either believes to be the case or considers as a viable possibility (Taber, 2013a, p. 179).

Ausubel (2000) saw meaningful learning as occurring when presented material was both potentially relatable to a learner's cognitive structure, and indeed became interpreted by the learner through that existing structure. From this perspective relevance could be related to *potential* meaningfulness. *For material to be relevant to learners it has to be relatable to some aspect of their existing conceptual structures for making sense of the world*. It should be noted however that meaningful learning is not necessarily the learning intended or desired by the teacher (Taber, 2014). The canon of constructivist studies offer a good deal of evidence that meaningful learning - making sense of teaching in terms of existing understanding - only sometimes leads to an understanding comparable with canonical target knowledge (Gilbert & Watts, 1983; Taber, 2009).

It is possible then to argue for the relevance of teaching in terms of disciplinary structure; in terms of accessibility in relation to the cognitive demands made on learners; or in terms of being potentially meaningful by being relatable to learners' prior learning (what they have actually learnt, rather than just which prerequisite ideas they have been exposed to in instruction). Discussions of relevance in chemistry teaching have however come to be increasingly seen to be about engagement and motivation through linking with students' interests (J. Osborne & Collins, 2001; Pintrich, Marx, & Boyle, 1993). We might consider this a 'democratic' turn in thinking about curriculum content and how to present it, because it is now widely seen as unreasonable to expect learners to find something relevant simply because some external authority decides it should be taught. Perhaps for some this is a principled shift, related to the student voice movement which argues that learners should have input into aspects of their education, including aspects of curriculum, assessment, and teaching approaches (Edgar W. Jenkins, 2006). For others, this may be a more pragmatic consideration - having perhaps concluded that it is not much fun teaching a wonderful and fascinating subject such as chemistry to a class who are only fascinated by how to avoid doing any work and only wonder about how long they have left till the end of the lesson.

Relevance in terms of student interests

In this approach, topics, projects or examples are chosen not just because they are relevant to chemistry as a subject (and suitably structured, accessible to the students' cognitive level, and potentially meaningful in terms of prior learning) but because they will interest learners, who will see their relevance *beyond* the curriculum. So teachers look to link curriculum topics to learners' extra-curriculum interests and activities both because this will be appreciated by learners, and because this will motivate and engage them by triggering interest in the subject matter. From this perspective, *for material to be relevant to learners it has to be seen by the learners as offering them greater knowledge or skills in a domain of personal interest.* Working from this perspective clearly requires knowledge of students' actual interests - not simply assuming that pupils will be interested in domestic appliances because they are familiar from and useful in the home (Jones & Kirk, 1990). Moreover, having an interest in something does not *necessarily* motivate learning more about it - at least not in technical terms. Our interests may be pragmatic. A chemistry teacher may be fascinated by how chocolate manufactures provide a product that melts in the mouth and has a pleasing texture: many chocolate lovers are simply happy enough that chocolatiers have specialist skills and would not enjoy chocolate any more for understanding its manufacture.

Despite this proviso, there is certainly a valid educational argument here. Before students can learn they need to be attentive to what is being taught. Much we wish to teach in chemistry is abstract and complex, and often chemical principles seem counter-intuitive. Conceptual change has often been found to be something that is hard-won - by scientists as well as novice learners - and relies upon extended (mental) engagement with ideas (Vosniadou, 2008). Ideally we want learners to be in a 'flow' experience where they are engrossed with their work to the exclusion of other distractions (Csikszentmihalyi, 1988) - something that is not typical of learners' experiences in many classrooms and lecture theatres. The starting point, then, is to get students interested in what we are to teach - to provide a 'hook' to pique their interest, and then draw them into chemistry content through its relevance to that initial issue, question or context that they already consider to be of interest and worthy of their engagement.

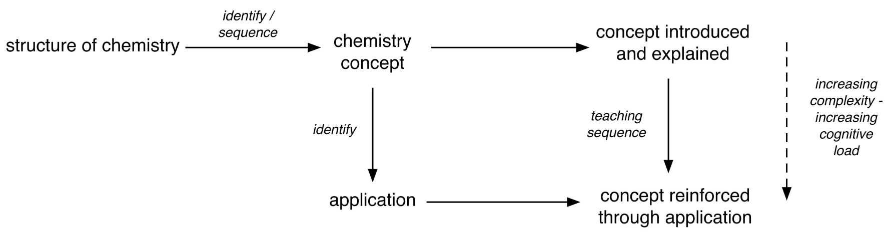

Figure 2. Applications introduced to reinforce teaching of chemical concepts

Re-ordering the presentation of concepts and applications

This approach to some extent reverses the logic of organising teaching *within* a topic. Traditionally (see figure 2) applications of chemical concepts may be discussed after teaching about the concepts themselves. The argument is that students need to understand the concept before they can appreciate how it might be applied. Moreover, from the cognitivist perspective it is important not to overload learners' working memory by asking them to mentipulate too much information in mind at any one time (Baddeley, 2003). From this perspective it is best to teach the concepts, and then once they are well understood, show how they can be applied in various contexts - so reinforcing and helping consolidate understanding of the concepts themselves (Taber, 2013a). In this approach, the topic is selected based on the structure of chemistry as a discipline, and applications are then selected to fit the concepts being taught. So, for example, after considering the nature of chemical equilibrium, the example of the industrial binary synthesis of ammonia might be chosen as one context in which the concept is useful.

