science-education-research.com

This is the author's manuscript version.

The version of record is:
Taber, K. S. (2015). The role of conceptual integration in understanding and learning chemistry.
In J. García-Martínez & E. Serrano-Torregrosa (Eds.), Chemistry Education: Best Practices, Opportunities and Trends (pp. 375-394): Wiley-VCH Verlag GmbH & Co. KGaA.

https://onlinelibrary.wiley.com/doi/10.1002/9783527679300.ch15

Chapter 10

The Role of Conceptual Integration in Understanding and Learning Chemistry

Keith S. Taber

Abstract

Conceptual integration - that is, being able to relate different concepts within a coherent overall structure - can be understood to be important in the learning of science subjects from two quite different perspectives. From the perspective of the theory of learning, the linking of concepts within current understanding is considered to facilitate further learning and later accessing of that learning: the learner with a well-integrated conceptual framework for a subject will tend to be an effective learner in that subject. In addition, conceptual integration within the sciences can be seen to reflect the nature of science (NOS) itself. Within science subjects, learning about NOS itself is increasingly considered a central curricular aim. In science, coherence between theories, and the subsuming of concepts under a limited number of key principles, are highly valued, and science education should reflect and represent such values. In this regard, the nature of chemistry offers particular challenges. One particular issue in chemistry education is helping students to relate ideas about the submicroscopic realm of molecules, ions and electrons to the macroscopic description of the subject. In addition, the nature of much chemical knowledge is in the form of typologies, categorisations and models that often seem to the learner to be offering distinct alternative descriptions (such as different definitions of acids; different models of atomic structure; etc).

Keywords: conceptual integration; conceptual structure; conceptual coherence, conceptual inductive effect; multiple models

10.1 Concepts, coherence and conceptual integration

This chapter explores the idea of conceptual integration in science, and in chemistry education, in order to suggest that conceptual integration should be a major focus of work in chemistry education (and science education more widely). There has been limited explicit research into this area, despite its clear significance for teaching chemistry and other subjects. It is considered that conceptual integration should be an explicit aim of science education, and given a much higher profile in both research into student understanding of science and in science teaching itself. However, chemistry as a subject offers particular challenges in terms of demonstrating conceptual coherence (a prerequisite for effective integration), as it heavily draws upon both (i) concepts that have shifted over time and (ii) multiple models and representations that are used as complementary ways of understanding target concepts. As the theme of the present chapter is conceptual integration, it is useful to begin by explaining how that term is understood here.

10. 1.1 The nature of concepts

There is an extensive literature on the nature of concepts and related themes such as concept acquisition, formation and development [1-3]. Gilbert and Watts [4] pointed out that the term ‘concept’ is widely used to refer to both “an individual's psychological, personal, knowledge structure *and to* the organisation of public knowledge systems” (p. 64-65, present author’s emphasis), and they suggested that the term ‘conception’ should “be used to focus on the personalised theorising and hypothesising of individuals” (p.69). This is an important consideration in science education where it is often important to distinguish learners’ (often alternative) conceptions from the canonical concepts represented in the curriculum.

Yet there is a potential problem with this distinction that becomes apparent if we ask what kind of ‘things’ concepts are. Concepts are mental features - mental objects (categories) or actions (discriminations) - that are part of how humans make sense of the world. Consider as examples the concepts ‘acid’ and ‘delocalisation’. Acids exist in the world, or at least there are entities in the world that chemists class as acids. However, arguably *the concept of* acid is not part of the physical world, but only exists in minds. Of course many acids existed in the world before anyone came up with the idea of an acid, but without the concept no discriminations could be made to identify acids. The acid *concept* has shifted historically such that what precisely should be classed as an acid has changed over time [5]. The nature of particular substances that have been classified as acids has not changed, but whether they can canonically be considered acids certainly has.

So *there is a sense* in which acids only exist in human minds. That is not to adopt an idealist position that the material world is only a construction of the human mind. Rather, even if one adopts a realist position that the material world has existence independent of human minds (which is surely a pre-requisite commitment for natural science) our thinking about it is structured through mental constructions such as concepts. There are regularities in the natural world (another basic commitment of natural science) and we might see the role of science as being to develop conceptual schemes that make the best sense of those regularities [3] . However, whilst the regularities are external to minds, their perception and conceptualisation occur in the cognitive systems of individual human beings. Acids, as substances, exist regardless of what we think - acids *as acids* only exist when we make those discriminations within a conceptual framework.

Unlike ‘acid’, ‘delocalisation’ does not refer to physical objects as such at all, but rather is a theoretical idea used as part of explanatory schemes to make sense of ‘observed’ properties of certain substances: such as the relative stability of benzene, or the electrical conductivity of graphite or copper, for example. The term ‘observed’ is placed in inverted commas because the descriptions used here (relative stability; electrical conductivity) do *not* refer to what can be observed in the normal meaning of the term. Rather these are inferences from observed phenomena [6] - for example the colour being retained when benzene is mixed with dissolved bromine or the movement of an ammeter needle when a switch is closed in a test circuit. We infer that benzene does not readily undergo addition reactions; or that graphite has relatively low resistivity - but this is the theoretical language of chemistry, not the language of observed phenomena. This example reflects a good deal of the content of high school and college chemistry in that actual observed phenomena (which we try to make sense of as regularities in the natural world) are often conceptualised at two distinct levels - a theoretical re-description of phenomena at the ‘bench’ level using chemical concepts, and at a further level of explanation based upon theoretical ideas relating to the structure of matter at submicroscopic scales [7-9]. This is represented in Figure 10.1. We explain the observations in terms of the formation of delocalised molecular orbitals from the overlap of unhybridised p-orbitals - conjectured processes involving non-observable theoretical entities.

