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THE MANY FACES OF HIGH SCHOOL CHEMISTRY

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The goal of this chapter is to review research on teaching and learning science that focuses on the specific domain of chemistry, with particular emphasis on the high school level.

The *introductory section* of this chapter deals with a concise overview of high school chemistry curriculum reform in the past 50 years. Then, two general themes in modern chemistry education are reported. First, we consider studies of attempts to make chemistry more meaningful by using contexts taken from students' interests, from society, or from professional practices. Second, we discuss studies of characteristics of models in chemistry and chemical education, especially their presentation from three related perspectives: macroscopic, submicroscopic, and symbolic.

In the *next sections*, the theme of models is further elaborated for two difficult core topics at school level: chemical reactions (especially at junior high level) and chemical bonding (especially at senior high level). For both topics, students' main conceptual difficulties are discussed. They are conceptualised in terms of three interrelated factors: the student, the chemistry content, and the teacher/textbook. Studies of approaches designed to support students overcoming learning difficulties are reviewed. Suggestions for improving the teaching of chemistry are also presented.

The *final section* of this chapter deals with a look to the near future of chemical education, concisely focusing on directions for new research and coherent innovations in chemistry education. Suggestions for priority areas for further research and curriculum development are offered at several places.

WAVES OF CHEMISTRY CURRICULUM REFORM

Reform in the 1960s

In the last 50 years, several waves of chemistry curriculum reform, as part of science curriculum reform, can be identified in many countries. An important starting point of the first wave can be located in the middle of the Cold War era, in 1957, when the former Soviet Union launched the first artificial satellite (the 'Sputnik") into an orbit around the Earth. This evoked a shock around the world, and was considered to show the relative weakness in science and technology in several other big industrialized countries, especially the USA. Educational experts pointed out that one of the main causes of the perceived deficit was the relative low quality of the existing science and technology curricula. They criticised the existing curricula by characterising them as old-fashioned, overloaded, and mainly isolated facts-oriented. Although this criticism was not new, the 'Sputnik' effect made the policy makers in the western world more willing to pay attention to it and to invest in the development of new national chemistry curricula. These curricula were designed in large part by chemists themselves and, for that reason, were academically rigorous. Most of the reform was large-scale, for example, the USA projects 'Chemical Education Materials Study' (CHEMS) (Pimental, 1963) and 'Chemical Bond Approach' (CBA) (Strong, 1964), and the UK project 'Nuffield Chemistry' (Halliwell, 1966).

The leading projects for high schools focused on understanding basic chemistry concepts and processes instead of knowing a large number of largely unrelated facts.

Disciplinary knowledge was emphasised and very few applications of chemistry or links to daily experiences of students were included. The new curricula also focused on stimulating the development of basic scientific skills, and a growing number of classrooms were adapted (or added) for conducting laboratory work by students. This lab work did not have much to do with independent inquiry activities because students had to carry out prescribed tasks that imitated the way chemists themselves did their work. Finally, teachers were often prepared by offering them teacher guides and short workshops on the new curriculum topics.

Although the expectations of the effects of the innovations were high, in general, the results were quite disappointing (Goodlad, 1984; Welch, 1979). For instance, according to high school students, practical work was not useful or challenging because it involved applying cookbook recipes. They also complained that the new curriculum content was still difficult to understand and teachers encountered difficulties in handling innovative project materials. The failure of this wave of curriculum reform can be explained by several factors, for instance the curricula content that was quite isolated from societal issues, modern chemistry, and students' interests. In addition, teacher courses offered a 'top-down' preparation of chemistry teachers that soon lost its impact when teachers returned to daily classroom practice.

Reform in the 1980s

Because of the disappointments of the 1960s reform and stimulated by an alarming report from the USA, 'A Nation at Risk' in 1983, pointing to the poor performance of American youth in mathematics and science, a second wave of chemistry curriculum innovation was initiated in several western countries. This time, curricula were mainly designed by teams in which chemists cooperated with experts from other disciplines, for instance curriculum designers and education specialists. In this reform, most leading projects started on a more modest scale, for example, the USA project 'Chemistry in the Community' (ChemCom) (ACS, 1988), and the UK project 'Chemistry: The Salters Approach' (UYSEG, 1989).

In the 1980s reform, the design of many courses was more student-oriented and focused on 'active learning' approaches, for instance by introducing inquiry tasks in the high school lab. Moreover, because of the constant criticism of the former curricula and the upcoming interest in environmental issues, efforts were made to relate chemistry concepts and processes to situations from everyday life that were believed to be of interest for students. In other words, contexts were introduced aiming at fostering a more positive attitude and a better understanding of chemistry. When contexts strongly focused on issues concerning the relationship between chemistry, technology and society (CTS issues), the main aim was to develop students understanding of chemistry and relevance of chemistry in the personal, social, and societal domains ('chemistry literacy'). Finally, teacher training courses were launched which not only focused on new curriculum content but also on new insights in teaching and learning strategies.

Despite all these innovations, in general, the results of this wave of curriculum reform were still disappointing (Cuban, 1992; Postlethwaite & Wiley, 1991; Wahlberg, 1991). For instance, high school students did not see the relevance of the given contexts for understanding related concepts and processes, and teachers encountered difficulties in guiding student inquiry activities instead of prescribing student activities. Several factors contributed to the limited success of this wave of reform, for instance a lack of sufficient understanding of students' real interests and authentic ways of reasoning, and a lack of attempts to actively involve teachers in the process of developing innovative teaching approaches.

Reform in the 1990s/2000s

In order to cope with the difficulties encountered during the 1980s, a third wave of chemistry curriculum innovation projects was initiated. Some examples from the 1990s/2000s were the UK project 'Salters Advanced Chemistry' (SAC) (SAC Project, 1994), the Dutch project 'New Chemistry' (NC) (Driessen & Meinema, 2003), and the German project 'Chemie im Kontext' (ChiK) (Gräsel, Nentwig, & Parchmann, 2005).

A main focus of the new generation of projects concerned the use of contexts that not only provided a better fit for many students' interests but also put them in a position that they felt a necessity to extend their existing knowledge of chemistry. The newly acquired knowledge could be used for a broader exploration of the initial context or could be applied in a new context. For instance, the aim of introducing contexts such as water supplies and food was not only to evoke students' interest and a need to know more of relevant chemistry topics. The aim is also to stimulate students to apply the acquired knowledge for developing evidence-based ideas and decision-making regarding societal issues such as the need to conserve natural resources. Another main focus of the new curriculum projects concerned 'nature-of-chemistry' issues, especially the issue of nature and function of (particle) models and modelling in chemistry, and the issue of open-inquiry activities. The latter provided students the opportunity to work on complex chemistry problems and to foster their ability for self-directed learning which they will need when they face problems in their future careers. New modes for the professional development of teachers were also introduced. For instance, university experts and interested teachers often cooperated in learning communities in which the experts design a curricular framework that guided the collaborative development of prototypical modules for students. The innovative modules were field-tested and revised in several cycles. In this way, chemistry teachers can become 'co-owners' of the innovations, which is an important condition for success in bringing new teaching materials and approaches into classroom practice (Borko, Jacobs, & Koellner, 2010).

Several curriculum projects are still evolving, and, for that reason, the value of the most recent wave of curriculum reform cannot yet be evaluated properly. Nevertheless, the first results of some leading projects focusing on the use of contexts were quite promising (Bennet & Lubben, 2006; Bulte, Westbroek, De Jong, & Pilot, 2006; Parchmann et al, 2006; Schwartz, 2006). In general, students showed an active involvement in learning activities and they positively valued the relevance of contexts given. Teachers who were involved in designing and teaching context-based materials changed the focus of their classroom work towards a more context-based and student-oriented teaching approach. Further research is needed to get a deeper insight into factors that promote or hinder successful chemistry curricula innovations.

For each wave of chemistry education reform, some characteristic issues and teacher preparation approaches are summarised in Table 1. Finally, it can be noted that the interest in computer-assisted instruction (CAI) arose between the second and third wave of reform, followed by the growing use of the Internet and computer-based multimedia tools in chemistry education practice.

Table 1
Chemistry Education Reform, Characteristic Issues, and Teacher Preparation

Wave of reform	*Characteristic issue*	*Teacher preparation approach*
1960s	* Availability of student data books * High school labs with 'cookbook' tasks	* Teacher guides, short workshops * Focus mainly on content
1980s	* Context-based teaching approaches * Inquiry tasks for students	* Extended inservice courses *Focus also on teaching strategies
1990s/2000s	* Meaningful connections between contexts and concepts * 'Nature-of-chemistry' issues, such as chemistry models and open-inquiry	* Learning communities of expert and teachers * Focus on common development of teaching and learning modules

CONTEXTS IN CHEMISTRY EDUCATION

Domains of Origin

One of the most promising contributions abolishing curriculum content isolation is the use of relevant and meaningful contexts for teaching chemistry topics (Bennett & Holman, 2002). The concept of 'context' is a 'container' concept, that is, it can be defined in several ways. In general, contexts are often considered as situations in which chemistry or other science concepts, processes, and so on, can help communicate meaning to students. This definition can be expanded by the notion that contexts can also be described as practices that help students to give meaning to activities in the high school lab such as inquiry and designing. Gilbert (2006) has elaborated the nature of contexts in chemistry education and suggested the use of contexts that are based on physical settings, together with their cultural justifications, and which are taught from a socio-cultural perspective on learning. Contexts can be classified by looking at the domain of origin (cf. Van Aalsvoort, 2004). The following distinction can be made:

a) Contexts taken from the *personal domain* are important because high high schools should contribute to the personal development of students by connecting science and technology with their everyday lives. For instance, the issue of clothes and what they are made of can be linked to fibres, threads, fabrics, their applications, and the relationship between properties and structure of materials and chemical substances (Campbell, Lazonby, Millar, Nicolson, Ramsden, & Waddington, 1994).

b) Contexts taken from the *social and society domain* are important because high schools should be preparing students for their roles as responsible citizens who are able to participate in debates on science and technology and their impact on social issues. For instance, the contexts of public discussions about low-fat and low-carbohydrate diets can be used to promote learning about carbohydrates and fats in chemistry and to foster students' competency in reflecting upon the use of chemistry-related information in everyday life (Marks, Bertram, & Eilks, 2008).

c) Contexts taken from the *professional practice domain* are relevant because high schools should prepare students for their coming role as professional workers in public or private areas. For instance, the practice of (bio)chemistry analysts can be related to investigations of the quality of surface water, including the use of (bio)chemistry concepts and procedures for determining the presence of (non)acceptable substances (Van Aalsvoort, 2004).

d) Contexts taken from the *scientific and technological domain* are relevant because high schools should contribute to the development of scientific and technological literacy of students. For instance, the context of modelling drinking water treatment can be used to foster students' epistemological view on models and modelling (Prins, Bulte, & Pilot, 2011).

Relationship between Contexts and Concepts

Contexts and concepts can be related in multiple ways. For instance, the context of the greenhouse effect can be linked with several concepts, such as the chemistry concept of gas reactions and the physics concepts of infrared radiation and heat. Conversely, one concept can be related to several contexts, for instance, the concept of tap water can be linked with a personal/societal context as well as a chemistry context. Note that the meaning of a concept can vary with the related context. For instance, in a personal/societal context, tap water is considered as pure because it looks clear and it is safe to drink (according to the requirements of the law), but in a chemistry context, tap water is not defined as pure because it contains other substances.