A different logic is employed in teaching approaches that start, not from the concept itself, but from discussion of some context where the chemical concept is important.This approach is seen with teaching and learning of chemistry (and other science subjects) through contexts-based courses.The argument here is that the more traditional approach of explaining the science concepts, *and then* presenting applications to show how these ideas are applied should be reversed (see figure 3).

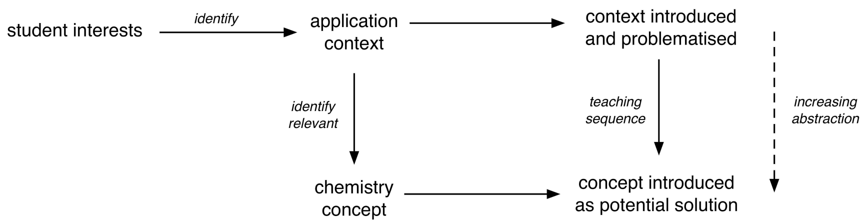

Figure 3.Applications introduced to motivate the learning of chemical concepts

The traditional approach considers cognitive factors: students first have to understand the basic principles, and then they will be in a position to see how they are applied in diverse applications. Logically they cannot make sense of the particular application of the idea until after they understand the basic general principle they are being asked to conceptualise in that specific context. How can a learner apply principles of chemical equilibrium to the Haber process, before they have been taught and developed a clear understanding of what those principles are?

Context-based approaches derive from the view that the traditional approach considers the cognitive aspects of learning, but that these are irrelevant if the learner is *not motivated* to engage in the required cognition. Students, especially younger or less motivated students, it is argued, will not be engaged enough during the presentation of the science to get to the point where they can appreciate the applications. Rather, the logic goes, we should engage students through the presentation of an issue or problem that they can see the relevance of, and then use that as a hook to interest them in some science that may be useful in addressing that issue or problem. From the learner perspective, it is argued, we should start from something that already interests the learner, problematise it, and then show how science explains or offers solutions - introducing the core concepts as they are needed along the way (see figure 3). After all, for most people science is valued for its utility value, rather than developing knowledge for its own sake, so in teaching most learners will be more impressed by how science enables us to do things people want to do rather than because it offers a largely consistent conceptual framework for understanding the world.

An issue that needs to be considered in context-based teaching is that raised by research which suggests student thinking is influenced by context - that the ideas brought to mind in a particular topic area may be quite different depending upon the context in which they are presented (Engel Clough & Driver, 1986; Mestre, Thaden-koch, Dufresne, & Gerace, 2004). However, this applies to academic as well as everyday contexts (Taber, 2000; Teichert, Tien, Anthony, & Rickey, 2008), and might be considered more of a challenge than a problem *per se*. It does however suggest that studying an abstract concept within a particular context offers no assurance of generalisation later to other contexts. This raises the question (perhaps for empirical study) of whether context-led approaches to teaching chemical concepts could shift issues of near-transfer of learning to become more akin to far-transfer (Gilbert, Bulte, & Pilot, 2010; Hammer, Elby, Scherr, & Redish, 2005) if the student perception is less of being asked to apply a familiar concept to an unfamiliar example than being asked about a completely different topic (i.e. context) than that studied .

A recognised problem of context-based teaching is that of designing contexts that both interest students and do motivate the need for the concepts we feel it important to teach. Identifying particular contexts that work as good hooks for particular groups of students is certainly possible (e.g., Stuckey & Eilks, 2014). However, designing a set of contexts that both genuinely links to students' interests and collectively allows us to teach the full range of concepts we would like to include in the chemistry curriculum may be more difficult. The teaching of conventional concept areas may need to be split across several different contexts (which may offer useful opportunities for review and reinforcement of some ideas, but may also lead to fragmentation of concept areas across the course) and the order in which learners meet concepts may require considerable compromises on the kind of 'logical' sequencing that would derive from the conceptual analysis of the discipline itself. Adherents of the context-based approach would argue that any losses in terms of teaching according to the internal logic of the subject are more than outweighed by the increase in student motivation and engagement. This may explain why studies seem to show that generally learners attain similar levels of understanding in context-based courses as in more traditional approaches despite any compromises in terms of disciplinary structure (Bennett, Hogarth, & Lubben, 2003).

Changing priorities in teaching chemistry

As well as the move to teach chemistry concepts through contexts, related to thinking about student motivation and engagement, the teaching of chemistry also responds to changing views about the relative importance of different curriculum aims. One example might be the recognition that it is important for all citizens to understand about environmental issues, and the role that 'green chemistry' can play in contributing to a less polluted and more energy-efficient world (Emsley, 2010).

Another example might be the increased recognition of the potential of inquiry-based teaching and learning and the importance of offering learners authentic experience of scientific enquiry as a context for developing their enquiry skills (Alsop & Bowen, 2009; Lawson, 2010; Taber, 2011a). Experience of formally assessed 'investigations' in secondary science in the English context (Edgar W. Jenkins, 2000) became little more than exercises in following instructions in how to score marks given the high status of the outcomes (for students, teachers and schools). Even when students followed through on the full inquiry cycle in one assessment, there was little clear value in 'investigating' such issues as how reaction rate varied with the concentration of acid or temperature of a solution when all the students would already be aware of the expected results. Such 'investigations' were *relevant to assessment schemes*, but had little relevance to scientific inquiry, to learning authentic enquiry skills, or indeed to any questions that the students might genuinely be looking for an answer to.