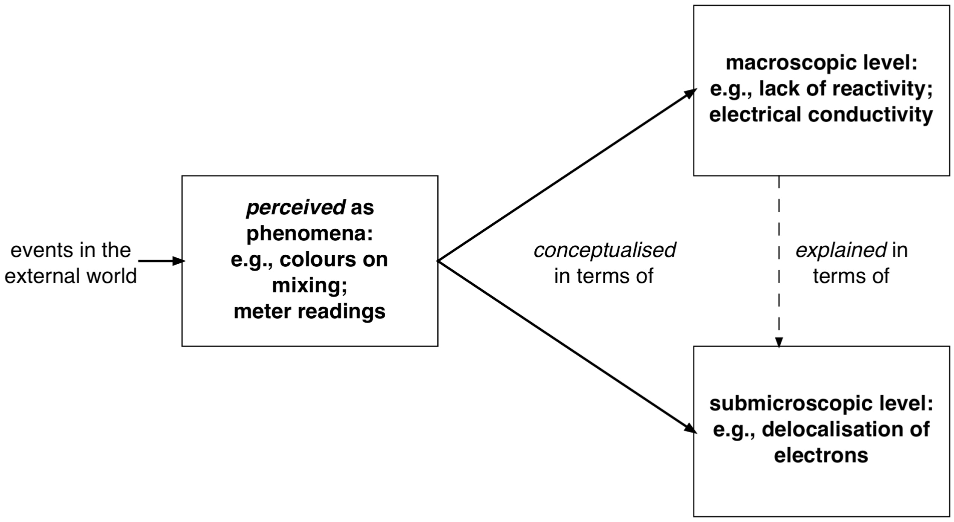


Figure 10.1: Chemists commonly conceptualise their observations at two distinct levels [Adapted from Reference 8, Fig.2, p.159]

Human conceptual development is interpretive and iterative (we make sense with and build upon our existing understanding), such that we do learn to see in terms of our concepts: over time chemistry teachers are in effect ‘seeing’ the stability of benzene when a sample is shaken with bromine solution or ‘seeing’ the conductivity of graphite when a meter needle moves in a test circuit. That is, through developing expertise (discussed further below) over extended periods of engagement, these inferences have become automated in a somewhat similar manner to how many initially challenging motor skills can become automated - as for example in riding a bicycle. Our students, especially when new to the subject, do not yet have the conceptual structures in place to be able to perceive phenomena as experts do. This kind of chunking in perception and learning to ‘see’ inferences is not particular to chemistry of course. Many readers of this chapter will have become experts in using the visual interface of their computers, and will now automatically ‘see’ the representations on their screen *as* drives, folders and documents, and will effortlessly copy files between computer drives by dragging (moving a mouse or track pad) icons across the screen.

10.1.2 Concepts and systems of public knowledge

Concepts are best understood as mental entities, but as Gilbert and Watts [4] pointed out, the term ‘concept’ is also widely used in referring to “the organisation of public knowledge systems”. That is, we commonly refer to canonical knowledge: the meaning of ‘acid’ as understood in chemistry, for example. Indeed a good deal of attention is paid in both chemistry teaching and chemical education research to aspects of student knowledge and understanding *in relation to* canonical target knowledge.

The notion of public systems of knowledge (such as canonical chemical knowledge) is therefore a very useful one: yet it is also problematic. Although we regularly refer to canonical knowledge - it is the key referent in teaching chemistry - it is rather difficult to locate. The primary literature is hardly a unified account of the subject, and in any case a constructivist perspective suggests that knowledge cannot be found in books and papers: rather they contain the (imperfect) representations of their authors’ own knowledge, which have to be interpreted in the minds of readers.

We might suggest scientific knowledge is not located in the literature but rather in the scientific community instead. This seems a more viable suggestion if we consider knowledge can only exist in minds [3], but the scientific community is not of one mind (literally, and on some particular matters figuratively as well); most scientists are only experts in some part of their discipline or field; and they can only at best represent their knowledge not transfer it wholesale to anyone else.

A third option is that knowledge can be considered to exist in in some ‘third world’ of ideas and abstractions in and of themselves. This is World 3 in relation to World 1 being the material world, and World 2 that of subjective experience [10]. This Platonic notion finds a ‘place’ to locate scientific knowledge, but - as we are not considered to have direct access to World 3 - leaves open the question of how any one (scientist, teacher or student) can ever really be said to know what canonical knowledge actually is. This is not the place to explore these issues in detail (see [3] for an extended discussion) , but given the key role paid by canonical knowledge in education, it should be acknowledged that it ultimately proves an elusive referent. Arguably canonical knowledge, such as scientific knowledge, is a fiction, albeit a very useful fiction - a kind of educational philosopher’s stone that does useful work for us even if we can never actually firmly grasp it.

10.1.3 Conceptual integration

We might consider concepts to be well integrated when they are organised into coherent and strongly linked structures. The idea of concepts being structured is well established, so Vygotsky wrote that

> “Concepts do not lie in the child’s mind like peas in a bag, without any bonds between them. If that were the case, no intellectual operation requiring coordination of thoughts would be possible, nor would any general conception of the world. Not even separate concepts as such could exist; their very nature presupposes a system.” [11, p.197]

Yet this raises the question of precisely what is meant by a structure of concepts if concepts are themselves mental categories. One approach to this was taken by George Kelly who developed Personal Construct Theory [12] or PCT. Kelly referred to constructs but acknowledged this was in effect what others often referred to as concepts. For Kelly constructs are the basis of discrimination, and are organised into hierarchical structures. In PCT the basic unit of perception/cognition is the bipolar construct that supports discriminations: good-bad; black-white; acid-base; etc, and it is considered that each person develops their own personal system of such constructs.

Kelly’s way of thinking about concepts is reflected in the methodology he developed for exploring an individual’s systems of constructs: the construct repertory grid [13]. This involved a two stage process of (i) eliciting constructs by asking respondents to discriminate a triad of three ‘elements’ into two that were more similar in some way and one that was the ‘odd-one-out’, and then repeating this for other triads; then (ii) asking respondents to suggest where each ‘element’ was positioned on each of the elicited constructs. The outcome of the analysis is a tree-like representation (a dendrogram) of the person’s constructs. In Kelly’s work as a psychological counsellor the elements might have been significant others in the client’s life, but the basic approach can be applied widely - so for example students can be asked to sort figures representing molecules and other sub-microscopic chemical structures [14].

The idea that concepts (or constructs) can be seen as hierarchical and part of branching conceptual trees has informed work in conceptual analysis to inform curriculum development and planning teaching [15]. This way of thinking about concepts also has much in common with the way Chi and her colleagues have explored students' ontologies of the world [16, 17]. Chi has argued that one source of tenacious alternative conceptions among students is the development of concepts on the wrong ontological tree. In particular, when students are taught about processes they may commonly think about these inappropriately in terms of substances: e.g. heat as a substance, rather than heating as a process.

Kelly's methodology has proved a useful tool for eliciting aspects of people's implicit knowledge but it is questionable whether hierarchical tree-like structures can capture the full complexity of our concepts. Rather concepts have a strong associative aspect, in the sense that concepts are often better seen as embedded within propositional networks [4], akin to the kinds of concept maps that are sometimes used to represent student knowledge. That is the 'meaning' a person holds for any particular concept depends upon how that concept is understood in relation to their other concepts. As a simplistic example, if a person's concept of 'element' is linked to their concept of 'substance' because they understand an element to be a type of substance, then their understanding of element is clearly tied to *how they understand the notion of substance*. This is illustrated in Figure 10.2 which shows how the concept of 'concept' might be understood in relation to a number of other concepts - this does include hierarchical relationships (e.g., implicit knowledge is a form of knowledge), but is not limited to these sorts of links.