Another kind of relationship between contexts and concepts is the sequence of presentation in teaching. This order can vary, and, for that reason, the function of contexts can also vary (see Table 2). In quite traditional approaches in the context-based teaching of chemistry, two functions of contexts are dominant. First, contexts are presented as illustrations of concepts that already have been taught, especially in the case of abstract concepts. Second, contexts are presented to offer the possibility to students of applying their knowledge of a concept. For instance, at the end of a series of lessons about acids and bases, students can be asked what type of solution they would use at home to apply to a wasp sting (George & Lubben, 2002). In more modern approaches, two other functions of contexts are emphasised. First, contexts are presented as the starting point or rationale for teaching concepts. For instance, at the beginning of teaching a topic, students can be asked to write a short story on an experience they have had related to the topic (George & Lubben, 2000). Second, these contexts not only have an orienting function, but can also enhance motivation for learning new concepts. In some recent approaches, both orders of presentation of contexts are combined. For instance, an introductory context on the water-absorbing capacity of a diaper can be linked to relevant organic chemistry concepts while thereafter the acquired knowledge can be applied in a follow-up context of fire-resistant materials (Stolk, De Jong, Bulte, & Pilot, 2011).

Table 2
Trends in Context-based Approaches and Functions of Contexts

Context-based approach	*Dominant function of context*
* Contexts follow concepts (quite traditional)	* Illustration of concepts * Application of conceptual knowledge
* Contexts precede concepts (more modern)	* Orientation on topics * Motivation for learning topics
* Contexts precede concepts and (other) contexts follow them (quite recent)	* All functions given above

Teachers' Views on Context-based Chemistry Teaching

Although nearly every chemistry teacher has his or her personal opinion about the value of context-based teaching, only a few studies have explored teachers' views in a systematic way. Some of these studies are reviewed below.

Bennet, Gräsel, Parchmann, and Waddington (2005) reported on teachers' views by comparing two groups of British chemistry teachers. The first group of teachers had experience teaching a particular context-based course, namely Salters Advanced Chemistry (SAC). The other group of teachers had experience teaching conventional chemistry courses only, but it was known that most of them were familiar with the SAC materials. The results of the study showed that, in general, both groups agreed that context-based teaching had positive effects on students' motivation and interest and that student taught by this approach would be more likely to go to university to study chemistry. Both groups also agreed that students enrolled in a context-based course would be better able to study independently but would find it more demanding to study chemistry. However, the results also indicated differences in views between the two groups. The conventional course teachers were unconvinced that the context-based course delivered the concepts in sufficient depth. In contrast, the SAC teachers believed that their course did indeed cover the concepts adequately and that there were significant advantages in using the context-based approach as a good foundation for further study at the university.

In another study of teachers' views, Marks et al. (2008) found that German chemistry teachers reported a very active and motivating learning atmosphere when they were involved in context-based lessons. These results correspond with the outcomes of a similar British study reported by Millar (2006).

In general, studies of teachers' views showed that chemistry teachers have positive thoughts about the influence of context-based teaching on students' interest, but they think differently about the impact on students' learning outcomes. Research on this impact is addressed in the next subsection.

Vignette

In a senior high school class, students conduct an experiment on the liquid-absorbing capacity of a disposable diaper. This experiment functions as an introductory context for learning about structure-property relationship at polymers. Later on, in an inservice course for teachers, the teacher reports on the use of this context as follows:

> *"That diaper was full of water (. . .). I could not get it out of the diaper. But there was a very strong boy who tried to squeeze it out. He squeezed too hard, and the filling squirted out of the diaper. However, he did not get the water out. From that moment, that diaper passed from hand to hand, and they were deeply involved".*

This observation of a classroom event is taken from a study by Stolk, De Jong, Bulte, and Pilot (2011) and shows the motivating power of an introductory context.

Effects of Context-based Chemistry Teaching on Students' Understanding and Motivation

It is not easy to come to a unanimous judgment about effects of context-based chemistry teaching on students' learning outcomes and motivation.

Some studies indicated that there is no advantage of context-based courses in terms of the development of students' understanding. For instance, Ramsden (1997) compared the effects of a context-based course and a more traditional course to British high school students' understanding of key chemistry concepts. Her study indicated that there is no difference in levels of understanding of concepts such as element and compound, chemical reaction, and the periodic table. However, other studies reported some advantages to students in context-based courses in terms of their understanding. For instance, Barker and Millar (2000) undertook a comparative study of British high school students enrolled in a context-based course or a conventional course. They found a slight advantage in students' development of an understanding of chemical bonding and thermodynamics among students in the context-based course. Nevertheless, they also reported the tenacity of a number of misunderstandings among students of both groups.

Some studies have also looked at effects on students' motivation. The comparative study of Ramsden (1997), dealing with British high school chemistry students, showed some benefits associated with a context-based approach in terms of stimulating students' interest in chemistry. Vaino, Holbrook and Rannikmäe (2012) reported that students from Estonian high schools were much more willing to engage with context-based chemistry modules than with more traditional materials.

A meta-analysis of 17 studies, from eight different countries, on the effects of context-based (and STS) approaches was reported by Bennett, Lubben, and Hogarth (2007). They reviewed studies of approaches that use contexts as the starting point for the development of scientific ideas. Their in-depth systematic review findings indicated that context-based/STS approaches resulted in improved student motivation and fostered positive attitudes toward science in general. The review results also showed that the understanding of scientific ideas developed is comparable to that of conventional approaches.

In conclusion, the outcomes of context-based science teaching are positive from an affective development perspective, but they are somewhat disappointing from a cognitive development point of view. A comparison between context-based approaches and traditional approaches has methodological limitations. It may be that the conceptual learning outcomes of context-based approaches are of a qualitatively different kind, for instance students may learn concepts more deeply. Another potential factor is the difficulty of effectively implementing connections between contexts and underlying concepts that are meaningful for students. This implementation problem is reported in some studies of recent projects and will be elaborated in the subsection after the next subsection.

Four-phase Model of Context-based Chemistry Teaching

Two recent examples of context-based curriculum projects are the German project 'Chemie im Kontext' (ChiK), and the Dutch project 'New Chemistry' (NC). In both projects, university experts and teachers worked together in learning communities to transform a curricular framework, developed by the experts and derived from theories and relevant empirical data, into teaching and learning practice. The communities focused on the development, implementation and evaluation of units for a range of chemistry topics.

In the ChiK project, these units usually fit a four-phase model of teaching (Parchmann et al., 2006). In the introductory phase, a context is introduced to students by using authentic material often from media such as newspapers and TV-clips. A relevant context can be the traffic-related issue of developing hydrogen cars for the near future. This is likely to fit students' interest and allows possibilities for students to investigate aspects of the context in a scientific way. In the next phase of curiosity and planning, students identify questions concerning the given context, for which they want to find answers, and they make plans regarding how to address these questions. The focus is on what chemistry can contribute to clarify the issue. The teacher helps to structure the questions and give suggestions about how to carry out the investigations. Subsequently, in the phase of elaboration, teachers guide the students when they undertake the necessary inquiry to find answers to their questions, for instance by exploring types and function of fuel cells. The results are presented and discussed. Finally, in the phase of deepening and connecting, students reflect on the presented results, for instance by discussing future possibilities, and they apply their knowledge, for instance by studying the use of energy in other contexts.

In the NC project, a quite similar multi-phased teaching model is used (Bulte, et al., 2006). In the introductory phase of orientation and motivation, a context is introduced that motivates students to become involved in the unit, for instance an investigation of the water-absorbing capacity of disposable diapers. In the following phase, students become aware that their existing knowledge is insufficient to answer questions that are raised by the context given, for instance to explain the surprisingly large amount of water uptake by the diaper. Subsequently, in the phase of extending knowledge, students look for answers by studying relevant underlying concepts in their chemistry textbook and other sources of information. For instance students may seek information about the structure of water-absorbing materials and properties of constituent polymers. The teachers guide the presentation and discussion of the results. Finally, in the phase of reflection and application, students reflect on what they have learned and apply their knowledge of chemistry concepts they have studied previously, for instance by investigating super absorbent polymers in the context of fire-resistant materials.

Although there are slight differences between the two teaching models, the core of the models can be combined; the result is given in Table 3.

Table 3
Four-phase Model of Context-based Chemistry Teaching

Phase of context-based teaching	*Aim of the phase*
Phase 1 * Offering an introductory context	* Orientating students to the unit * Motivating students to become involved
Phase 2 * Structuring meaningful questions * Suggesting search procedures	* Inducing a 'need-to-know' * Preparing students for finding answers
Phase 3 * Guiding students' inquiry * Guiding presentations and discussions	* Extending students' knowledge of chemistry * Communicating this knowledge
Phase 4 * Supporting students' reflections * Suggesting a follow-up context	* Deepening students' knowledge * Inducing a 'need-to-apply'

Empowering Chemistry Teachers for Modern Context-based Teaching

During the last decade there has been a growing interest in involving chemistry high school teachers in an early stage of curriculum reform, especially in case of new context-based curricula. This often implied that teachers not only taught new modules but also cooperated with experts in the preceding stage of designing teaching and learning materials. Studies reported a positive impact of involvement in designing activities on teaching the results. For instance, German teachers involved in designing ChiK units became empowered for more context-based and student-oriented teaching than before their involvement (Parchmann, et al., 2006). Another comparative study indicated that Dutch science teachers, among them chemistry teachers, who were involved in teams for designing context-based materials showed more context-based competence than their non-designing colleagues (De Putter-Smits, Taconis, Jochems, & Van Driel, 2012).

Several studies reported on a specific difficulty in teaching context-based materials. Regarding the ChiK project, Parchmann, et al. (2006) found that, although students became aware of the relevance of chemistry in everyday life and societal issues, they sometimes experienced a sense of getting lost in the context. In line with this outcome, Vos, Taconis, Jochems, and Pilot (2011) reported that ChiK teachers encountered difficulties in taking students' questions, evoked by the introductory context, and using them as an orientation event for the subsequent lessons. In these lessons, students and teachers explored the content of the questions and look for possible answers by investigating underlying concepts, for instance through high school laboratory work. However, the contexts given were too general and broad to be effectively applicable as a setting in which such activities as students developing their ideas and exploring them systematically could take place.

A similar hindering factor is reported by Stolk, De Jong, Bulte, and Pilot (2011) in a study of the implementation of the first version of a NC teaching unit. When preparing interested teachers in how to implement the unit in their classroom, university experts asked them to design strategies for connecting the introductory context with related chemistry concepts. Some teachers wanted to use a 'look for unknown words' teaching strategy. That is, after the context, students should read the background text in the unit and when they stumble upon a word they do not understand they can look it up in their textbook. Other teachers wanted to use a 'carefully guiding' approach focused on helping students in shifting focus from the context to related concepts. After applying these strategies, it became clear to the teachers that their approaches were not sufficient to evoke the students' need-to-know sufficiently for connecting context and concepts. In a follow-up study of the revised version of the unit, Stolk, Bulte, De Jong, and Pilot (2012) reported that the teachers wanted to select and reformulate students' questions about the given context in such a way that students were encouraged to find answers to their own questions by using appropriate chemistry concepts. The teachers appreciated the application of this strategy, and, afterwards, they designed a set of 'do's and don'ts' for handling students questions. Most teachers considered this set useful for their teaching practice, although its contribution to stimulating students to connect context with concepts is still unclear.