Risking losing the baby: relevance as an contended notion

It seems then that there are different possible notions of what we might mean by relevance in chemistry education (cf. Stuckey, Hofstein, Mamlok-Naaman, & Eilks, 2013), each likely to inform the selection, sequencing and presentation of materials in different ways (see Figure 4). These different considerations are not always necessarily in opposition to each other, but they do present different priorities and this can lead to tensions in making judgements about the planning of teaching. There is a saying to 'throw out the baby with the bath water' meaning to make changes that lose what is valued in the current situation as well as what is considered to need replacing. There is a danger when shifting from judging relevance in terms of discipline and conceptual structure to considering relevance in terms of student interests that one might lose the coherence and central chemical character of a course in order to jettison an approach judged not to sufficiently engage learners.

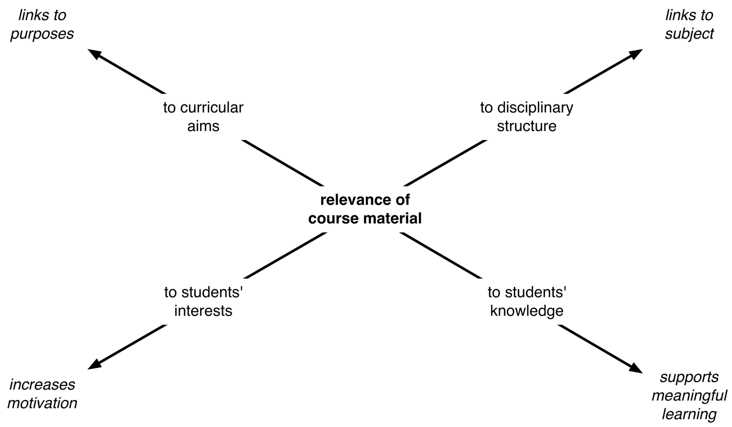

Figure 4. Different forms of relevance

Similarly, a shift from judging relevance in terms of the structure of chemistry to considering relevance to societal issues also brings risks. Science educators have strongly argued for science education which develops an understanding of the way science impacts upon society, is channelled by societal pressures, and feeds into discussion of key issues faced by communities (Sadler, 2011; Sadler & Zeidler, 2009). Here our curricular aims, our purposes, may be as much about understanding science in society and the politics of science and the way science is used and abused in politics, as about understanding scientific concepts. Arguably such an understanding is at least as important for future citizens as understanding the concepts themselves (E W Jenkins, 1999). What is clear however is that class time and teacher input (into planning, into developing materials, into supporting learners) are finite and limited resources: and prioritising teaching about science in social contexts inevitably puts less emphasis on the science itself. Indeed, to use the English context as an example again, the decision to reduce the prescribed subject (i.e. science) content in the National Curriculum to allow more time for broader educational aims related to science for citizenship (QCA, 2007a, 2007b) led to a strong campaign of criticism that characterised the revised curriculum as only being fit to support discussion of science at the level found in the pub (i.e. public house, a place for social conversation and drinking), and not suitable as a genuine science education (Perks, 2006). Whilst such criticisms can sometimes fail to appreciate the significance of important broad aims of science education they do remind us that greater relevance to the needs of the learner as future citizen may - just as prioritising a focus on the relevance of teaching and learning to students' current interests - require some compromise on the relevance of teaching and learning to the internal logic and structures of the science disciplines.

The needs of the few?

Sometimes the questions raised here are framed in terms of the needs of the many versus the needs of the few. A minority of students will select chemistry as a post-compulsory subject. Quite a small proportion of the school population will choose to specialise in chemistry and undertake degree studies to become a chemist, and then go on to work professionally as chemists. Perhaps, it may be argued, this few would make better progress if chemistry teaching was structured primarily in accord with the logic of the subject. However, these are not only a small fraction of the population, but they are going to be among the more capable learners, who will surely cope with a slightly less coherent path to expertise. It seems to make little sense to design a curriculum for all learners primarily in terms of the needs of this small group.

The assumptions behind this argument might be characterised as:

1. Most students benefit greatly from a curriculum which compromises the structural coherence of the discipline in order to either (a) prioritise student engagement with learning; and/or (b) emphasise science for citizenship over science for its own sake;
2. The main advantage of prioritising disciplinary relevance within curriculum design is to support the learning of those few who will go on to specialise in the subject, and this requires putting the interests of this small group over the needs of the wider cohort;
3. Any losses in terms of limiting the progress of the few in coming to better understand the conceptual content and structure of chemistry can be readily made up once those individuals enter specialist courses at university level .

The present chapter derives from a perspective which recognises some strengths in this position - but also some important weaknesses. There is certainly an argument that the needs of the most able learners are not always being met when the disciplinary structure of a subject is down played, but what is easily missed is the potential value of *disciplinary relevance* to learners in general. That is, we may indeed be in danger of discarding a baby that needs nurturing as we empty out its soiled bathwater.

The needs of the gifted learners

Various terms are used to describe students who show particular ability and aptitude in academic areas. Here I am using the term 'gifted', although I am aware that has unfortunate connotations (of something inborn, fixed) for some people. Alternative terms include the highly able or the talented. The area of gifted education is complex, and there is no clear consensus on important questions such as what is meant by gifted; how best to identify gifted learners; how broad such gifts need to be to deserve special attention in education; and what kind of special provision - if any - is appropriate for gifted learners (Taber, 2007). Whilst gifted education is a major issue in some educational contexts, there has been a rather modest focus within the scholarly literature on gifted education in science education or chemistry education more specifically.