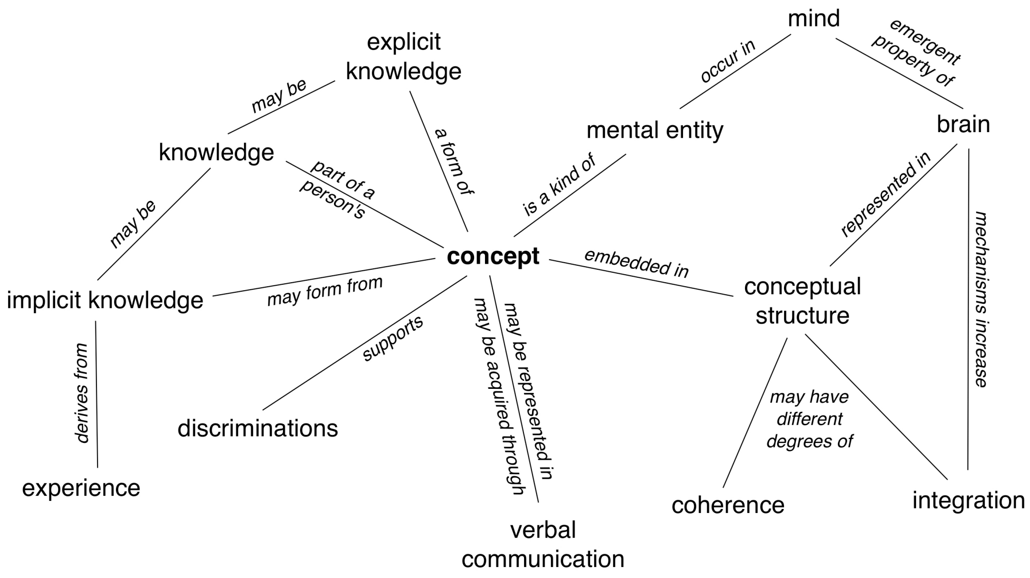
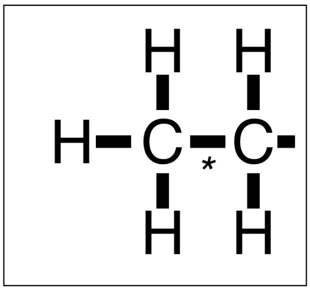
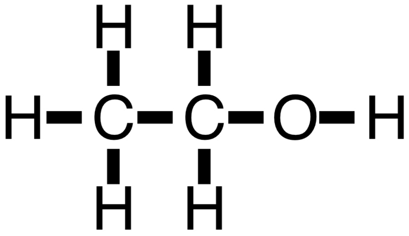


Figure 10.2: Concepts take their meaning within a network of other concepts

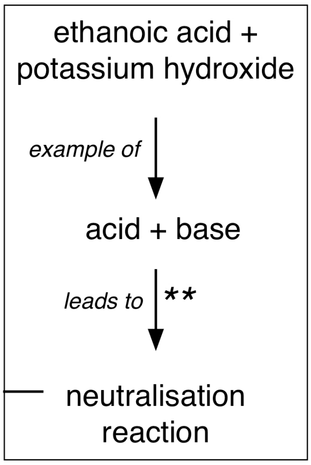
The student who recognises that antimony is an element, and whose conceptual structure includes the link that each element is a type of chemical substance has a different conceptual understanding *of antinomy* than another student who has learnt that antinomy is an element, but has not formed any further association *for element*. The same is true of whatever other links may or may not be formed in individual learners' minds. Thus, in any particular class of students, there is going to be a sense in which every student has a somewhat unique concept of acid (or element, or delocalisation, or metal, etc.) Consider for example two students in a class who when presented with the phrase 'ethanoic acid + potassium hydroxide' are both able to identify this as an example of a neutralisation reaction. If one of the students (but not the other) holds the alternative conception that a neutralisation reaction always leads to a neutral product [18], then the two students have conceptualised the reaction differently even if their public statements (e.g., 'that is a neutralisation reaction') are the same. There is a kind of 'conceptual inductive effect' at work here (see Figure 10.3) where specific propositions cannot be fully appreciated without knowing about adjacent linkages in conceptual structure.

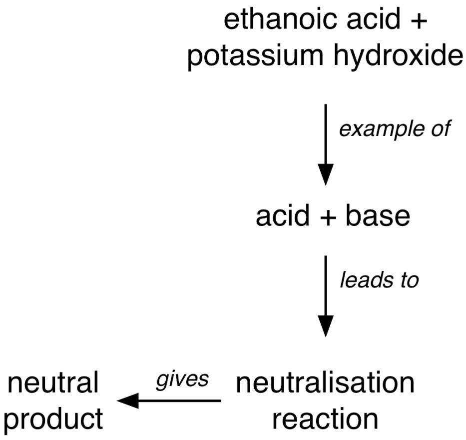

$\mathrm{H-\underset{H}{\overset{H}{C}}\underset{*}{-}\underset{H}{\overset{H}{C}}-}$


$\mathrm{H-\underset{H}{\overset{H}{C}}-\underset{H}{\overset{H}{C}}-O-H}$

** This would seem to be a bond with symmetrical electron distribution along the bond axis...*

...if we are not aware that one of the carbon centres is connected to an electronegative centre.





*** If we elicited this conceptual link from a student we might think that they had understood the nature of the reaction:...*

...however, their other associations for the concept also influence their understanding.

Figure 10.3: The conceptual inductive effect. In a similar way to how effects are transmitted through the bonding framework of a molecule, a student's particular conceptualisation depends on a network of propositional linkages

The message for teachers is that it is important to both explore the links students hold for concepts under discussion, and to take time to explicitly map out the most important links whenever introducing, reviewing, or developing, key chemical concepts. Given the likelihood of conceptual inductive effects, this should not be limited to primary links, but also the most important indirect links. Time invested in regularly highlighting conceptual linkages in this way can help identify learners' alternative conceptions, reinforce the conceptual structure of chemistry, and model for students the value of thinking of chemical concepts within an overarching structure rather than as isolated ideas.

The complexity and subtlety of people's conceptual knowledge is such that any elicited mapping (cf. Figure 10.2) is only ever likely to be a very partial representation of some segment of a person's actual conceptual structure. The notion of conceptual integration can however be understood (and modelled) in such terms. Concepts are integrated to the extent to which they are strongly linked with other concepts.