In conclusion, the outcomes of these projects suggest that a crucial aspect of context-based teaching, viz. connecting an introductory context with underlying concepts in a meaningful way for students, is difficult to implement. This difficulty can explain why the outcomes of context-based teaching have been somewhat disappointing from a conceptual development point of view (see two subsections earlier). Revisions of the existing projects are needed to improve relevant curriculum materials and to further empower teachers for context-based chemistry teaching.

MODELS: CHEMICAL PHENOMENA, CHEMICAL CONCEPTS, AND THE MOLECULAR REALM

There are many kinds of models relevant to chemistry teaching and learning (Harrison & Treagust, 2000b). Developing models is a major part of the scientific enterprise (Rosenblueth & Wiener, 1945; Develaki, 2007), and some of those scientific models, in particular those posited as representing the structure of matter at submicroscopic scales, will be the core concern here. However, it is also important to acknowledge that in forming a chemistry curriculum (or preparing a textbook) there is usually a process of both selecting and simplifying those scientific models that are considered important and accessible at the educational level concerned. This is not a trivial matter, and the presentation of models in chemistry curriculum / textbooks has been criticised for failing to offer authentic current or historical scientific models (Justi & Gilbert, 2000).

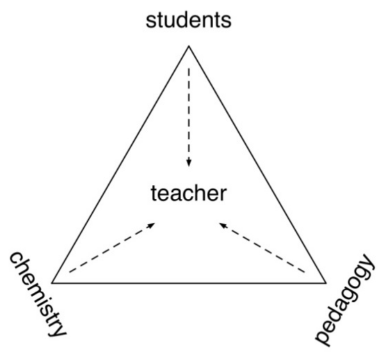


FIGURE 1. Teaching decisions are informed by the teacher's knowledge of the subject matter, the learners and pedagogic principles. (Redrawn from Taber, 2000)

Moreover, it is well recognised that the intended curriculum does not always become the enacted curriculum (Keys, 2005). Teachers may offer distorted versions of curricular models, and this may occur inadvertently (perhaps due to limited teacher subject knowledge); regretfully (e.g. due to pressures to complete scheduled teaching in limited contact time); or deliberately – for example where the teacher judges the need to mediate between a formal model that is considered too difficult for a particular class, and what is judged likely to be suitable as target knowledge for those learners (cf. Figure 1). Here the aim of the teacher will be to find the optimal level of simplification accessible to students whilst providing as authentic a representation of the science as possible.

Teachers use a range of teaching models including physical models (such as ball-and-stick models of molecular structure, or glued spheres showing crystal structure); computer simulations (e.g. showing how the speed of gas particles changes with temperature; or showing how changing the conditions of an industrial process effects yield or costs); simplified diagrams, and various figures of speech, such as simile and analogy.

Very commonly, teachers draw upon the social world as a source of familiar comparisons for the rather unfamiliar properties of submicroscopic entities (Dagher & Cossman, 1992; Talanquer, 2007): atoms are said to like to 'share' electrons; molecules may be said to 'want' to break free of the crowd and get some personal space during evaporation; or electrons may be said to behave like people on buses – preferring to sit next to an empty seat where possible rather than sitting next to another electron. Even some technical terms retain traces of anthropomorphism: electrophiles, nucleophilic substitution, hydrophobic, chemical affinity and so on. Sometimes similes or analogies become so familiar among chemists and chemistry teachers, that we may not even notice we are using them. The example of 'sharing' electrons in covalent bonding is one example: the idea that electrons 'spin' is another.

The Nature of Models

Scientific models may be developed as part of the process of scientific work itself, developed – at least initially - as thinking tools, and so judged successful if they suggest fruitful hypotheses and productive paths for empirical work allowing further progress to be made.

Simulations may play a similar role – whether carried out as thought experiments in the mind of scientists (Brown, 1991; Gilbert, 2005), or modelled in some kind of computer (analog or digital) – they allow conjectures - about mechanism, for example - to be subjected to critique.

Scientists communicating abstract results may refer to a model that has potential to make the unfamiliar more familiar (Muldoon, 2006). Teaching is often about taking something unfamiliar and introducing it to learners by showing how, in some respects, the unfamiliar thing or idea is somewhat like something we already know about and are quite comfortable with. For example, teachers may assume shared understanding with learners of a familiar social schema where a more attractive partner displaces the less attractive partner that a young person was dancing with or talking to: so, they may suggest that competition/displacement reactions are *a bit like that*: the petite fluorine replacing the more rotund iodine to win the affections of the fickle potassium. That is, teachers develop (or adopt from other teachers) teaching models that they consider accessible to learners as a means of mediating between formal curriculum models and students' existing knowledge and understanding (Harrison, 2001).

Learners' Notions of Models and Modelling

This general strategy of looking to make the unfamiliar familiar fits well with the constructivist approach to thinking about teaching and learning considered below. However, it is important to acknowledge that students may lack the epistemological sophistication to understand the nature of the models, analogies and similes that we so readily use in teaching. Research suggests that many younger secondary level students will primarily think of models in terms of scale replicas (like model cars or aircraft), and growing appreciation of more abstract types of modelling may only develop slowly (Driver, Leach, Millar, & Scott, 1996; Treagust, Chittleborough, & Mamiala, 2002). So when showing learners a structural model of a molecule or arrangement of atomic cores in a crystal, it is quite likely that students will consider that the 'real' thing is just the same, only a lot smaller. This may be particularly problematic when we are modelling the submicroscopic scale of matter because (as will be discussed below) we do *not* think what we are representing *is* like a lot of spheres stuck together, or balls connected with sticks: rather our physical models are attempts to represent some key aspects of a molecular world which is quite unlike the things of common experience.

One of the consequences of a limited appreciation of the nature of models is that in teaching we often present series of quite incompatible models which if taken literally (as students may often do) cannot all be valid, leading to confusion and commonly a sense that in chemistry we teach things we know are wrong, only to later dismiss and replace them as students progress through the subject. Examples would include what we understand by 'acid', or 'oxidation', or 'metal', and in particular when we teach about atomic and molecular structure and bonding (discussed in more detail below). This can be frustrating for learners, and if we are going to teach through models (which is surely inevitable in chemistry) we must also teach *about* models and modelling so learners appreciate the purposes, natures and limitations of the models they are introduced to (Taber, 2010). The importance of teaching learners about the nature and role of modelling as part of science education is increasingly being recognised in curriculum development and reform – for example in the United States (NRC, 2012), England (QCA, 2007) and Australia (ACARA, 2012).

There is now a great deal of work exploring teaching and learning with analogies (Harrison & Coll, 2008; Mozzer, & Justi, 2011; Haglund & Jeppsson, 2012). It is now recognised that it is important to point out which features of an analogue are not to be carried over to a target (Taber, 2001b), as well as stressing those that are. In many ways the same advice should be adopted when we use other types of models in our chemistry teaching as well.

Anthropomorphism in Chemistry Learning

The tendency to describe the world of atoms and molecules as if such entities are actors in a tiny social world is almost ubiquitous in chemistry teaching. In part this may indicate something about the human psyche, and reflects Piaget's (1929/1973) findings with young children who readily engage in anthropomorphism to explain natural phenomena; but its commonplace nature also reflects how teachers find it a successful strategy: learners do tend to remember the stories of heartbreak on the atomic dance-floor, and seem to relate to notions of atoms that are driven to fill their shells, and find both cooperative (i.e., sharing) and more aggressive (i.e., electron transfer) ways to do this.

Such narratives seem to be effective ways of initially making the abstract world of molecules and ions accessible to learners, but what is somewhat less well understood is how those stories support (or perhaps impede) further conceptual development. It is clear that in many cases students seem to retain these social descriptions of molecular behaviour long after being taught more abstract formal models, and often it is the social accounts which are most readily brought to mind. There are important questions about whether and when the teacher's use of 'weak' anthropomorphism (as a means to help students get an initial grasp on an abstract idea) tends to lead to a stronger form of anthropomorphism where these social accounts are adopted as satisfactory explanations so that learners are less open to the more authentic scientific accounts they meet later (Taber & Watts, 1996). Clement (2008) argues that the most useful models have explanatory power, and gives the example of the "analogue of a pole vaulter … used to introduce the idea of activation energy for a reaction", pointing out that the analogy offers no explanation of the target physical system. It seems sensible for teachers to make clear to students that these ideas are only meant as introductory analogies, and to seek to move student thinking on as soon as possible.

The Centrality of Substance, and the Epistemic Significance of Particles

Certain concepts within a discipline can be considered central in the sense that they provide structure for whole areas of knowledge - Fensham (1975) referred to them as 'big concepts'. Other concepts may be important from a pedagogic perspective because they act as 'threshold' concepts (Park & Light, 2008) that learners must master in making progress towards understanding the big concepts of the subject. For students to begin to appreciate some key ('big') chemical concepts (such as chemical reactions and chemical bonding) that are used to make sense of much of the subject, they need to already have an understanding of the basic particle theory, i.e., that apparently continuous matter is quantised, being comprised of myriad tiny 'particles'. This is something that is not intuitively obvious, especially in the case of large pieces of materials like metal, plastic or glass.

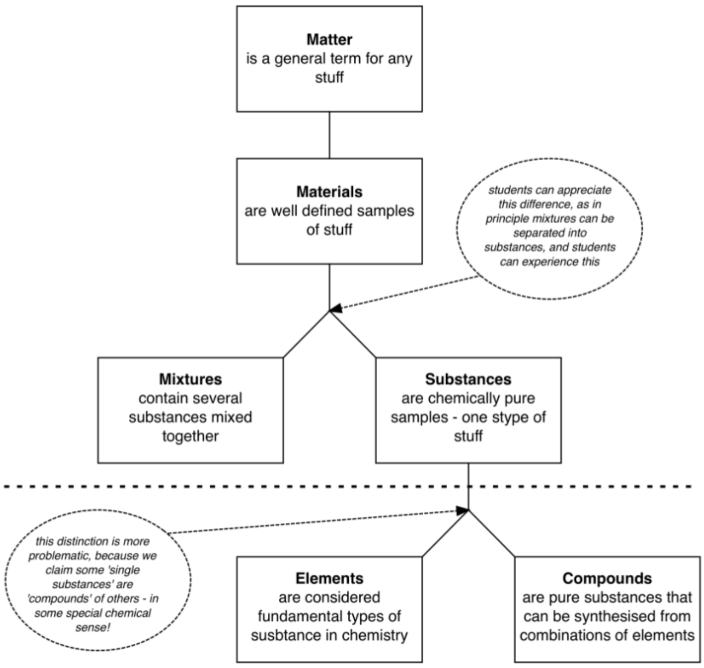


FIGURE 2. Fundamental distinctions that are important in teaching chemistry (after Taber, 2012b)

Indeed the reference to materials here reflects an important complication in teaching introductory chemistry. Chemistry is a science that is primarily concerned with substances. The notion of substance is not only central to chemistry, but can only be fully appreciated from within the framework of the discipline. Substances are often considered to be fundamental types of matter, of which pure samples can in principle be obtained. In terms of the internal logic of the subject discipline, teaching about this substance – mixture distinction should precede teaching about elements and compounds, as suggested in Figure 2. Yet in everyday life, outside of the chemistry classroom, nearly all of the materials that youngsters are familiar with are more complex than substances, often being mixtures (e.g. alloys, the air, fruit juice) or composites of various kinds (e.g. wood; milk; rocks).