Despite these provisos, it seems undeniable that students vary considerably in their level of attainment in academic subjects such that a minority of students in any year-cohort are likely to be capable of working at a level that far exceeds what their more typical classmates can currently manage. This can present a major challenge for teachers. Setting (and in-class setting), acceleration, enrichment classes, peer tutoring, differential support, individualised working etc., may all be adopted to some degree in different contexts (NDoE, 1997; Stepanek, 1999).

The gifted are certainly not a discrete category - as attainment, and the abilities that support it, vary on continuous scales. So there is always a demarcation issue of where to 'draw the line' between gifted and simply able or highly achieving that may make us cautious in employing labels such as 'gifted'. Development is not uniform and even - so a student who is seen as gifted at one point in their school career may not see so especially capable some years earlier or later. Of course, what a person is capable of today depends in part on the developmental experiences, and so opportunities, they have been through - so in societies where opportunities are inevitably unequal due to the reality of impoverished or advantaged upbringing we would expect students from some socio-economic backgrounds to be over-represented among those we might label as gifted.

Moreover, a student who is exceptionally strong at (for example) using mathematics in chemistry, may not be exceptional in some other areas of the subject. Some students who appear highly gifted in their oral performance in class may be limited in their written work by modest literacy, and there are indeed students sometimes labelled 'twice exceptional' who show gifted characteristics in some curriculum contexts whilst also being diagnosed with specific learning difficulties (Winstanley, 2007). Such consideration may also make us wary to label students.

However, if we ignore the issue there will be learners in many classes who are not being offered genuine educational opportunities in their lessons. According to Vygotsky's (1934/1986, 1978) model of development, learners will make progress when they are scaffolded to achieve more than they can currently achieve unaided in their zone of next (or proximal) development. Ignoring the phenomenon of gifted learners will often equate to asking some students to undertake work which is within their zone of actual development, where they may hone their existing skills and knowledge, but have few opportunities to move beyond what they can already do.

The challenge of developing post-formal thinking for all students

In common treatments of Piaget's theory of development, the fourth major stage, formal operations, is considered as the highest level of development. It has been considered as necessary for scientific thinking because it enables a person to apply logical thought patterns to abstractions. Not only can the person at formal operational level form abstract representations of objects, but they can treat these 'mental objects' as the subject of further mental operations. This kind of mentipulation is considered characteristic of, and so necessary for, scientific thinking. Indeed science contexts have been presented as suitable for encouraging the development of formal operations among early adolescents, and so that 'cognitive acceleration' can result from suitably structured and scaffolded engagement in science learning activities (Adey, 1999; Adey & Shayer, 2002). From this perspective, traditional inductive science learning activities requiring the recognition and testing of abstract patterns in data remain a valuable part of any science curriculum.

However, there are good reasons to think that formal operations is a necessary but not sufficient facility for scientific thinking. For one thing, as Kuhn (T. S. Kuhn, 1977) pointed out, science proceeds through an essential tension between the convergent thinking associated with testing experimental ideas, and the divergent thinking needed to look beyond existing scientific concepts. Science, even in periods of non-revolutionary 'normal' science (T. S. Kuhn, 1996), depends upon creative thinking to generate the ideas that logical thought will operate upon during critique (Taber, 2011b). Moreover, logical thinking is an excellent tool when we have complete, clean data sets that match one or other theoretical possibility: but is limited in responding to fuzzy situations characterised by incomplete information of uncertain quality.

Some scholars have described a 'fifth stage' (Arlin, 1975) of 'post-formal' (Kramer, 1983; Sternberg, 2009) operations that characterises the kind of thinking needed to deal with the complexity and uncertainty often faced in real-world problem solving (and this would include much front-line scientific work that has not been simplified and bowdlerised to make it seem suitable for classroom presentation; as well as many socio-scientific issues). Research suggests that adolescents and even college students do not readily deal well with the complexities of real-life problems (Perry, 1970), and that commonly students respond to the loss of certainty when faced with fuzzy, complex issues by a retreat into relativism: so when there is no clear right answer, then (students decide) all possible answers are equally acceptable and selection is little more than opinion or personal taste (D. Kuhn, 1999).

This should be a major issue for education, and science education in particular. Science, unlike mathematics, does not claim to produce certain knowledge but rather a provisional form of knowledge that is always open to new evidence and alternative perspectives (Taber, 2008b). Yet we do have criteria for evaluating scientific ideas - such as conceptual coherence (Taber, 2008a) - , and science offers robust and not just arbitrary knowledge. This is just the kind of complex issue that most (school and even college) students are not ready to fully deal with (Perry, 1970), inviting relativistic judgements:

- If science cannot be absolutely sure, then astronomy is no better than astrology;
- If evolution is 'just' a theory, then it is on par with the ideas of young-earth creationists;
- If scientists cannot all agree on the extent to which climate change is due to anthropocentric inputs into the atmosphere, then we can choose not to believe it, or at least not to worry until scientists get their act together and all agree on what the evidence means.

Arguably one of the key tasks of science education is to help learners understand how science can be both generally reliable yet concerned with producing fundamentally uncertain knowledge (Taber, 2008b) - as this is a key basis for understanding science in the context of citizenship, political debate, social issues and personal decision-making. Science can tell us about the costs, risks and possibilities of nuclear energy, genetic engineering, kidney transplants, recycling waste, rooftop solar panels, hormone replacement therapy, and upgrading our broadband service. Science cannot however tell us what decisions to take about such matters. Research tells us that by the end of schooling many students are able to apply scientific concepts in unambiguous contexts - but are not ready to deal with the uncertainty and patchy information characteristic of the problems and situations characteristic of much human experience beyond the simplifications of the classroom.