10.2 Conceptual integration and coherence in science

Science values conceptual integration and coherence. Science is a diverse activity, encompassing a range of disciplines and a vast area divided into fields and subfields. Each specialist area has its own 'disciplinary matrix' [19] with its particular key concepts and preferred theories and models. The number of 'scientific concepts' that have currency in contemporary science must be vast.

Despite this diversity, coherence is considered very important in science. Science is built upon certain assumptions. Historically, early scientists may have espoused a realism and positivism that seems naive today, yet a more nuanced form of realism is still inherent is most scientists' work even if epistemologically a post-positivist understanding of the nature of science (NOS) is widely held [20]. Scientific work requires a worldview that includes some key metaphysical commitments [3, 21] . An obvious, ontological, one is that there is an external objective reality: different scientists interact with the same external physical world, even if their own subjective experiences of it are individual [22]. Another ontological commitment is that at some level that external world exhibits a degree of stability which makes it feasible to undertake programmatic enquiry into its nature. We may observe change, but we assume that there is some more permanent level of stability to be found underpinning that change. It is also usually assumed that the most basic aspects of the physical world are invariant from place to place, as well as from time to time: thus the notion of the 'laws' of nature. Newton proposed Universal gravitation, and school children are taught that his law applies everywhere in the Universe: however that is of course a conjecture rather than a known fact. These ontological commitments are a kind of professional version of Pascal's wager. Where Pascal argued that it was rational to believe in a God who could offer you eternal life (as there was so much to lose by not believing, if this indeed transpired to be the case), scientists wager that the universe is stable and consistent enough to make enquiry into it worthwhile. Considering the universe to not have any underlying stability and order is a perfectly admissible perspective, but not one that can motivate scientific enquiry.

The accompanying epistemological commitment is that human beings are actually able to know the world, at least well enough to make the whole business of science viable. It is now widely accepted that scientific methodology necessarily underdetermines unique conclusions, and that human cognition and psychology do not allow direct knowledge of how the world is. Rather we seek to build concepts, models, theories and the like which - though necessarily human constructions - are constrained enough by empirical evidence (collected in as objective a way as possible) that we feel justified to consider it scientific knowledge. That is, not absolute knowledge, but sufficiently well supported knowledge to provisionally be reported as our best understanding to date. The logic and practical limitations of scientific investigation will always underdetermine certain scientific knowledge - but where there is clear inconsistency between different scientific theories or principles this suggests a definite problem with our current best understanding. Scientists, then, test for coherence between different concepts and theories and feel more confident in those ideas which fit well with other well established ideas. The converse is also the case: that where there are known problems of inconsistency between different scientific ideas this provides a kind of collective 'cognitive dissonance' that can motivate attempts to seek greater coherence.

Moreover, there is a common view in science that the most useful ideas are those which offer widely applicable frameworks for understanding and explaining broad ranges of phenomena. The rejection of evolutionary theory by students from some cultural backgrounds, including in some parts of the US [23], is considered particularly problematic because evolution is the key unifying idea of modern biology [24]. Maxwell's work was lauded because it was seen to unify electricity, magnetism and (what is now known as) electromagnetic radiation. Physicists today look to explore how quantum theory can be made consistent with other key physical theories, and seek a grand unifying theory which can subsume different areas of physics. The prominent display of periodic tables in so many schools and college chemistry laboratories reflects the value of the periodic system as an organising principle in the subject.

The relationship between different disciplines and fields is more complex one. A notion that once had currency was that one day biology would be reduced to chemistry, and chemistry to physics. This now seems rather naive. *In principle* all chemical (and ultimately biological) concepts *could* be re-described purely in terms of physics. That might be an immense intellectual achievement - akin to Alfred North Whitehead and Bertrand Russell's (ultimately incomplete) project to set out the principles on which all mathematics is ultimately based - but it would not negate the need for chemical and biological concepts in their own right. Whilst presumably any example of oxidation or of nucleophilic substitution or of a steroid (just to select a few of many possible examples) could in principle be described purely in terms of physics, that would not make such a level of description the most useful for many purposes. We might consider oxidation to be an emergent property of a chemical system, and the concept of 'oxidation' therefore does useful mental work in thinking about chemistry. However, whilst it would usually be unhelpful to re-describe oxidation in purely physical terms, it would not be acceptable for such a concept to be *inconsistent with* physics. For example, electrical charge is expected to be conserved during oxidation processes: it is not exempt from the physical conservation principle because we class oxidation as a chemical rather than a physical process.

In the same way, bond breaking is understood as an endothermic process in chemistry. So chemistry teachers become frustrated when their students read about 'energy-rich' phosphate bonds in some biology texts, as bond breaking in ATP cannot (of itself) release energy regardless of whether the context is the chemistry or biology class. It has been argued that when understood *within a biological context*, it is defensible to describe how in photosynthesis "light energy becomes chemical bond energy" [25], but from a chemical perspective it is inappropriate to consider energy to be stored in bonds.

10.2.1 Multiple models in chemistry

Although we expect scientific theories to be consistent within and across scientific disciplines, our application of models offers more latitude for inconsistency. We acknowledge that our conceptual models are just that, models, and so may only relate to some aspects of the phenomena we study, and may have limited ranges of application. There are at least two different kinds of multiple model which will be met by students of the chemistry.

One area where students will come across apparently inconsistent models links to concept definitions that have shifted over time. There are different ways of defining oxidation or acids for example. This is less a matter of uncertainty about the nature of the phenomena studied in chemistry, than choices about how to usefully demarcate our concepts. It does not make good sense to think that for example, defining oxidation in terms of addition of oxygen is 'wrong' (because it misses some cases that are 'really' oxidation) and that a definition in terms of loss of electrons is more accurate. Rather as the theoretical apparatus of chemistry developed it became useful to have a more inclusive category and the choice of a most useful definition shifted. Similarly, the Lewis model of acid is more inclusive than the Brønsted-Lowry model but that does not equate to the Brønsted-Lowry notion of an acid being 'wrong' because it misses some acids or the Lewis model being 'wrong' because it includes non-acids. If our concept was meant to map onto a clear distinction in nature then having two inconsistent sets of definitions would indicate error - but students need to understand that the acid concept is a human construction and the chemical community can choose how to restrict or extend it in relation to objective differences in the properties of different substances, and our theoretical models of why they react as they do.