In effect, we have *a conceptual model* here that is assumed as the basis of chemistry and much chemistry teaching: the various everyday materials found around us can be considered to be mixtures or composites of (and so more complicated than) the more basic special types of material called substances. This conceptual model underpins the teaching of a subject which, in many curriculum contexts, initially ignores the majority of materials learners encounter in their everyday lives outside the laboratory, and instead asks students to learn about substances that most learners will never directly encounter anywhere *but* in the teaching laboratory.

Substance is a threshold concept in learning chemistry as the distinction between materials that can be considered samples of single substances, and those which are not, is fundamental to making sense of chemical reactions (see later in this chapter) as changes in which some substances are changed into different substances. There is a sense in which the compound water contains or incorporates *the element* hydrogen, even though it certainly does not contain *the substance* hydrogen as that sample of hydrogen no longer existed once it is reacted to form water. Hydrogen, the element, is considered to have some kind of essence which is retained in all its compounds, allowing the element hydrogen to be parts of many substances each with their own unique set of chemical and physical properties.

All of this can begin to make good sense when we adopt a model of matter at the submicroscopic level that allows us to appreciate what it is of an element that is conserved when reactions take place. The 'particle' models of matter that are ubiquitous in chemistry teaching are arguably essential to make good sense of the most fundamental concepts of the subject (substance, and chemical change).

The Centrality of Particle Models in Learning Chemistry

For the chemist, models of the world at the submicroscopic scale of molecules, ions and electrons do useful explanatory work, because the properties of those 'particles' (i.e. the molecules, ions, electrons etc) are understood to interact to give rise to structures at the phenomenological macroscopic level, so lead to the emergent properties that can be observed. This has long been a metaphysical premise of chemistry, but with the advent of nanoscience is increasingly being demonstrated by empirical studies (Sadownik & Ulijn, 2010; Stoddart, 2012). The interactions are therefore very important in this explanatory scheme, and thus the notion of chemical bonding (considered later in the Chapter), and its significance as part of an academic course in chemistry.

So, as a general rule, the properties of the 'particles' themselves are not the same as those of the bulk material, but rather the bulk properties are an emergent property of the systems of 'particles'. So, for example, a solid may be hard because this is an emergent property, at the macroscopic level of phenomena, of the system of 'particles' – the structure that emerges when the 'particles' interact. It is neither helpful nor meaningful to consider the individual submicroscopic particles as 'hard'. The particle-theory is useful because it offers explanations of bench-level phenomena in terms of the *rather different* properties of the conjectured submicroscopic particles from which matter is considered to be composed.

'Particle' as Analogy

In effect, in referring to molecules and ions as particles, the term 'particle' is being extended from its everyday meaning and used to describe entities that are quite different from familiar particles because they are at a scale where their quantum nature gives them properties *unlike* traditional particles. The 'particles' of particle theory, are *particles by analogy*, but unlike the particles of everyday phenomena, such as the billiard balls to which they are often compared, do not necessarily have precise location in space (for example) or discrete edges. So we may 'map' out the 'location' of electrons in terms of probability distributions and electron density diagrams and consider that atoms overlap so that two of these 'particles' may occupy the same space (in a way two billiard balls do not). Molecules and ions do not have bound surfaces (even if for simplicity we sometimes represent them as if they do), but rather become increasingly more tenuous over extended distances.

It is worth focusing on these features because they are significant in understanding the properties of entities such as electrons, molecules and ions, *and* because they are in sharp contrast to the familiar particles – granules of salt or sugar, grains of sand, etc - that are part of the common experience of learners and which therefore provide a fairly poor model of the nature of the theoretical entities (molecules, ions, etc) that are being conjectured when chemists think of particles at the molecular scale. Yet, we know that although students often accept our teaching about everything being made of tiny particles, they very commonly misunderstand the particle model (Adbo & Taber, 2009; Johnson & Papageorgiou, 2010) - as we would expect from the constructivist notion that new meaningful learning can only occur by building upon existing understandings.

Common Misunderstanding 1: Misjudging Scale

A common misunderstanding of teaching is that the particles being referred to are the specks and grains and granules that are directly perceptible. After all, if we can see that some materials are made of these tiny particles, then it is not so inconceivable that all particles are actually composed of this type of particle, even if it is not always obvious to the naked eye. This is perhaps not such a serious misconception (except that it may reinforce the second learning difficulty to be described next), in that *if* students can accept this general principle it is only a matter of shifting the degree of granularity to persuade students that we are talking about a much smaller scale beyond the limits of the most powerful (optical) microscopes.

Common Misunderstanding 2: Misjudging Type

More serious, however, is the very common misunderstanding that the particles being presented in chemistry lessons are just like familiar particles, but a great deal smaller. This might be a useful starting point (i.e. an opportunity to 'anchor' a new idea in the learner's existing conceptual structure), but students are likely to think they have understood the teaching, whilst completely missing the most important point that these 'particles' are not like familiar particles, but rather have quite different properties than those we are familiar with at the phenomenological level.

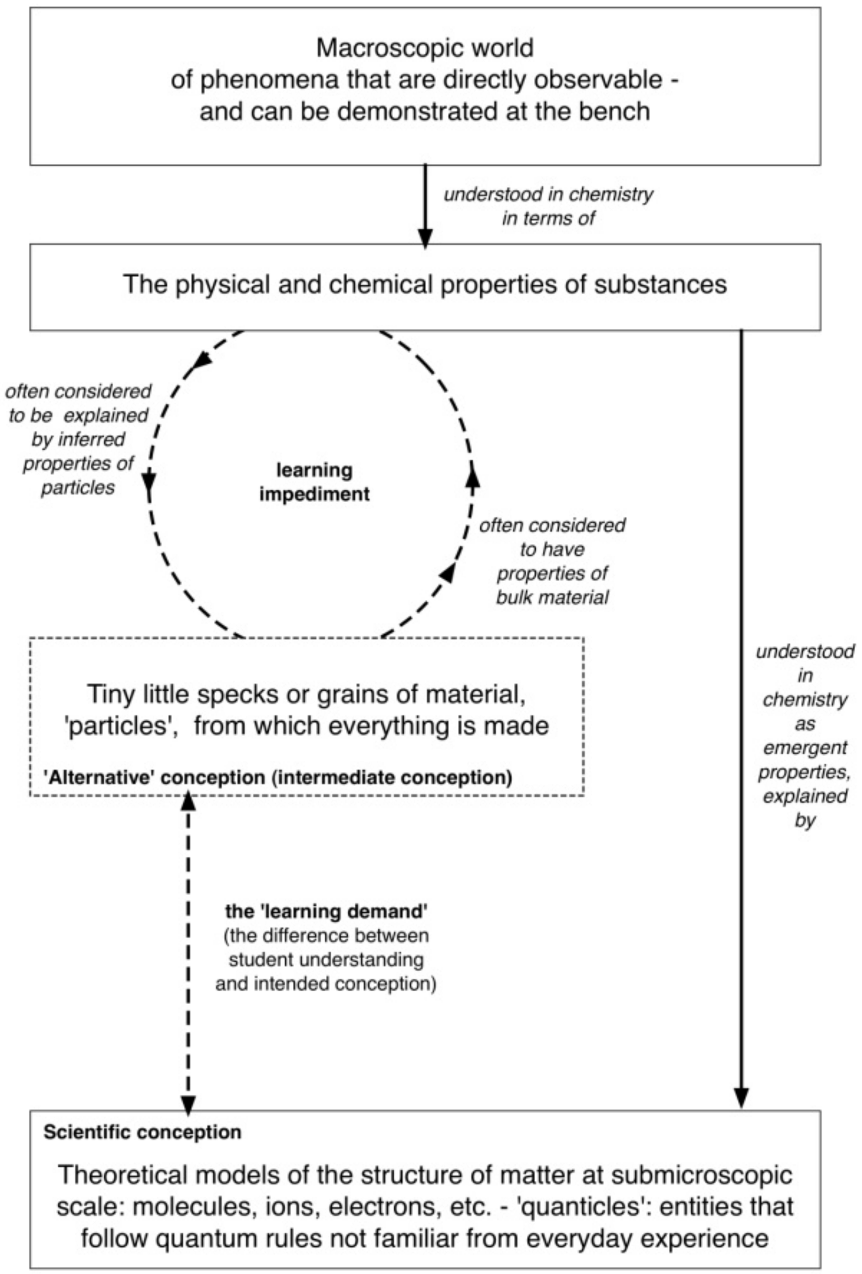


FIGURE 3. A common student misconception of the nature of submicroscopic particles invoked in chemistry lessons

Learners who acquire this idea will tend to invoke circular reasoning when using the particle models to produce explanations of phenomena (Taber, 2001a). This is shown in Figure 3, which suggests that it is common for students to take from teaching about 'particles' an alternative conception that, unlike the scientific conception, has limited explanatory value. So for example, if a learner thinks that butter is made up of a great many 'butter' particles that are soft (because butter is soft) they may seek to then suggest that butter is soft *because* it is made of soft particles. This misses the key feature of the scientific model (that macroscopic properties emerge from the interactions of entities with quite different properties), and results in tautological explanations based on such notions as, e.g., glass is made up of transparent particles; wax particles melt easily; copper particles are conductors, etc. In many of these cases, the chemical bonding between the individual submicroscopic entities is a core part of the scientific explanation for how the macroscopic properties emerge, but the learner's explanation completely ignores this when they assume that the property of the bulk material simply reflects the properties of the individual particles from which it is made.

From a constructivist perspective, the teacher needs to plan the presentation of a new concept so that it will be connected to a student's existing conceptual structures such that the concept will be understood in the way intended. The vast literature on students' 'misconceptions' (Duit, 2009; Taber, 2009b) suggests teaching-learning can readily go wrong (Gilbert, Osborne, & Fensham, 1982): it is a complex system that readily admits 'learning impediments' (cf. Bachelard, 1940/1968). Indeed analysis of what is involved in effective teaching for understanding suggests a range of different types of learning impediment may occur when teaching is not well matched to the specifics of a learner's existing conceptual frameworks (Taber, 2005) - and in any class, each learner brings their own idiosyncratic prior learning. The present case offers an amalgam of potential difficulties (see Figure 4).