The developmental relevance of theoretical chemistry: Cognitive acceleration through chemistry education

If science education has been shown to be valuable in helping students acquire formal operational thought - then perhaps it also has potential to support development of post-formal thinking as well. Cognitive acceleration through science education (Adey, 1992) has drawn upon contexts where there are physical patterns to be found (such as the principle of moments) by helping students practice the control of variables and fair testing. Perhaps supporting learners in the next stage of development requires similarly carefully scaffolded engagement in working in contexts where patterns are less clear cut, where there are more variables to be considered (not all of which can be controlled at any time), and where data sets may more often be incomplete or imprecise. Rather than leading learners to simple clear preferred conclusions (such as the principle of moments) sometimes learners may have to settle for several complementary models with different preferred ranges of application.

Arguably the social sciences could provide relevant contexts here - and indeed those gifted students who are operating effectively with post-formal thinking whilst still at school may (sadly) find history and social studies more engaging and challenging than the sciences with their tendency to focus on 'right' answers and canonical theories. However, an authentic science education, one that offered insight into science in the making and not just the resulting rhetoric of conclusions (Niaz & Rodriguez, 2000), could certainly hold its own against the social sciences.

Chemistry, in particular, is a discipline that has an extensive set of concepts, principles and theories that provide useful thinking tools, but which lack the law-like nature of so much taught in physics. It has been argued that many ways chemistry is an idea subject to challenge the most able learners who thrive on the theoretical, and relish having to make sense of complexity (Taber, 2010). This logic can however be extended. All adolescents need to be supported in dealing with uncertainty and complexity without simply retreating into relativism, and accepting that 'anything goes'. The theoretical problems and conceptual tools of chemistry offer just the intellectual challenge that some of the most able are ready for and thrive upon. Many other students will require considerable support in this area - so suitable scaffolding will need to be provided, and then faded as students develop.

Offering epistemological relevance for teaching chemical theory

For many of the most able students, then, the abstract and theoretical nature of chemistry can be a welcome opportunity to stretch themselves intellectually. This aspect of chemistry also offers potential educational experiences that can be of value to all learners in terms of supporting cognitive development, but there remains the problem of theory appearing not only abstract, but somewhat arbitrary and of little personal relevance. As suggested above, it is this consideration which often leads to a decision to teach through contexts and applications which can motivate the need to introduce particular knowledge, skills, concepts - but may mean that concepts are introduced in isolated ways detached from the disciplinary context.

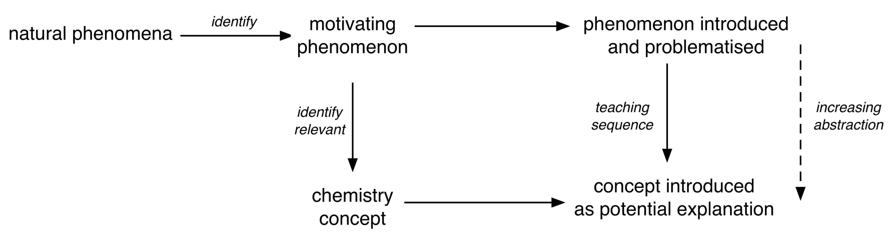

Figure 5: Epistemic relevance for introducing chemical concepts

An alternative approach is to revisit the history of the subject, and consider the original motivation for the creation of the ideas which have have become part of the theoretical toolkit of chemistry (cf. Allchin, 2013). Chemical concepts are introduced as a means to help make sense of phenomena studied in the laboratory, and principles and theories are put forward as a means to explain and relate different aspects of phenomena. Every canonical concept started out as a conceptualisation formed by some individual looking to make personal sense of some aspect of chemistry. Science is motivated by awe and wonder, and an epistemic hunger to better understand. Yet planning education in these terms has become tainted as elitist as most young people do not aim to be scientists. However, most young children tend to be 'natural scientists' in terms of their curiosity and drive to explore and make sense of their environment. This suggests that if teaching starts from phenomena, then these naturally motivate a need to label, characterise and explain (see figure 5).

It is widely found that learners are often fascinated by simple chemical phenomena in lower secondary school, but many become disenchanted as they pass through the school and lessons often become more theoretical. Chemistry as a discipline is certainly highly theoretical, but as a science it develops through the interaction of theory and experiment. Courses that consist of sequences of theoretical topics, with practical work apparently bolted on to teach the theory reverse the logic of the subject, and are not authentic in offering insight into the interplay between theory and experiment at the heart of the discipline. Perhaps a major problem with chemistry teaching is that too often it has short-cut the awe and wonder by moving from bang and smells (attention grabbing, but atheoretical) in introductory classes, to de-contextualised theory (challenging, but lacking relevance) in more advanced grades, sometimes supplemented by practical work designed to meet assessment needs rather than providing experience of the chemistry (Taber, 2008b). Perhaps in part this relates to health and safety concerns, but with the increasing availability of high quality videos of chemical processes to supplement laboratory work students can vicariously experience the toxic and extreme without being exposed to the risk. It would be interesting to see how students responded to a chemistry course designed from the structure of the discipline and based around making sense of chemical phenomena, and that introduced concepts and theories as they were motivated by the need to better make sense of nature itself.