A rather different situation is met when modelling chemical structures at the submicroscopic level. Students will meet various ways of modelling and representing atomic, molecular and crystal structures. Whilst some models a student may meet are best now considered anachronistic and judged historical scientific models [26], much of the diversity arises from the difficulty posed by entities which cannot be fully represented in terms of what is familiar at the macroscopic scale. So models of molecules showing atomic centres linked along major bond axes reflect some aspects of interest, whilst space filling models reflect other aspects. Neither type of model effectively represents all the features of molecules we wish to highlight at various times. Rather we maintain alternative models as part of our ‘conceptual tool kit’, to be selected for particular cognitive work [27]. Some aspects of crystal structures are best shown by close-packing - other aspects make little sense when represented that way. Showing pairs of electrons around atomic cores is sometimes useful and sometimes unhelpful: ditto electron density maps; ditto electronic orbitals.

Where the teacher may be well aware of the limitations of the models presented in class, their ontological status as partial representations, and their epistemological status as thinking tools and perhaps elements of theories under test and development, none of this is necessarily obvious to students unless the teacher makes it explicit. From a NOS perspective, the teaching of any chemical model is necessarily inadequate unless the teaching makes it clear that what is being taught *is* a model, and explores its limitations and range of application.

Where different models of the same target concept (e.g. of the atom, of the covalent bond, etc.) are met at different stages of education teachers should take the opportunity to compare the strengths, limitations and range of application of the new model being presented with the alternative model(s) students have been taught perviously. This is important to avoid students being frustrated because they feel they are being told that what they learnt in earlier grades was wrong. However, this is also important from a NOS perspective both because (a) historical sequences of models can reflect how progress in chemistry involves a dialectic between theory and experiment, with proposed models suggesting empirical work which reveals their limitations and informs and motivates more sophisticated models; and because (b) contemporary chemists often retain multiple alternative models in their ‘conceptual toolbox’ from which to select according to the needs of particular tasks [27].10.3 Conceptual integration in learning

Conceptual integration is an important factor in learning - both in relation to how students make sense of teaching, and in terms of how they are subsequently able to apply learning. Ausubel [28] wrote about meaningful learning in terms of what was to be learnt being both relatable to some aspect of a learner’s existing cognitive structure, and being perceived as relevant. When teaching is not meaningful because it is not understood in terms of existing knowledge, it can only be learnt by rote. However, when it is meaningful it can be associated with existing knowledge, which makes for more accessible and flexible learning.

Meaningful learning is more accessible because it is more likely to be activated when it is connected to other mental representations: in effect there are multiple routes to reaching that specific knowledge representation. Meaningful learning is more flexible because it is understood more deeply (and so can more readily be applied in different contexts) by acquiring its meaning from its associations with other related concepts. To give a very simplistic example, knowing that ammonia is a compound, and that compounds are chemical substances, enables someone to use the information 'ammonia is a compound' in more ways (in the most basic terms, as a response to the question 'name a chemical substance', as well as as a response to the question 'name a chemical compound').

A common problem in much school and college learning is that even when learning is meaningful in Ausubel's terms, it later proves rather fragile. This can be understood in terms of how the formation of memories commonly occurs in two stages [29]. When a learner associates new learning with existing representations in their conceptual structure, the association is itself represented within the brain by synaptic changes, but initially mediated by a particular brain structure that is involved in memory formation by acting as an intermediary connected to both the established and new representations. These linkages decay over time as a matter of course, such that the initial association may no longer be strongly represented. However, regular activation of the temporary association leads to new, more direct, linkages being formed that provide a more permanent association once the temporary indirect link has decayed. Sufficient reinforcement of learning can lead to strong permanent links between representations such that there will be a low threshold for activating the link (so that when thinking of one knowledge component represented in memory, we are likely to bring to mind the other).

From a constructivist perspective [30, 31], relevance must be understood within the context of an individual's conceptual ecology - as it is the learner who must perceive teaching as meaningful in terms of existing knowledge and understanding, and so form associations. However, part of the work of teaching is seeking to facilitate such linkages to 'make the unfamiliar familiar' [32] by making explicit how new learning fits with previously taught material, and by seeking examples, analogies and metaphors for new ideas that will help learners make sense of teaching.

10.3.1 The drive for coherence

The high value put on coherence between different theoretical ideas in science is reflected (or perhaps better, reflects) what seems to be a basic drive towards coherence within human cognition. This works at two levels. In perception, we are biased to see the world in terms of existing perspectives and frameworks. We seek to make sense, and the way to make sense is to interpret new information such that it fits with those categories, principles and expectations about the world we have already formed. Much of this occurs at a preconscious level, so we are not even aware of how sensory date is filtered, selected, and arguably sometimes distorted, by these processes. This means that students who seem to be making sense of teaching may not be understanding it as intended. For example, one response to being taught about the concept of electronic orbitals is to subsume the teaching under the existing concept of electron 'orbits', so conflating two quite distinct models [33]. As suggested above, the teacher can pre-empt such problems to some extent by explicitly presenting the orbital model of the atom as a model and explaining its adoption in part by contrasting its features and characteristics with those of the alternative atomic model already familiar to the students.

There are also processes at work after initial learning of material that can lead to modifications in what has been learnt. It appears that the cognitive system has an in-built process for bringing material represented in the brain into greater coherence, even if this means modifying what we might consider memories. There seems limited explicit research on this effect in science education. Gauld [34] reported a study in physics education where learners who appeared to have been persuaded to shift from alternative conceptions about electric circuits by a teacher's demonstration later reverted to less scientific thinking *and* then recalled the demonstration in a distorted way inconsistent with the scientific model, but consistent with their alternative conceptions. Like whig historians or Stalinist officials we all (inadvertently) rewrite our personal histories to better suit our currently preferred narratives. Human memory does not seem to have evolved as a means of providing us with high fidelity records of past experience: rather it seems to be an aspect of cognitive apparatus that has evolved to best help us form a coherent model of experience to support decisive action now (a tendency which may have been important in human evolution as prevarication and waiting for the luxury of a strong evidence base are unlikely to have been helpful traits in the conditions under which most of our ancestors lived). It seems both that the way we perceive experience now is heavily influenced by the interpretive frameworks we have constructed from prior experience, and that our representations of prior experience (memories) become modified over time to better maintain a coherent model of the world.

This is an important theme that does not seem to have been explicitly explored in much research in chemistry education. In one study I found intriguing suggestions that some time (almost 4 years) after a student had studied a chemistry course he demonstrated a linkage between two ideas he had considered complementary but not related at the time of his studies [35]. This was despite my study participant reporting that he had not had reason to think about the material (i.e., consciously) since completing his course. However, this is one example. Given the importance of this theme to teaching and learning it deserves more attention. Teachers are well aware of the importance of reinforcing new learning to support consolidation, but this aspect of pedagogic knowledge seems to largely be based on work on memory function undertaken in psychology, often using rather artificial target material, rather than studies in the context of authentic classroom learning.