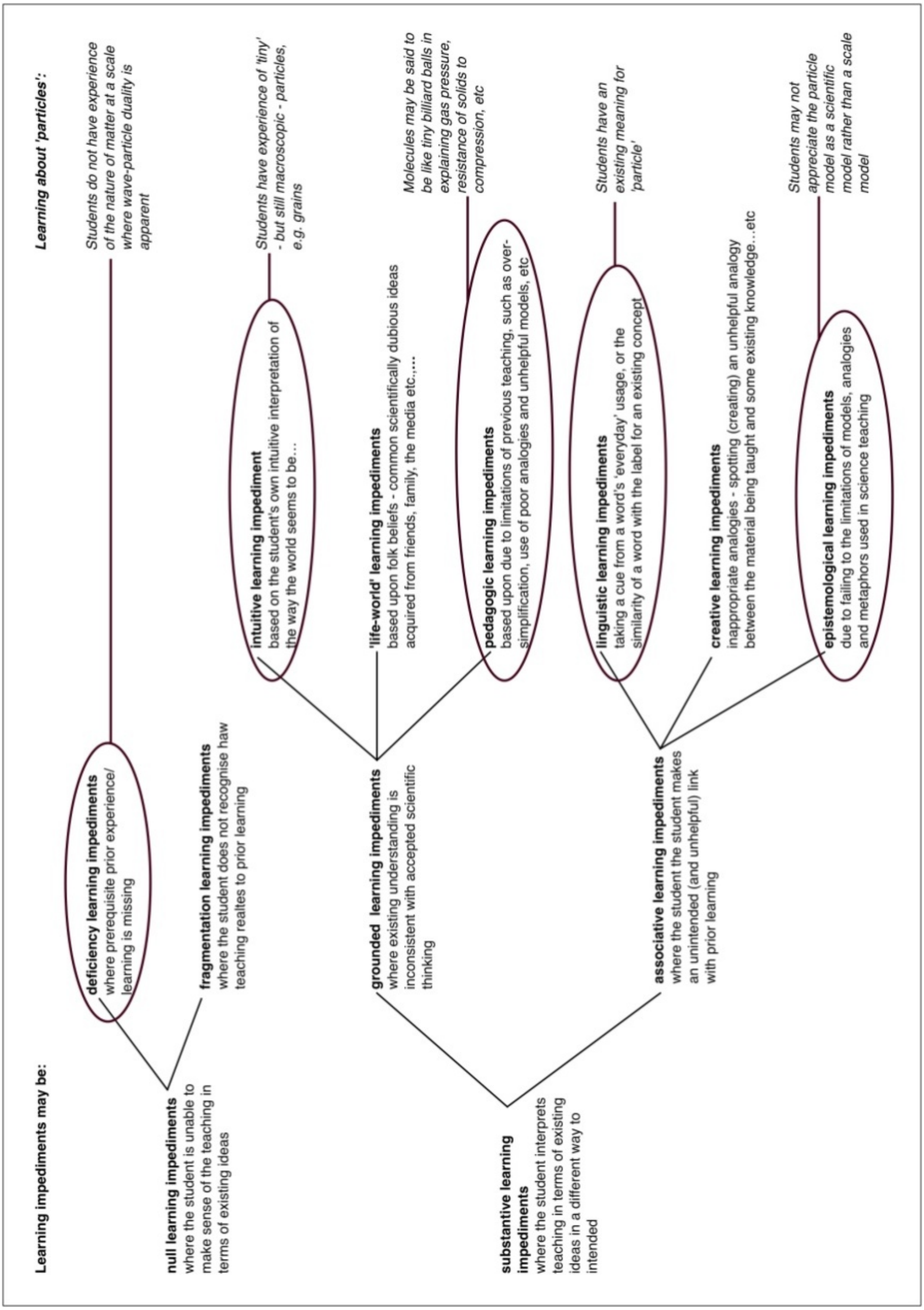


FIGURE 4. Student learning about particles can readily lead to alternative conceptions

Mediating the Multiple Meanings of Chemistry

Some decades ago, Johnstone (1991) suggested that one reason science was difficult for students was that students are commonly presented with explanations that involve being asked to think about very different types of things at the same time. He suggested that in chemistry students were asked to consider the macroscopic (tangible and visible 'macrophenomena'), the submicroscopic (molecules and ions) and the symbolic (such as formulae equations). Johnstone illustrated his point with a simple figure showing a triangle with the three apices labelled as 'macro', 'submicro' and 'symbolics' (the basis for Figure 8 below), and argued that rather than teaching being focused at one apex, or even along one side of the triangle, it often happened inside the triangle where students were expected to cope with all three domains of meaning at once. Jensen (1995) developed a similar argument, but distinguished between submicroscopic structure at the molecular and electronic levels. Jenson described how the topics taught in chemistry fit into a matrix depending upon the level of scale and three dimensions of composition and structure; energy; and time (see Figure 5).

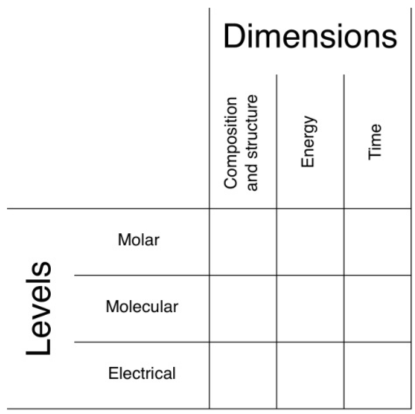


FIGURE 5. Jensen's grid setting out the logical structure of chemistry (after Jensen, 1995, p. 680).

Johnstone's (1989) key point related to the demands made upon learners when teaching required learners to think about the three domains at once, something that was informed by consideration of the limitations of information processing within the human cognitive system. Often chemistry teaching starts from an observable phenomenon – a reaction, something dissolving or crystallising, a measurement of a melting temperature – and then explains this in terms of atomic structure, intermolecular interactions and the like; accompanied by a summary of the process in terms of chemical formulae or other symbolic representations. So the learner is asked to hold in mind the phenomenon, the theoretical model, and the formal representation at the same time – potentially overloading working memory (Baddeley, 2003; Tsaparlis, 1994). Examples of learning difficulties reported are explored later in the chapter.

There are good reasons to think that much of our more advanced teaching needs to be of this kind, and given time learners can 'chunk' related information so that complex material can be more readily manipulated as a single chunk of information. However, at the introductory level, it makes sense to first teach students about a range of chemical phenomena that can be observed, and systemized, *prior to* introducing the particle theory at all. This reflects the historical development of the subject, and is equivalent to a 'natural history stage' (Driver & Erickson, 1983) of chemistry teaching where we focus on classifying substances and their reactions – and introducing suitable concepts for the classes discovered: metals, acids etc. As Johnstone (1991) pointed out, there is considerable chemistry that can be taught and learnt at the macroscopic level.

Students should be given time to acquire and consolidate chemical concepts linked to the phenomenological (macroscopic) level, and to therefore also build up a wide range of explananda to motivate an appreciation of the value of a broad explanatory scheme, before a particle model is introduced. Too often in teaching science subjects, students are offered explanations that answer questions they are not yet in a position to pose, and a period of exploring chemistry at the macroscopic level can offer intellectual motivation for then considering a theory of matter at the submicroscopic level. Chemistry at the macroscopic level needs to be represented symbolically if we are to communicate it through the specialised forms of representation used in the subject. So we have technical names for substances ('ammonia', 'hydrochloric acid', etc) and we use word equations to represent the changes we observe when substance react (or dissolve, or melt etc). There are many other aspects to the symbolic representations we use in chemistry – for example standard diagrams of apparatus set-ups, or graphs showing how the volume of a gas produced in a reaction changes over time. Learning about the particular forms of representation used in science subjects is an important part of a scientific education. However, a key subset of the symbolic representations used in chemistry allows us to bridge *between* the macroscopic phenomena and the theoretical models posited at the submicroscopic scale (see Figure 6). So when the chemistry teacher writes formulae such as H_2O or NaCl there is a valuable ambiguity in what is represented. Representations such as these might refer to *either* (a) substances that may be observed and manipulated at the bench (i.e. at macroscopic scale) or (b) the molecules and ions that are part of the theoretical models of matter at submicroscopic scale.

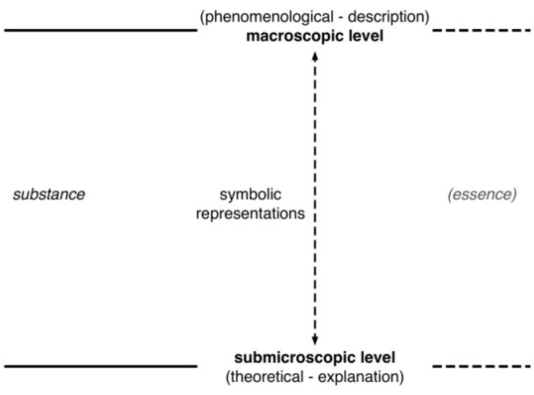


FIGURE 6. Mediating the multiple meanings of chemical discourse

This ambiguity offers an important affordance in discussing chemistry as we frequently use these symbolic representations as a bridging device to mediate between the macroscopic descriptions and the submicroscopic explanations (Taber, 2009a). So 'hydrogen' can mean either the substance or the molecules from which we consider the substance to be composed, and this can even help us with the notion that an element can be considered to have an essence which it retains in its compounds - the sense in which there is hydrogen 'in' the compound water even though it is a completely different substance with different properties.

This issue has been discussed in more detail elsewhere (Taber, 2009a), but the key points are that:

i) a major subset of the formal symbolic representations we use in chemistry can refer to both substances and 'quanticles' (submicroscopic entities such as molecules etc);

ii) this is valuable because it allows chemists and chemistry teachers to readily shift between the changes in substance they work with and the submicroscopic models used to explain those changes;

iii) but it also provides a potential area of confusion for learners if they are not sure when a representation is being used to refer to a substance or a molecule (or ions etc);

iv) therefore in teaching we should be very explicit in specifying when we are using these symbolic representations for referring to the macroscopic level of substance, and when to refer to theoretical models at the submicroscopic level, so learners can spot how we use this specialised language to shift our focus between these domains of meaning.

Having various ways to represent information is found to support learning. The forms of symbolic representation used in chemistry should be taught both because they are important in an authentic chemistry education, and because ultimately they do useful work in making sense of learning to use chemical concepts. However, it is important to pace the introduction of new material over extended periods of time so that new learning can be consolidated before it is considered available for supporting further learning (see Figure 7).