Conclusion

This chapter is offered as a warning against incautious enthusiasm for chemistry teaching that is organised around contexts intended to reflect students' own interests regardless of the cost to maintaining other kinds of relevance that are important in curriculum development and lesson planning. Teaching through contexts assumes that students are motivated by everyday contexts that can be presented as applications of chemistry - rather than motivated by an epistemic hunger to make better sense of the natural world. In many cases this may indeed be so - but we should not forget that many young people (and arguably in particular many who are likely to be attracted to science) may be fascinated by the apparent mysteries of natural phenomena and the ideas, concepts, and theories that can allow us to build up models and explanations of our world. These learners may be especially impressed with how science as an enterprise aspires to develop a coherent conceptual framework where new conceptual bricks are expected to be fit within a the existing edifice - something that may not always be fully recognised by high achieving students (Taber, 2008a) and may be especially hard to appreciate if science subjects are taught in a piece-meal way without strong reference to overarching concepts and disciplinary structure. Perhaps this is not the most pressing consideration when working with some student groups, but it may be very relevant for ('gifted' and other high achieving) learners in some classes.

If we assume that everyday contexts do often motivate student interest then we run into new challenges. We have to identify suitable contexts that both enthuse students and link to the chemistry we feel we should teach. One problem here is that chemistry is a fundamental science about substances and their purification, identification, characterisation and reactions: whereas many suitable applications may offer better contexts for teaching about materials rather than substances. Materials science builds upon chemistry - but as a science needs to be built upon an existing understanding of chemistry.

Perhaps even more serious in some ways is the question of fairness and equity. If we select chemistry topics for a course in terms of disciplinary relevance, and some students are more interested than others in the chemical phenomena and our associated concepts and explanations, then those who are not engaged are at least basing their disinterest on the nature of the subject. If instead we seek to teach chemistry through topics such as, say, Formula 1 motor racing technology, or fabrics used in the fashion industry, then we are introducing an immediate bias in terms of which students have existing knowledge, and indeed any interest, in that particular topic (Taber, 2003). This criticism is perhaps assuaged if we select contexts recognised to be major socio-cultural issues we would want *all* students to learn about in their own right - energy sources, climate change, environmental protection, quality control in food and medicines - but the problem of fitting issues to a broad and integrated conceptual framework for the subject remains.

The argument here is not that context-based teaching is necessarily a bad thing, and certainly not that the design of all chemistry teaching should be solely or primarily focused on the history and logic of disciplinary structure. Rather the argument is that there are different forms of relevance that need to be taken into account in considering how to make chemistry teaching relevant to learners (Stuckey et al., 2013) and epistemic relevance, and potential to support cognitive development needs to be considered. We have a range of potential curriculum aims, and these might direct us to make different choices with different groups of learners, or at least to adopt a different profile of responses to the different imperatives with different students or groups. If we want science teaching to contribute to the development of the whole person, then some of the more conceptual and theoretical nature of chemistry (with its multiple models) may actually offer a useful basis for supporting the development of post-formal thinking. If we want students to experience something of the awe and wonder that many scientists feel about natural phenomena and the intellectual excitement of science, then organising some teaching to give an authentic flavour of how and why chemical concepts, models and theories are proposed and modified in response to the natural phenomena themselves may provide a valuable form of epistemic relevance. There is a place for context-based teaching, problem-based learning, inquiry-based courses, and various other ways of organising chemistry teaching that might seem more progressive and student-friendly. But if such innovations need to come at the cost of students failing to see any overall disciplinary structure within the diverse chemical ideas they meet, and reversing the logic of scientific development (so starting from existing technology, rather than from the observable natural phenomena that sparks the desire to understand) then the chemical baby might well find itself abandoned with its soiled curricular bathwater.

References

Adey, P. (1992). The CASE results: implications for science teaching. *International Journal of Science Education, 21*(5), 553-576.

Adey, P. (1999). *The Science of Thinking, and Science For Thinking: a description of Cognitive Acceleration through Science Education (CASE)*. Geneva: International Bureau of Education (UNESCO).

Adey, P., & Shayer, M. (2002). An exploration of long-term far-transfer effects following an extended intervention program in the high school science curriculum. In C. Desforges & R. Fox (Eds.), *Teaching and Learning: The Essential Readings* (pp. 173-209). Oxford: Blackwell Publishing.

Allchin, D. (2013). *Teaching the nature of Science: Perspectives and Resources*. Saint Paul, Minnesota: SHiPS Educational Press.

Alsop, S., & Bowen, M. G. (2009). Inquiry science as a language of possibility in troubled times. In W.-M. Roth & K. Tobin (Eds.), *Handbook of Research in North America* (pp. 49-60). Rotterdam, The Netherlands: Sense Publishers.

Arlin, P. K. (1975). Cognitive development in adulthood: a fifth stage? *Developmental Psychology, 11*(5), 602-606.

Ausubel, D. P. (2000). *The Acquisition and Retention of Knowledge: a cognitive view*. Dordrecht: Kluwer Academic Publishers.

Baddeley, A. D. (2003). Working memory: looking back and looking forward. [10.1038/nrn1201]. *Nature Reviews Neuroscience, 4*(10), 829-839.

Bennett, J., Hogarth, S., & Lubben, F. (2003). *A systematic review of the effects of context-based and Science-Technology-Society (STS) approaches in the teaching of secondary science: Review conducted by the TTA-supported Science Review Group*. London: EPPI-Centre, Social Science Research Unit, Institute of Education, University of London.