10.3.2 Compartmentalisation of learning

This is particularly important as despite the in-built drive to develop coherent models of the world, it is also a common classroom phenomena that learners will fail to make the links teachers might hope, and sometimes even those that seem obvious to the teacher.

One (c.17 year old) student I interviewed was able to explain the origin of van der Waals' forces in terms of transient induced dipoles, but could not suggest a mechanism by which a balloon that had been charged by friction might remain attached to an uncharged wall [36]. Perhaps more mystifying to a teacher would be why a (c.11 year old) student who demonstrated that he had learnt that everything was made of particles in one science topic would be unsure whether a new substance he came across in another topic, chlorophyll, might be made of particles; or why it was not obvious to a (c.14 year old) student that the nucleus of a cell *must* be very much larger than the nucleus of an atom [37] .

It is well recognised that the context of learning - where and when we learn something - can be significant for how readily we access and apply that learning. The issue of transfer of learning is a core issue in education research [38]. However as teachers we may lose sight of this. I interviewed a (c.16 year old) student who told me about how she had learnt about covalent bonds and ionic bonds. When shown an unfamiliar image of resonance forms of BF_3, Annie identified 'single bonds'. I asked her whether these were the same as covalent or ionic bonds, or something else. Her initial response was that "single bonds are different" [39]. She later acknowledged that actually this was probably just a different label, but still suggested that "they can probably occur in different, things like in organic you talk about single bonds more than you talk about covalent, and then like in inorganic you talk about covalent bond, more than you talk about single bonding or double bonding". That is, Annie went to classes with different lecturers, and in her classes on organic chemistry bonds were generally described differently from how they were discussed in her inorganic chemistry classes (because different teaching points were being emphasised). It would seem that prior to my interviewing her, Annie had not considered relating the two ways of talking about bonds she met in her classes[1].

Again teachers can plan to teach in ways which minimise such problems by always thinking in terms of the potential links they want learners to make, and considering where terminology or styles of presentation in different branches of the subject can potentially obscure links. Chemistry offers many potential areas where such breakdown of communication can occur - outer shells sometimes but not always labelled valence shells; noble gases still sometimes referred to as inert gases; common use of traditional as well as systematic names for some substances (acetic acid, toluene, etc.); treatment of acids and bases in biochemistry/pharmacy; treatment of reaction mechanisms in inorganic and organic chemistry; and so on.

10.3.3 When conceptual integration impedes learning

The gist of this chapter is that conceptual integration is generally a positive thing - and that teachers should support students in developing highly integrated conceptual systems as these are more robust and offer greater facility to learners. However, major conceptual

---

[1] This example is presented in more detail on the ECLISE project website: see http://www.educ.cam.ac.uk/research/projects/eclipse/ (accessed 8th January 2014)

change may require us to entertain alternative inconsistent ways of thinking about a topic as an intermediate stage if we are to shift away from strongly held inadequate conceptions [2, 40].

A learner may have well-integrated conceptual knowledge of chemistry (or any other subject) without their conception matching canonical knowledge. Sometimes learners acquire relatively isolated alternative conceptions - such as notions that all acids are dangerous or all metals are hard. However, learners can also develop well integrated conceptual frameworks around alternative conceptions.

An example from chemistry learning is the ‘octet’ conceptual framework [41], based around the explanatory principle that atoms ‘need’ or ‘want’ octets of electrons or full outer shells and that chemical processes happen so that atoms can meet this need. The framework was first identified among students in England, but research in other contexts suggests it is widespread [42]. Students can develop quite extensive networks of related conceptions based around this explanatory principle - in terms of why reactions occur, the nature of bonds and what counts as a chemical bond, patterns of ionisation, and which chemical species should be considered stable. These networks commonly consist of a mixture of alternative and more acceptable conceptions, but the ability to develop an extensive and coherent linked conceptual structure around the core principle is reflected in just how tenacious an alternative conception this can be [35].

A key feature of the ‘octet’ framework is how it is highly anthropomorphic (in that it is described in terms of atoms as active agents that have desires), and this seems a strong feature of many students’ explanations of chemistry at the submicroscopic level, even at high school level [43] - and indeed beyond [44]. It was reported in one study [45] that substantial proportions of senior high school level students actually consider atoms to be alive . This reflects the difficulty for learners of acquiring the abstract theoretical models used at the submicroscopic scale to explain phenomena in chemistry (cf. Figure 10.1) - something well recognised as a core issue in chemistry education [46-50].

Teachers use metaphors and analogies to teach about abstract ideas, and this is often a sensible strategy to ‘make the unfamiliar familiar’ to students. However, teachers’ classroom talk that anthropomorphises atoms and molecules offers a familiar way of thinking about the submicroscopic realm that many students not only readily adopt, but find difficult to move beyond. Teachers are advised that if they do use such anthropomorphic language they need to do so with care, always making sure that students appreciate that terms such as ‘the atom needs...’ do not suffice in scientific explanations, and to seek to shift classroom discourse from such ‘social’ descriptions to more physical accounts (e.g. in terms of ideas such as charge, force, energy) before students begin habitually adopting anthropomorphic language.

10.3.4 Conceptual integration and expertise

It is considered that one of the most significant differences between novice and expert is the degree of conceptual integration of an expert's knowledge. An expert has a highly organised knowledge base to support their thinking [51]. Expertise in a field is considered to result from engagement with the field over an extended period of time - perhaps typically something like a decade of working in that area [52]. In that sense, teachers need to be aware that it is unreasonable to expect most of our students to demonstrate knowledge similar to that of experts, and this is especially so at school level where students follow a wide spread of curriculum subjects and have limited engagement with each. This does however raise an issue about the educational logic of standards and curriculum specifications which set out objectives across a diverse range of teaching topics. Regular shifting from topic to topic, especially if this is perceived by students as a complete disconnect and 'moving on' to 'something else' - such as when a (c.11 year old) student was unclear why her class did a lesson on magnets when they were supposed to be studying electricity [37] - would not seem to support extensive engagement. Chemistry is underpinned by a range of core concepts and principles that are not only fundamental to the discipline, but also to learning in the discipline: the student experience may not always reflect this unless teachers work hard to stress what is fundamental and how other material fits around that conceptual core.