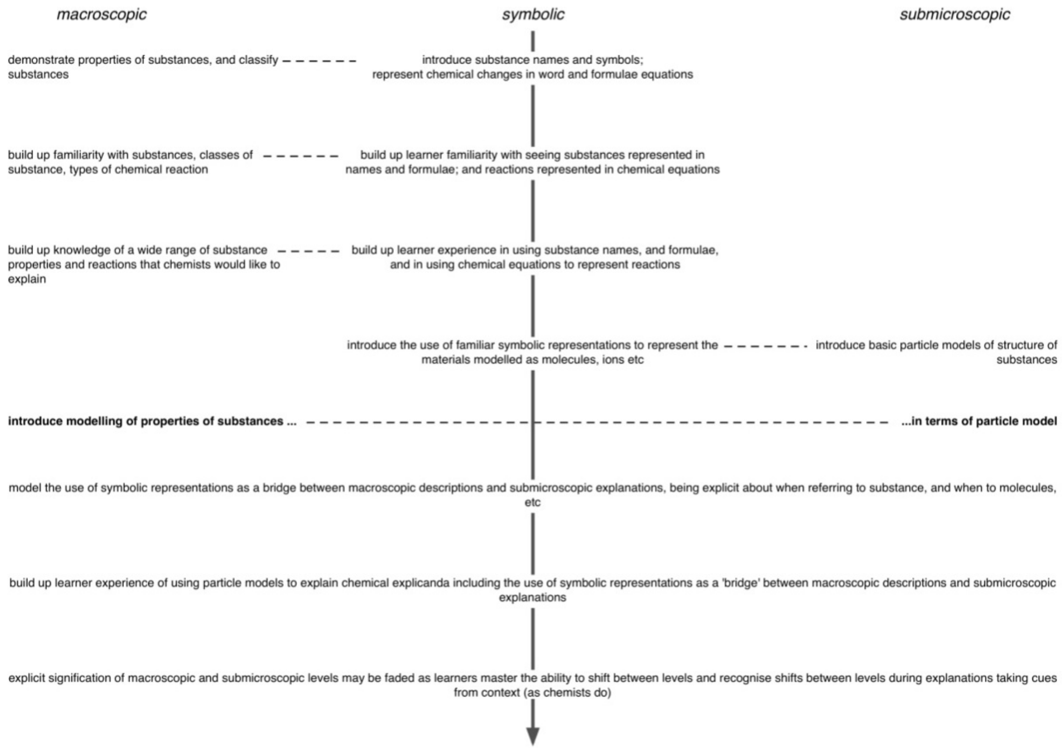


FIGURE 7. Progression in teaching learners to think like a chemist

Empowering Chemistry Teachers to Teach about Models and Modelling

Chemistry teachers should have a well-developed knowledge base concerning specific models used in chemistry and related science disciplines. They also should have a sound knowledge *about* models in general, for instance about their nature and function, and their use (modelling) in the process of developing new scientific insights in nature. Moreover, they should have adequate knowledge of how to teach specific models and modelling and how to teach general aspects of models and modelling. However, several studies have shown that, in general, teachers' knowledge about models and modelling is quite limited and so often inadequate (Harrison, 2001; Justi & Gilbert, 2002; Van Driel & Verloop, 1999). For instance, although teachers present the idea that models are simplified representations of specific parts of reality, they do not generally acknowledge the important function of models for making predictions of phenomena and they consider modelling as a straightforward, rational process (Van Driel & Verloop, 1999).

Studies of courses focusing on empowering prospective and experienced chemistry teachers to develop their knowledge about models and modelling and how to teach these issues are fairly limited. Nearly all of them concern mixed groups of science teachers that include chemistry teachers. In the realm of empowering prospective teachers, Justi and Van Driel (2005) examined a post-graduate teacher training course about models and modelling. The participants were five prospective science teachers (four of them of chemistry); they also conducted an inquiry project about this theme in their high school classes (as part of the course). The results show that the teachers developed personal knowledge about models and modelling, especially about the role of models in the development of scientific knowledge, the nature and role of modelling, and the use of both teaching models and modelling activities in teaching. De Jong, Van Driel and Verloop (2005) reported on a course about the use of particle models in teaching chemistry. The course emphasised learning *from* teaching by connecting authentic teaching experiences with institutional workshops. The participants were 12 prospective chemistry teachers. The outcomes of the study reveal that, after teaching, all prospective teachers demonstrated a deeper understanding of their students' problems with the use of particle models. In addition, about half of the participants had become more aware of the possibilities and limitations of using particle models in specific teaching situations.

In relation to empowering experienced teachers, Henze, Van Driel, and Verloop (2007) investigated the development of knowledge of teaching about models and modelling in the context of the implementation of a new syllabus, which emphasised models and modelling. The study followed nine experienced science teachers (three of them of chemistry) during the first year of this implementation. The results show three related types of knowledge development. First, the learning of model content was combined with critical reflection on the nature and role of models in science. Second, modelling as an activity undertaken by students was combined with the learning of specific model content. Third, The learning of model content involved both students' production and revision of models, and a critical examination of the nature of models in general.

In conclusion, the reported studies show the importance of courses for chemistry teachers focused on improving their knowledge about models and modelling and how to teach these issues (cf. De Jong, Blonder, & Oversby, 2013). However, studies of the design and outcomes of relevant courses are too scarce. Seeking to improve this situation will be an important challenge for chemistry education research in the near future.

INTRODUCING MULTIPLE MEANINGS OF CHEMICAL REACTIONS

Multiple Meanings

Many chemistry topics can be viewed or taught from three potential perspectives that are mutually related (Figure 8). The macroscopic perspective (hereinafter: macro domain) mainly focuses on substances and phenomena that can be observed, smelled, and so on. The submicroscopic perspective (hereinafter: submicro domain): mainly focuses on particle models for describing, explaining and predicting properties of substances and characteristics of processes. The symbolic perspective mainly focuses on symbols, formulae, equations, ionic drawings, and the like. The use of this three-cornered relationship of domains of meaning (Johnstone, 1993) plays a more dominant role in chemistry than in the other natural sciences. The triangle of meanings has been adopted by many chemistry educators, curriculum designers, and researchers, but it is also adapted in several ways. Based on a review of chemistry education literature, Talanquer (2011) reported an overview of some adaptations. For instance, macro meanings can be split up in meanings of experienced phenomena and meanings of macro models of these phenomena such as the concepts of pH and concentration. Submicro meanings can be distinguished into meanings about one single-particle and meanings about clusters of many particles. Finally, symbolic meanings can be specified as meanings of symbolic systems such as element letters and word equations and meanings of algebraic systems such as formulas and graphs. Despite all these possible refinements, Johnstone's basic triangle will be used in the present section for presenting chemistry teaching and learning issues.

In introductory chemical education, the central core content deals with the topic of chemical reactions. In primary schools, if this topic is introduced, students only have to learn the macro meaning in terms of conversions of substances. High school students should also learn the submicro meaning in terms of the rearrangement of particles (molecules, atoms, ions), and the intended meaning of symbolic representations in terms of reaction equations (words, iconic drawings, formulas). These students also should become able to switch mentally between these meanings in an adequate and flexible way.

This section addresses studies of students' conceptual difficulties related to chemical reactions that can be considered to proceed to completion, taking place in one direction. Difficulties in understanding reversible reaction types are treated elsewhere, including problems with understanding the nature of equilibrium reactions and factors influencing the equilibrium position (Van Driel & Graeber, 2002), and specific reaction types such as acid-base reactions (Drechsler & Schmidt, 2005), and redox reactions (De Jong & Treagust, 2002). The present section also offers explanations of the reported difficulties by analyzing three interrelated factors: the student, the chemistry content, and the teacher/textbook. Courses aiming at preventing and responding to students' difficulties are discussed. Suggestions for improving the teaching of chemical reactions are also presented.

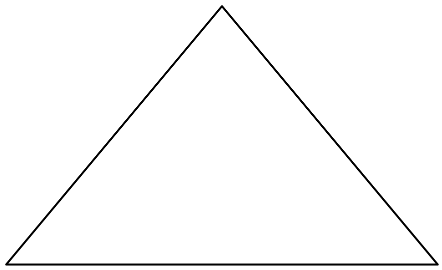


FIGURE 8. The triangle of meanings

Student Learning Difficulties

In the last two decades, numerous articles on students' difficulties in understanding multiple meanings of chemical reactions have been published. The following list of important recurrent difficulties has been compiled from studies and reviews by Ahtee and Varjola (1998), Chandrasegaran, Treagust, and Mocerino (2007), Cheng and Gilbert (2009), Kern, Wood, Roehrig, and Nyachwaya, (2010), Lőfgren and Helldén (2009), and Krnel, Watson, and Glazar (1998).

Recurrent difficulties with the *macro meaning* are:

* Students may fail to recognise a process as a chemical change, through lack of sufficient knowledge of substance identity. For instance, students may interpret the product of a chemical change as a mixture where the original substances still persisted.

* Students may believe that during chemical changes substances are displaced without any change of their properties. This is illustrated by students who think that parts of burning wood are driven off as smoke.
* Students tend to interpret chemical reactions as a process of modification, that is, chemical changes are seen as physical or biological changes, for instance rusting of iron is considered as ageing of iron. Properties of substances are seen as changing whereas the substances themselves remain the same. For instance, students may believe that the only change consists of a change of colour or that the black coating formed on a piece of copper metal during heating represents black or burnt copper.
* Students may interpret chemical changes as a transmutation of a given substance into another substance or into energy. This is demonstrated by students who believe that burned steel wool has been turned into carbon.
* Students sometimes seem unaware of the interactive role of 'invisible' (gaseous) reactants or products. For instance, students may believe that the mass of a rusty nail is the same as the nail before rusting.
* Students may believe that chemical changes always imply the involvement of only two substances that are combined and form a third substance. For instance, they do not consider grape juice that has become wine as an example of chemical change.

Recurrent difficulties with the *macro meaning* ↔ *submicro meaning* are:

* Students often hold the view that molecules or atoms are in substances like raisins in a raisin cake instead of thinking that substances are composed of molecules or atoms. In other words, they think that particles are additional to the substance.
* Students often attribute a number of features from the macro domain to individual molecules or atoms but this ignores how the macro features emerge as a result of interactions between systems of molecules or atoms (see above). For instance, they may

attribute the colour of a substance to particles, such as the idea that individual atoms of copper are reddish-brown, and individual copper ions in aqueous solutions are blue. They may also believe that atoms of iron and chlorine become green when iron powder is added to dilute hydrochloric acid.

* Conversely, students may attribute features from the micro domain to substances by considering substances as if they were the same as particles. For instance, they may think that the substance of magnesium (instead of the particles) has a charge of +2, and may use expressions like 'substances form bonding' and 'substances give up and receive electrons'.
* Even when students have knowledge of atoms and molecules, they may fail to invoke atoms and molecules as explanatory constructs of observed chemical phenomena. For instance, students may explain the 'disappearance' of the wax of a burning candle by using intuitive ideas rather than using particle concepts learned in school.

Recurrent difficulties with the *submicro meaning* ↔ *symbolic meaning* are:

* Students may have difficulties in understanding the meaning of stoichiometric coefficients and subscripts of formulas. A typical example: students may consider $3H_2$ as a series of six linearly linked atoms.
* Students tend to interpret the formulas of compounds from an additive rather than from an interactive perspective. This is shown by students who were able to balance the reaction equation $N_2 + H_2 \rightarrow NH_3$ in a correct way but, when drawing this equation, they draw a diatomic molecule of nitrogen and at some distance a series of six atoms of hydrogen.
* Students may consider balancing reaction equations as mainly mathematical manipulations of symbols without much insight in the submicro meaning. For instance, students tend to change the value of the subscripts in formulas of reactants or products instead of changing the value of coefficients.

* Even when students are able to correctly balance simple chemical equations, they may fail to provide particulate drawings that are consistent with the notation of these equations, particularly in correctly translating the subscripts and coefficients of chemical formulas.
* Students may not properly interpret equations of reactions between ionic compounds in solution when these equations consist of molecular formulas. For instance, regarding the reaction between dilute nitric acid and aqueous sodium hydroxide, students tend to think that sodium and nitrate ions react to produce sodium nitrate molecules.

In conclusion, important student difficulties concern interpreting observable chemical phenomena as transformations of substances. Other student difficulties include giving descriptions and explanations of these transformations in terms of rearrangements of particles and interpreting and writing formula reaction equations. An overall student difficulty concerns switching mentally between the three domains of meaning.