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

Bruner, J. S. (1960). *The Process of Education*. New York: Vintage Books.

Csikszentmihalyi, M. (1988). The flow experience and its significance for human psychology. In M. C. Csikszentmihalyi, I. S. (Ed.), *Optimal Experience: Psychological studies of flow in consciousness* (pp. 15-35). Cambridge: Cambridge University Press.

Danili, E., & Reid, N. (2004). Some strategies to improve performance in school chemistry, based on two cognitive factors. *Research in Science & Technological Education, 22*(2), 203-226. doi: 10.1080/0263514042000290903

de Jong, O., & Taber, K. S. (Forthcoming). Teaching and learning the many faces of chemistry. In N. Lederman (Ed.), *Handbook of Research in Science Education* (Vol. 2). New York: Routledge.

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

Duit, R. (2009). *Bibliography - Students' and Teachers' Conceptions and Science Education*. Kiel, Germany: IPN - Leibniz Institute for Science and Mathematics Education.

Eilks, I., & Rauch, F. (2012). Sustainable development and green chemistry in chemistry education. [10.1039/C2RP90003C]. *Chemistry Education Research and Practice, 13*(2), 57-58. doi: 10.1039/c2rp90003c

Emsley, J. (2010). *A healthy, wealthy, sustainable world*. Cambridge: RSC Publishing.

Engel Clough, E., & Driver, R. (1986). A study of consistency in the use of students' conceptual frameworks across different task contexts. *Science Education, 70*, 473-496.

Gilbert, J. K., Bulte, A. M. W., & Pilot, A. (2010). Concept Development and Transfer in Context-Based Science Education. *International Journal of Science Education, 33*(6), 817-837. doi: 10.1080/09500693.2010.493185

Gilbert, J. K., Osborne, R. J., & Fensham, P. J. (1982). Children's science and its consequences for teaching. *Science Education, 66*(4), 623-633.

Gilbert, J. K., & Watts, D. M. (1983). Concepts, misconceptions and alternative conceptions: changing perspectives in science education. *Studies in Science Education, 10*(1), 61-98.

Hammer, D., Elby, A., Scherr, R. E., & Redish, E. F. (2005). Resources, framing, and transfer. In J. P. Mestre (Ed.), *Transfer of Learning: from a Modern Multidisciplinary Perspective* (pp. 89-119). Greenwich, CT: Information Age Publishing.

Hansen, K.-H., & Olson, J. (1996). How teachers construe curriculum integration: the Science, Technology, Society (sts) movement as Bildung. *Journal of Curriculum Studies, 28*(6), 669-682. doi: 10.1080/0022027980280603

Herron, J. D., Cantu, L., Ward, R., & Srinivasan, V. (1977). Problems associated with concept analysis. *Science Education, 61*(2), 185-199.

Jenkins, E. W. (1999). School science, citizenship and the public understanding of science. *International Journal of Science Education, 21*(7), 703-710.

Jenkins, E. W. (2000). The impact of the national curriculum on secondary school science teaching in England and Wales. *International Journal of Science Education, 22*(3), 325-336. doi: 10.1080/095006900289903

Jenkins, E. W. (2006). The Student Voice and School Science Education. *Studies in Science Education, 42*(1), 49 - 88.

Johnstone, A. H. (1982). Macro- and microchemsitry. [Notes and correspondence]. *School Science Review, 64*(227), 377-379.

Jones, A. T., & Kirk, C. M. (1990). Gender differences in students' interests in applications of school physics. *Physics Education, 25*(6), 308.

Justi, R., & Gilbert, J. K. (2000). History and philosophy of science through models: some challenges in the case of 'the atom'. *International Journal of Science Education, 22*(9), 993-1009.

Kramer, D.A. (1983). Post-formal operations? A need for further conceptualization. *Human Development, 26*, 91-105.

Kuhn, D. (1999). A Developmental Model of Critical Thinking. *Educational Researcher, 28*(2), 16-46.

Kuhn, T. S. (1996). *The Structure of Scientific Revolutions* (3rd ed.). Chicago: University of Chicago.

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

Lawson, A. E. (2010). *Teaching Inquiry Science in Middle and Secondary Schools*. Thousand Oaks, California: Sage Publications.

Mestre, J. P., Thaden-koch, T. C., Dufresne, R. J., & Gerace, W. J. (2004). The dependence of knowledge depolyment on context among physics novices. In E. F. Redish & M. Vicentini (Eds.), *Research on Physics Education* (pp. 367-408). Bologna/Amsterdam: Italian Physical Society/IOS Press.

Millar, R., & Osborne, J. (1998). *Beyond 2000: Science education for the future*. London: King's College.

NDoE. (1997). *Promising Curriculum and Instructional Practices for High-Ability Learners Manual*. Lincoln, Nebraska: Nebraska Department of Education.

Niaz, M., & Rodriguez, M. A. (2000). Teaching chemistry as a rhetoric of conclusions or heuristic principles - a history and philosophy of science perspective. *Chemistry Education: Research and Practice in Europe, 1*(3), 315-322.

Osborne, J., & Collins, S. (2001). Pupils' views of the role and value of the science curriculum: A focus-group study. *International Journal of Science Education, 23*(5), 441-467. doi: 10.1080/09500690010006518

Osborne, R. J., & Wittrock, M. C. (1985). The generative learning model and its implications for science education. *Studies in Science Education, 12*, 59-87.

Perks, D. (2006). What is science education for? In T. Gilland (Ed.), *What is Science Education for?* (pp. 9-33). London: Academy of Ideas.