10.4 Conclusions and implications

The intention behind this chapter was to highlight the importance of the notion of conceptual integration in teaching and learning chemistry, given that it has not been subject to the attention in chemistry education that it might seem to warrant. What is known, or at least widely believed, about how learning occurs and how conceptual structures evolve can inform instruction; but more research is indicated to learn more about the details of how students integrate their chemistry knowledge, and what specific strategies teachers can employ to support them.

10.4.1 Implications for teaching

At the most basic level, thinking about the importance of conceptual integration can inform teaching in ways that are recognised in constructivist literature [53, 54]. Teachers should always seek to ensure learners recognise which aspects of prior learning are intended to be related to new ideas presented in class. Teachers should reinforce new learning regularly in a range of contexts to reinforce how new concepts 'fit' into the scheme of the subject.

The present analysis also suggests that teachers need to emphasise the idea of the importance of integrating knowledge, and to model this by being explicit about when ideas being discussed today link with or exemplify other topics. This is important both for supporting students' metacognitive development (so they acquire 'metaknowledge' related to the importance to learning of the degree of integration of their own knowledge structures, and metacognitive skills to monitor this aspect of their thinking) and for helping learners appreciate an important aspect of NOS - the epistemological commitments within science to finding coherence between ideas and to seek to subsume scientific concepts under a small number of fundamental principles.

In parallel with this, teachers need to emphasise the central role of models (in which I include typologies) within chemistry and help learners appreciate the epistemological status of models. Alternative models may not be consistent because our knowledge is uncertain, or (particularly in the case of the submicroscopic nature of matter) because we need to use complementary models, and different representations of those models, to highlight different features. This is important because research suggests learners tend to commonly treat scientific models as realistic replicas, and they often fail to appreciate the nature and role of models in science subjects [55]. It is also important because chemistry students need to appreciate that although we seek coherent and well integrated conceptual schemes in chemistry, and consider inconsistency between concepts as a sign of something being wrong, we also regularly present apparently inconsistent models for students to consider and apply. This is potentially very confusing for students unless we are explicit about the limitations of models [56], and why ambiguity and inconsistency often need to be tolerated in a subject which ultimately aspires to offer a coherent conceptual framework for understanding the material world.

Given the breadth of many school and college chemistry courses, where students meet a wide range of concepts - and may even experience different branches of chemistry as different subjects (taught in different styles by different subject experts, and sometimes apparently using a different specialist language) - it is important to identify core concepts which can act as organising principles for learning and which students can cling to as anchors (or perhaps buoys!) when meeting new concepts. There is now a programme of work being undertaken to explore 'learning progressions' in science that identify such key concepts and explore how they can be used as foci for planning teaching and assessing learning [57, 58], and this is one promising development.

Where possible, teaching staff should liaise over how they teach related topics. However, any chemistry teacher needs to analyse the content they are teaching in terms of desirable links with other topics, and potential points of confusion if other teachers (including those who taught our current students previously) may have adopted alternative terminology, metaphors, or approaches to presenting topics. Whilst many potential learning impediments may be identified from the research literature into student thinking, each student is unique, with their own somewhat idiosyncratic resources for interpreting new information, so effective teaching is always likely to be an iterative process where the teacher is regularly eliciting both student prior learning and how new teaching is being interpreted - checking both that intended links are being made, and that unhelpful misleading links are diagnosed and challenged before they are adopted and committed to by learners [37].10.4.2 Directions for the research programme

The analysis presented here might be considered to be grounded upon a firm but patchy research base. Within science education we have many studies which report aspects of how much different groups of students know about key chemistry topics, and where they commonly have learning difficulties or alternative conceptions [31, 59(Accessed 8th January 2014), 60]. We also have a good understanding of notions such as meaningful learning, the importance of reinforcement of learning, consolidation and forgetting effects, and the like, from studies undertaken in psychology and the learning sciences. We have fewer studies about the nature of conceptual integration in chemistry students' knowledge structures at different levels, let alone how this may shift over time, or how it might relate to such things as student metacognition and study habits; curriculum structure; and teaching styles. Guidance to teachers is therefore largely in terms of general principles. There is much scope here for research which is able to look in detail at this aspect of chemistry learning across topics, over time, and in relation to teaching and learning contexts.

References

1. Duit, R. and D.F. Treagust, *How can conceptual change contribute to theory and practice in science education?*, in *Second International Handbook of Science Education*, B.J. Fraser, K.G. Tobin, and C.J. MacRobbie, Editors. 2012, Springer: Dordrecht. p. 108-118.

2. Vosniadou, S., ed. *International Handbook of Research on Conceptual Change*. Educational Psychology Handbook Series2008, Routledge: London.

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

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

5. Oversby, J., *Acids and alkalis*, in *Teaching Secondary Chemistry*, K.S. Taber, Editor 2012, Hodder Education: London. p. 183-198.

6. de Jong, O. and K.S. Taber, *Teaching and learning the many faces of chemistry*, in *Handbook of Research in Science Education*, N. Lederman, Editor Forthcoming, Routledge: New York.

7. Johnstone, A.H., *Macro- and microchemsitry.* School Science Review, 1982. **64**(227): p. 377-379.

8. Taber, K.S., *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, 2013. **14**(2): p. 156-168.

9. Jensen, W.B., *Logic, History and the Teaching of Chemistry, text of the Keynote Lectures, given at the 57th Annual Summer Conference of the New England Association of Chemistry Teachers, Sacred Heart University, Fairfield, Connecticut*1995.

10. Popper, K.R., *Objective Knowledge: an evolutionary approach*. Revised ed1979, Oxford: Oxford University Press.

11. Vygotsky, L.S., *Thought and Language*, ed. A. Kozulin1934/1986, London: MIT Press.

12. Kelly, G., *A Theory of Personality: The Psychology of Personal Constructs*1963, New York: W W Norton & Company.

13. Fransella, F. and D. Bannister, *A Manual for Repertory Grid Technique*1977, London: Academic Press.

14. Taber, K.S., *Can Kelly's triads be used to elicit aspects of chemistry students' conceptual frameworks?*, in *British Educational Research Association Annual Conference*1994: Oxford.

15. Herron, J.D., et al., *Problems associated with concept analysis.* Science Education, 1977. **61**(2): p. 185-199.

16. Chi, M.T.H., *Conceptual change within and across ontological categories: examples from learning and discovery in science,*, in *Cognitive Models in Science*, R.N. Giere, Editor 1992, University of Minnesota Press: Minneapolis. p. 129-186.

17. Chi, M.T.H., J.D. Slotta, and N. de Leeuw, *From things to processes; a theory of conceptual change for learning science concepts.* Learning and Instruction, 1994. **4**: p. 27-43.

18. Schmidt, H.-J., *A label as a hidden persuader: chemists' neutralization concept.* International Journal of Science Education, 1991. **13**(4): p. 459-471.