Vignette

In a junior high school class, a chemistry teacher puts a burning piece of wood in a glass with water. The burning stops.

The teacher asks: *How is that possible?*

Student #1 answers:	*We do not understand, burning should go on because there is oxygen in the water, as we know because fish live in water.*
The teacher responds:	*But there is not enough oxygen in the water.*
Student #2 argues:	*We know that water is H_2O, so, one-third of water is oxygen, whereas air consists of oxygen for one-fifth only . . . so, teacher, how is that possible?*

In this vignette, student #2 compares water and air as providers of oxygen for a burning process. However, the student interprets the formula of water in an additive rather than from an interactive way: H_2O is seen as H_2 and O. This way of reasoning demonstrates a common difficulty in understanding symbolic representations.

Explanatory Analysis of Students' Conceptual Difficulties

The reported difficulties in understanding chemical change can be explained by analysing three interrelated factors: the student, the chemistry content, and the teacher/textbook. This analysis is concisely addressed below.

(i) The *student factor*. The initial knowledge of students, based on daily life experiences and expressed in everyday language is often not very fruitful for interpreting chemical phenomena. For instance, students may have ideas that parts of burning wood are driven off as smoke and their belief that the black coating formed on a piece of copper metal during heating represents black or burnt copper. Students consider their already existing conceptions, often deeply rooted in their everyday life, as more reliable than the new conceptions. They prefer to use superficial everyday life events for explaining chemical changes instead of using chemical models (Hesse & Anderson, 1992). Besides, students also have a lack of sufficient real experiences of different phenomena to be able to decide whether a particular phenomenon can be classified as a chemical change or not (Nelson, 2002). Finally, students tend to pay little attention to submicro models for giving meaning to the complex conventions of chemical symbols. This can foster students' alternative conceptions of formula subscripts and coefficients and will contribute to conceiving balancing reaction equations as mainly mathematical manipulations of symbols.

(ii) The *chemistry content factor*. Many school chemistry concepts are abstract and do not fit students' intuitive ideas. Such concepts are difficult to understand because they require formal reasoning and knowledge of models as representations of phenomena and the particulate nature of matter. This is not easy for many students, who tend to see, for instance, molecules and atoms as 'minima naturalia', that is the 'Aristotle' conception of small existing particles, instead of modern theoretical model concepts (De Vos & Verdonk, 1985). Chemical reactions are not only defined as conversions of substances but also as rearrangements of atoms including the breaking and forming of chemical bonds. However, many students find it difficult to mentally jump from the macro meaning of chemical reactions to the submicro meaning and reverse because they consider these domains of meaning as disconnected (Solsona, Izquierdo & De Jong, 2003).

(iii) The *teacher/textbook factor*. In many teaching practices and textbooks, the topic of chemical reactions is often considered predominantly in terms of submicro and symbolic meanings (cf. De Jong & Van Driel, 2004). This will hinder students from connecting these meanings properly with those in the macro domain. It will also promote the tendency among students to consider chemical reactions as very formal processes. Teachers and textbook authors are not always aware of students' alternative conceptions. For instance, students' intuitive idea that the colour of a substance corresponds with the colour of the individual particles is enhanced by many textbooks showing coloured pictures, such as yellow sulphur atoms. The subject matter expertise of teachers and textbook authors can also function as a source of students' difficulties. Teachers as school chemistry experts are very able to move mentally between the three domains of meaning easily and almost automatically. As a consequence, when teaching, they often do not pay much attention to highlighting the mutual relationship explicitly and repeatedly (Gabel, 1999). However, students as novice learners are not familiar at all with this relationship and encounter difficulties in connecting the three domains. Moreover, in chemistry classrooms, teachers tend to use expert language, for instance shortened expressions, that may evoke confusion among students, such as using the expression: 'copper is formed', without indicating explicitly if this statement refers to the substance copper, the type of atoms or the type of ions (De Jong, Acampo, & Verdonk, 1995).

In conclusion, this analysis of the three connected factors can contribute to developing a deeper insight in the complex background of students' difficulties in understanding chemical reactions and, perhaps, many other topics in high school chemistry.

Modern Approaches to Teaching Chemical Reactions

The reported students' conceptual difficulties have been found among students who have been taught in mainly traditional chemistry courses. Efforts to prevent and to respond to these difficulties have led to a series of chemistry courses based on modern perspectives on teaching and learning chemistry. Studies of five exemplars of courses focusing on the topic of chemical reactions are given below.

- A course that included three phases of the *learning cycle*, namely explication, concept introduction, and concept application, was investigated by Cavallo, McNeely, and Marek (2003). They reported on the development of understanding among 60 junior high school students with respect to the three domains of meaning of chemical reactions. Findings indicated significant positive shifts in understanding. A minority (about 20%) of the students, however, showed persistent conceptual difficulties, especially regarding the difference between chemical change and physical change, and the relationship between atoms and substances.
- A course that introduced a teaching strategy based on the *conceptual change perspective*, that is, confronting students with 'chemical events' that evoke cognitive conflicts because of existing everyday conceptions, was investigated by Nieswandt (2001). She reported on the development of understanding among 81 junior high school students with respect to macroscopic features of substances and chemical reactions (with particular emphasis on combustion). Results showed a significant 'erosion' of students' everyday conceptions in favour of scientific conceptions. A minority (about 25%) of the students, however, only developed 'mixed' conceptions, consisting of everyday conceptions and chemistry explanations.
- A course that incorporated a *context-based* teaching approach by presenting chemistry

concepts within the context of everyday events, was investigated by Barker and Millar (1999). They reported on the development of understanding among 250 senior high school students with respect to the conservation of mass in closed- and open-system chemical reactions. Data indicated that students' reasoning improved steadily as the course progressed. Nevertheless, a minority of the students retained misunderstandings about the conservation of mass in both closed systems (23%) and open system (29%), especially for reactions including gases.

- A course that included a *constructivist view* on learning by taking students' own conceptions into account was investigated by Jaber and BouJaoude (2012). They reported on the development of understanding among a group of 46 junior high school students with respect to macro-, submicro-, and symbolic meanings of chemical reactions. The study included an experimental/control group design. The control group (22 students) was subject to lessons that taught for conceptual understanding, however, without explicit attention to the epistemological nature of chemistry. Conversely, the experimental group (24 students) used the same lesson materials in terms of content while being explicitly introduced to an epistemic discourse paying additional attention to the interrelations between macro-submicro-symbolic meanings. Findings indicated that the majority of the experimental group developed adequate conceptual and relational understanding of chemical reactions, as compared to approximately half of the students in the control group. Despite the relative good learning gains in the experimental group, a minority (21%) of this group did not acquire sufficient understanding of chemical reactions.
- A course designed from a *mix of perspectives*, namely conceptual change, context-led, and constructivist, was investigated by Solomonidou and Stavridou (2000). They reported on the development of understanding among 168 junior high school students

with respect to macroscopic features of substances and various chemical reactions. Results showed significant positive shifts in understanding. A minority (percentage not given) of the students, however, did not change their 'concrete substance' idea toward the 'unknown substance plus properties' scheme, and the 'inert mixture' concept toward the 'interaction between substances' concept.

Some of the reported studies addressed only macroscopic features of chemical reactions (Barker & Millar, 1999; Nieswandt, 2001; Solomonidou & Stavidrou, 2000), whereas others also covered submicro and symbolic features (Cavallo et al., 2003; Jaber and BouJaoude, 2012). All studies reported a positive development of students' understanding, but all of them also indicated conceptual difficulties, despite the use of modern course designs and teaching strategies. This raises the question: what causes the persistency of the reported difficulties in these courses?

To answer this question, knowledge of the teaching-learning processes in the classroom could be helpful. Unfortunately, these reported studies only focused on learning outcomes, by using written questionnaires, sometimes combined with some interviews, in the context of pre-test/(repeated) post-test designs. As a consequence, they did not provide insight in relevant learning processes. However, in a study of a constructivist course, Laverty and McGarvey (1991) not only used a pre-test/post-test design and questionnaires but also other instruments, such as audio records of lessons and classroom observations This study offered a better insight into students' struggle for understanding. The researchers reported how students designed their own diagrammatic representations for the effect of heat on copper carbonate, why some of them mistook this decomposition for burning in air, and how they debated to find the best representation for the decomposition. In an older but still influential study of a constructivist course, De Vos and Verdonk (1985) also analysed audio-taped classroom discussions. They found that junior high school students were able to develop primitive particle models of matter in the context of a chemical reaction, for example, for explaining the appearance of the brilliant yellow line, consisting of glittering tiny crystals in a continuous motion, when lead nitrate and potassium iodide were placed in opposite positions in a Petri dish filled with water.

In conclusion, more in-depth investigations and longitudinal studies are needed to get a better 'ecologically' valid insight in the factors and conditions that hinder or facilitate the development of students' conceptions of the multiple meanings of chemical reactions.

A Curriculum Dilemma: Early or Late Introduction of the Submicro Meaning of Chemical Reactions

The five reported studies dealt with courses where the choice for a particular general teaching strategy is reported, but where the issue of an early or late introduction of particle models for understanding the submicro meaning of chemical reactions is hardly discussed. Nevertheless, this curriculum issue is the subject of an old but still on-going debate in chemical education.

Several scholars have proposed a delayed introduction of molecules and atoms because, according to them, students should first build up suitable practical experience through exploring a variety of phenomena (e.g. Ahtee & Varjola, 1998; Tsaparlis, Kolioulis, & Pappa, 2010). However, others have shown that students did not 'naturally' have a concept of substance identity, in a scientific sense, that allowed them to recognise chemical change in a proper way (e.g. Johnson, 2000; Stavidrou & Solomonidou, 1998). For instance, although many courses introduced the burning of substances in an early stage, students experienced a lot of difficulties in recognising and understanding this event as a chemical reaction (Watson, Prieto, & Dillon, 1997). Johnson (2002) even found that students began to accept the idea of substances changing into other substances only after a teaching unit in which atoms had been introduced. The model of atoms and changes in bonding was not the explanation for the idea of chemical change, but the means by which chemical change was acknowledged. On the other hand, premature introduction of the concepts of molecules and atoms was not suggested, because this approach may not enable students to consider particles as fruitful concepts for explaining chemical reactions, and may induce many difficulties in the submicro domain. For instance, Garcìa Franco and Taber (2009) explored how lower secondary school students explain physical and chemical changes commonly met in school science. They found that students generally used the notion of particles, although most of their particle-based explanations reflected alternative conceptions that have been reported in previous studies (see some subsections above).

In conclusion, a curriculum strategy of early introduction and regular application of the submicro meaning of chemical reactions is not of itself sufficient to support the desired progression in thinking with particle models. The studies reported in this subsection do raise the question: how could chemistry education escape from this content-related dilemma of the curriculum structure?