Perry, W. G. (1970). *Forms of intellectual and ethical development in the college years: a scheme*. New York: Holt, Rinehart & Winston.

Piaget, J. (1970/1972). *The Principles of Genetic Epistemology* (W. Mays, Trans.). London: Routledge & Kegan Paul.

Pintrich, P. R., Marx, R. W., & Boyle, R. A. (1993). Beyond cold conceptual change: the role of motivational beliefs and classroom contextual factors in the process of conceptual change,. *Review of Educational Research, 63*(2), 167-199.

QCA. (2007a). *Science: Programme of study for key stage 3 and attainment targets*. London: Qualifications and Curriculum Authority.

QCA. (2007b). *Science: Programme of study for key stage 4*. London: Qualifications and Curriculum Authority.

Sadler, T. D. (Ed.). (2011). *Socio-scientific Issues in the Classroom: Teaching, learning and research* (Vol. 39). Dordrecht: Springer.

Sadler, T. D., & Zeidler, D. L. (2009). Scientific literacy, PISA, and socioscientific discourse: Assessment for progressive aims of science education. *Journal of Research in Science Teaching, 46*(8), 909-921. doi: 10.1002/tea.20327

Shayer, M., & Adey, P. (1981). *Towards a Science of Science Teaching: Cognitive development and curriculum demand*. Oxford: Heinemann Educational Books.

Snow, C. P. (1998). *The Two Cultures*. Cambridge: Cambridge University Press.

Stepanek, J. (1999). *Meeting the Needs of Gifted Students: Differentiating Mathematics and Science Instruction*. Portland, Oregon: Northwest Regional Educational Laboratory.

Sternberg, R. J. (2009). A balance theory of wisdom. In J. C. Kaufman & E. L. Grigorenko (Eds.), *The Essential Sternberg: Essays on intelligence, psychology and education* (pp. 353-375). New York: Springer.

Stuckey, M., & Eilks, I. (2014). Increasing student motivation and the perception of chemistry's relevance in the classroom by learning about tattooing from a chemical and societal view. [10.1039/C3RP00146F]. *Chemistry Education Research and Practice*. doi: 10.1039/c3rp00146f

Stuckey, M., Hofstein, A., Mamlok-Naaman, R., & Eilks, I. (2013). The meaning of 'relevance' in science education and its implications for the science curriculum. *Studies in Science Education, 49*(1), 1-34. doi: 10.1080/03057267.2013.802463

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

Taber, K. S. (2003). Examining structure and context - questioning the nature and purpose of summative assessment. *School Science Review, 85*(311), 35-41.

Taber, K. S. (2007). Science education for gifted learners? In K. S. Taber (Ed.), *Science Education for Gifted Learners* (pp. 1-14). London: Routledge.

Taber, K. S. (2008a). Exploring conceptual integration in student thinking: evidence from a case study. *International Journal of Science Education, 30*(14), 1915-1943. doi: 10.1080/09500690701589404

Taber, K. S. (2008b). Towards a curricular model of the nature of science. *Science & Education, 17*(2-3), 179-218. doi: 10.1007/s11191-006-9056-4

Taber, K. S. (2009). *Progressing Science Education: Constructing the scientific research programme into the contingent nature of learning science*. Dordrecht: Springer.

Taber, K. S. (2010). Challenging gifted learners: general principles for science educators; and exemplification in the context of teaching chemistry. *Science Education International, 21*(1), 5-30.

Taber, K. S. (2011a). Inquiry teaching, constructivist instruction and effective pedagogy. *Teacher Development, 15*(2), 257-264. doi: 10.1080/13664530.2011.571515

Taber, K. S. (2011b). The natures of scientific thinking: creativity as the handmaiden to logic in the development of public and personal knowledge. In M. S. Khine (Ed.), *Advances in the Nature of Science Research - Concepts and Methodologies* (pp. 51-74). Dordrecht: Springer.

Taber, K. S. (2012). Key concepts in chemistry. In K. S. Taber (Ed.), *Teaching Secondary Chemistry* (2nd ed., pp. 1-47). London: Hodder Education.

Taber, K. S. (2013a). *Modelling Learners and Learning in Science Education: Developing representations of concepts, conceptual structure and conceptual change to inform teaching and research*. Dordrecht: Springer.

Taber, K. S. (2013b). Revisiting the chemistry triplet: drawing upon the nature of chemical knowledge and the psychology of learning to inform chemistry education. *Chemistry Education Research and Practice, 14*(2), 156-168. doi: 10.1039/C3RP00012E

Taber, K. S. (2014). *Student Thinking and Learning in Science: Perspectives on the Nature and Development of Learners' Ideas*. New York: Routledge.

Teichert, M. A., Tien, L. T., Anthony, S., & Rickey, D. (2008). Effects of Context on Students' Molecular-Level Ideas. *International Journal of Science Education, 30*(8), 1095-1114. doi: 10.1080/09500690701355301

Vosniadou, S. (Ed.). (2008). *International Handbook of Research on Conceptual Change*. London: Routledge.

Vygotsky, L. S. (1934/1986). *Thought and Language*. London: MIT Press.

Vygotsky, L. S. (1978). *Mind in Society: The development of higher psychological processes*. Cambridge, Massachusetts: Harvard University Press.

Winstanley, C. (2007). Gifted science learners with special educational needs. In K. S. Taber (Ed.), *Science Education for Gifted Learners* (pp. 32-44). London: Routledge.

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