19. Kuhn, T.S., *The Structure of Scientific Revolutions*. 3rd ed1996, Chicago: University of Chicago.

20. Losee, J., *A Historical Introduction to the Philosophy of Science*. 3rd ed1993, Oxford: Oxford University Press.

21. Taber, K.S., *Conceptual frameworks, metaphysical commitments and worldviews: the challenge of reflecting the relationships between science and religion in science education* in *Science Education for Diversity: Theory and practice*, N. Mansour and R. Wegerif, Editors. 2013, Springer: Dordrecht. p. 151-177.

22. Glasersfeld, E.v., *Cognition, construction of knowledge, and teaching.* Synthese, 1989. **80**(1): p. 121–140.

23. Long, D.E., *Evolution and religion in American Education: An ethnography*2011, Dordrecht: Springer.

24. Dobzhansky, T., *Nothing in biology makes sense except in the light of evolution.* The American Biology Teacher, 1973. **35**(3): p. 125-129.

25. Jin, H. and C.W. Anderson, *Developing assessments for a learning progression on carbon-transforing processes in socio-ecological systems.*, in *Learning*

Progression in Science: Current challenges and furture directions, A.C. Alonzo and A.W. Gotwals, Editors. 2012, Sense: Rotterdam, The Netherlands. p. 151-181.

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

27. Taber, K.S., *An analogy for discussing progression in learning chemistry.* School Science Review, 1995. **76** (276): p. 91-95.

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

29. Alvarez, P. and L.R. Squire, *Memory consolidation and the medial temporal lobe: A simple network model.* Proceedings of the National Academy of Sciences, 1994. **91**: p. 7041-7045.

30. Bodner, G.M., *Constructivism: a theory of knowledge.* Journal of Chemical Education, 1986. **63**(10): p. 873-78.

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

32. Taber, K.S., *Chemical Misconceptions - Prevention, Diagnosis and Cure: Theoretical background*. Vol. 1. 2002, London: Royal Society of Chemistry.

33. Taber, K.S., *Learning quanta: barriers to stimulating transitions in student understanding of orbital ideas.* Science Education, 2005. **89**(1): p. 94-116.

34. Gauld, C., *Models, meters and memory.* Research in Science Education, 1986. **16**(1): p. 49-54.

35. Taber, K.S., *Lost without trace or not brought to mind? - a case study of remembering and forgetting of college science.* Chemistry Education: Research and Practice, 2003. **4**(3): p. 249-277.

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

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

38. Goldstone, R.L. and S.B. Day, *Introduction to "New Conceptualizations of Transfer of Learning".* Educational Psychologist, 2012. **47**(3): p. 149-152.

39. Taber, K.S., *Stability and lability in student conceptions: some evidence from a case study*, in *British Educational Research Association Annual Conference*1993: University of Liverpool.

40. Thagard, P., *Conceptual Revolutions*1992, Oxford: Princeton University Press.

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

42. Taber, K.S., *A common core to chemical conceptions: learners' conceptions of chemical stability, change and bonding*, in *Concepts of Matter in Science Education*, G. Tsaparlis and H. Sevian, Editors. 2013, Springer: Dordrecht. p. 391-418.

43. Taber, K.S. and K. Adbo, *Developing chemical understanding in the explanatory vacuum: Swedish high school students' use of an anthropomorphic conceptual framework to make sense of chemical phenomena*, in *Concepts of Matter in Science Education*, G. Tsaparlis and H. Sevian, Editors. 2013, Springer: Dordrecht. p. 347-370.

44. Nicoll, G., *A report of undergraduates' bonding misconceptions.* International Journal of Science Education, 2001. **23**(7): p. 707-730.

45. Griffiths, A.K. and K.R. Preston, *Grade-12 students' misconceptions relating to fundamental characteristics of atoms and molecules.* Journal of Research in Science Teaching, 1992. **29**(6): p. 611-628.

46. Gilbert, J.K. and D.F. Treagust, eds. *Multiple Representations in Chemical Education*. 2009, Springer: Dordrecht.

47. Tsaparlis, G. and H. Sevian, eds. *Concepts of Matter in Science Education*. 2013, Springer: Dordecht.

48. Harrison, A.G. and D.F. Treagust, *The particulate nature of matter: challenges in understanding the submicroscopic world*, in *Chemical Education: Towards Research-based Practice*, J.K. Gilbert, et al., Editors. 2002, Kluwer Academic Publishers: Dordrecht. p. 189-212.

49. Lijnse, P.L., et al., eds. *Relating Macroscopic Phenomena to Microscopic Particles: a central problem in secondary science education*. Centre for Science and Mathematics Education1990, University of Utrecht/CD-ß Press: Utrecht.

50. Taber, K.S., *Building the structural concepts of chemistry: some considerations from educational research.* Chemistry Education: Research and Practice in Europe, 2001. **2**(2): p. 123-158.

51. Dolfing, R., et al., *Domain-Specific Expertise of Chemistry Teachers on Context-Based Education About Macro-Micro Thinking in Structure-Property Relations.* Research in Science Education: p. 1-22.

52. Gardner, H., *Extraordinary Minds*1998, London: Phoenix.

53. Taber, K.S., *Constructivism as educational theory: Contingency in learning, and optimally guided instruction*, in *Educational Theory*, J. Hassaskhah, Editor 2011, Nova: New York. p. 39-61.

54. Driver, R. and V. Oldham, *A constructivist approach to curriculum development in science.* Studies in Science Education, 1986. **13**: p. 105-122.

55. Treagust, D.F., G. Chittleborough, and T.L. Mamiala, *Students' understanding of the role of scientific models in learning science.* International Journal of Science Education, 2002. **24**(4): p. 357-368.

56. Taber, K.S., *Straw men and false dichotomies: Overcoming philosophical confusion in chemical education.* Journal of Chemical Education, 2010. **87**(5): p. 552-558.

57. Alonzo, A.C. and A.W. Gotwals, eds. *Learning Progressions in Science: Current Challenges and Future Directions*. 2012, Sense Publishers: Rotterdam.

58. Sevian, H. and V. Talanquer, *Rethinking chemistry: a learning progression on chemical thinking.* Chemistry Education Research and Practice, 2014.

59. Duit, R., *Bibliography - Students' and Teachers' Conceptions and Science Education*2009, Kiel: http://www.ipn.uni-kiel.de/aktuell/stcse/stcse.html.

60. Kind, V., *Beyond Appearances: Students' misconceptions about basic chemical ideas*. 2nd ed2004, London: Royal Society of Chemistry.