A Possible 'Way Out': Introducing a Meso Domain of Meaning

A possible 'way out' from the content-related dilemma of the curriculum structure is recently reported by Meijer (2011). From the literature, he concluded that the mental task of jumping between the macro domain and the submicro domain is very hard for many students. He referred to Millar (1990) when stating that breaking down the macro-submicro jump into smaller steps could support students' understanding. In other words, introducing intermediate (meso) domains might be functional in the learning of macro-submicro thinking. This idea can be considered as an extension of the usual triangle of meaning into a tetrahedron of meanings (see Figure 9). Meijer (2011) has elaborated this perspective by reporting a conceptual analysis of macro-submicro thinking in terms of structure-property relations and scales of meso domains. He clarified this issue by using the example of bread. This material can be defined as a final fixed form of dough. By zooming deeper into dough, it is possible to distinguish certain meso structures, such as walls of gas holes, threads, granules embedded in networks and entangled long molecules. These meso structures are related to properties such as the elasticity of gas holes. In general, a material has a specific property which is not caused by a single structure but is caused by the interactions between all substructures at the lower scale.

This conceptual scheme was used as a guide for designing some context-led constructivist modules for high school students. They were asked to explore structure-property relations for three kind of materials: gluten-free organic material (bread), fire-resistant material (bullet-proof jackets), and unbreakable ceramic material (crockery) (Meijer, Bulte, & Pilot, 2009; In press). The teaching of the modules was accompanied by an explorative study of students' learning (Meijer, 2011). The findings showed that students were able to acquire macro-submicro thinking using structure-property relations. However, students did not easily grasp the scales of meso levels below 10^{-5} m. Two reasons were found for this problem: (i) metaphors, related to the macro domain in students' materials and in discourses, both used as a tool to increase the understanding of the submicro domain, hindered the conceptual development of students, and (ii) the scaling of structures was also a problem for students.

In conclusion, further research is required to get a deeper insight into the most effective content/context-related curriculum structure for supporting students to really understand the relationship between macro meanings and submicro meanings of chemical reactions.

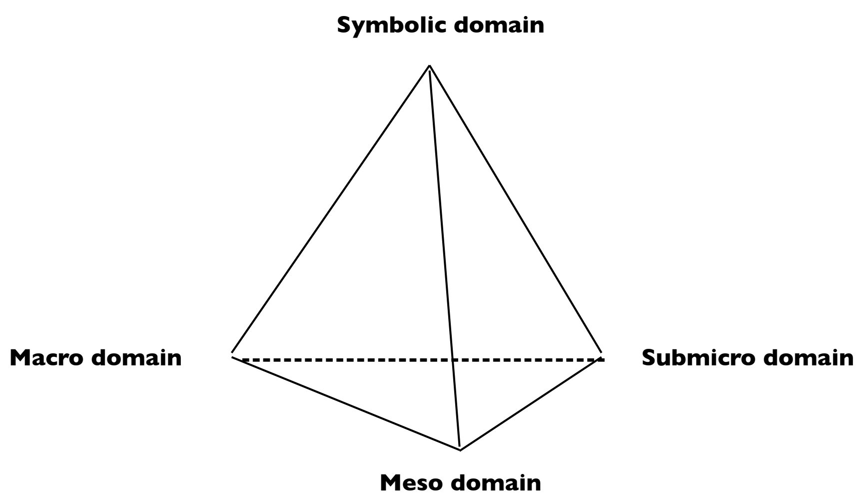


Figure 9. The tetrahedron of meanings

Empowering Prospective Chemistry Teachers for Teaching Multiple Meanings

Teaching the multiple meanings of chemical reactions through modern student-centred courses looks attractive, but it requires teachers to have a very good insight into this topic and how to teach it. This is necessary, because these courses, especially the courses that include a constructivist view on learning, often require students to address questions where the answers are not given in the textbook. This raises the questions: are prospective teachers sufficiently prepared for teaching the topic under consideration, and, if not, how could they be empowered? These questions will be concisely considered next.

At the primary school level, prospective teachers often show conceptual difficulties, especially when they have no high school background or limited high school background in chemistry, as many have. For instance, prospective primary teachers tend to believe that mass is not conserved when a piece of paper is burnt in a closed system (Ryan, Jiminez, & De Torre, 1989). They may also ignore the conservation of particles when drawing diagrammatic representations of chemical change (Gabel, Samuel, & Hunn, 1987). In more recent studies, Kokkotas, Vlachos, and Koulaidis (1998) indicated that prospective primary teachers may attribute macro properties to particles, and Del Pozzo (2001) found that they may have difficulties in interrelating macro- and submicro concepts describing the composition of matter in a proper way. Finally, Çalik and Ayas (2005) reported that prospective teachers and eighth-grade students (aged 14) had several similar alternative conceptions of chemical change despite more teaching of this topic to the prospective teachers.

At the secondary school level, prospective chemistry teachers also demonstrate conceptual difficulties, although not so many as primary school teachers. Nevertheless, prospective chemistry teachers may show good understanding of balancing chemical equations but lack the ability to apply the concepts of conservation of mass and of the number and kind of atoms present (Haidar, 1997). They may be able to draw diagrams depicting chemical reactions in terms of particles, but tend to ignore the creation of intermediate products, and to draw loosely packed representations of particles in solid ionic substances (Lee, 1999). Finally, De Jong, Ahtee, Goodwin, Hatzinikita and Koulaidis (1999) found that prospective chemistry teachers were not very familiar with current students' difficulties in understanding combustion in a macro domain.

Studies of courses focusing on supporting prospective teachers in understanding the multiple meanings of chemical reactions, and how to teach them, are rather scarce. Kokkotas, Vlachos, and Kouladis (1998) examined a training course for prospective primary teachers. The participants were confronted with students' authentic ideas as they are expressed when the students answer questions about the macro- and submicro meaning of the composition of matter and change. Results indicated that the participants showed improvement in terms of scientific understanding, and knowledge of students' conceptual difficulties. In a study of a teacher training course for prospective secondary school teachers, De Jong and Van Driel (2004) reported that the participants became aware of the need to show students the relations among the multiple meanings in a much more explicit way than they initially tended to do, and to ignore their own dominant orientation towards submicro meanings. Moreover, the prospective secondary school teachers noticed the importance of the careful and consistent use of symbolic representations, for example, not using the formulas NaCl(s) and Na^+Cl^-(s) in the same context.

In conclusion, these studies show the importance of courses for teachers that emphasise improving prospective teachers' knowledge of multiple meanings of chemical topics, and how to teach them. However, *how* prospective teachers link their 'course' knowledge with their classroom practice is still not very clear. This is a general problem, and requires further research.

INTRODUCING MULTIPLE MEANINGS OF CHEMICAL BONDING

The ('Imaginary') Nature of Chemical Bonding

Chemical bonding has long been recognised as a 'big' concept area in chemistry (Fensham, 1975). Chemical bonding can stand as a paradigm case for common difficulties in teaching and learning chemistry, because learning about chemical bonding involves meeting and making sense of a sequence of scientific models, each of which concerns theoretical entities (atoms, electrons, molecules, ions, orbitals, etc.) that are conjectured to exist at a scale many orders of magnitude below what can be directly observed by learners. Unlike the topic of chemical reactions, discussed above, chemical bonding does not relate to a specific set of identifiable chemical phenomena that are observable at the macroscopic level: rather bonding is a core part of the explanatory schemes, invoked to explain a great many different features of actual phenomena (such as melting temperature or solubility in a solvent).

Table 4
Inferring Bonding from Observations of Phenomena: The Example of Melting Point Determination

Stage	*Account*	*Notes*
Observation	White opaque/translucent grain becomes transparent, and looses shape: appears to have surface attaching to inside of tube.	On heating a small sample in a melting point apparatus.
Chemical description	The sample melts.	Observations linked to a standard (theoretical) category of change.
Evaluation	The substance has a 'high' melting temperature.	This relies on an understanding of the apparatus, and auxiliary observations (of a thermometer) that can be interpreted quantitatively. The sample is assumed to represent any pure sample of the same substance (i.e. observation is generalisable).
Inference	The substance may have ionic bonding (considering its initial appearance, and the high melting temperature).	Coordination of observations and interpretation at the macroscopic level are used to assign the substance to a category based upon features of the submicroscopic structure posited within a theoretical model.

This increases the challenge for the teacher, making chemical bonding more abstract, and so inherently more difficult, for many learners. In term of the progression scheme suggested in Figure 7, models of chemical bonding should only be introduced once learners are familiar with the macroscopic descriptions of chemical phenomena we wish these models to explain (the high melting temperature of diamond; the solubility of sodium chloride in water; and so forth). An example is offered in Table 4 that sets out how we move from observing some white material in a melting point tube to classifying the material as a sample of a substance 'with' ionic bonding.

We can represent bonding symbolically but in *these* cases those symbols *only* refer to the submicroscopic level, and not what learners can actually perceive when observing substances in the classroom or teaching laboratory (cf. Figure 7). That is, we may talk of this piece of metal as having metallic bonding, or that grain of salt as having ionic bonding, but in doing so we are transgressing the macroscopic/submicroscopic distinction, and talking, for example, of metallic bonding *as if* it is a property of the metal, when actually it is a theoretical construct which is part of the explanation of the observed properties (such as being shiny or elastic, etc). Chemists and chemistry teachers, have become so familiar with our models of matter at the submicroscopic level that we readily form categories of substances based on features of the theoretical submicroscopic models *as if* they can be considered properties of the substances themselves: so sodium chloride (the substance) is said to 'have' ionic bonding; and even to 'be' an ionic substance. As teachers, however, we need to be careful that we do not take short cuts in moving through the kinds of processes illustrated in Table 4 as we induct learners into our ways of thinking, but rather help our learners to move through the different stages from observation to conceptualisation - first as description, and then in terms of explanatory concepts.

Teaching Bonding as a Progression of Models

Learners will generally meet a series of different models of chemical bonding of increasing sophistication, and these models may not always be consistent. It is important therefore to present these various models as just that, models, rather than 'the way things are' (see the earlier section on models). This perspective can be introduced, when a particle model is first taught, on the basis that what is being described is so small that we cannot directly see what is going on, and therefore have to build up models that might explain what we know, and suggest hypotheses we can test through experiments. As learning progresses through the increasingly sophisticated models that are introduced, then students can be presented with an increasingly sophisticated account of *the nature of* these models *as models*, in parallel with their learning about the models themselves. As the teaching of this topic inevitably involves working with multiple models of the structure of matter, it can be used as a context for teaching about this important aspect of the nature of science.

There have now been quite a range of studies investigating students' learning about chemical bonding, and a number of reviews of this area are available (Levy Nahum, Mamlok-Naaman, Hofstein, & Taber, 2010; Özmen, 2004; Ünal, Çalık, Ayas, & Coll, 2006), as well as recommendations on teaching the topic area (Levy Nahum, Mamlok-Naaman, Hofstein, & Krajcik, 2007; Taber, 2001a, 2012a). Here, some of the key issues raised by this research will be considered.

The Immaterial Nature of Chemical Bonding

A key feature of chemical bonding is that it is understood as due to forces between different 'quanticles': binding atoms into molecules; ions into lattices; molecules into solids and liquids, etc. For learners to appreciate this, it is important that when basic particle theory is first introduced, the 'particles' are presented as having some inherent (but not absolute) ability to attract each other (Johnson, 2012). This is often initially omitted in introductory teaching, although it is a fundamental feature of the particle model. Research suggests that students may consider bonding between particles as being due to a kind of glue. In part, such references may simply be the limitations of available language, and in some case such statements are meant metaphorically. However sometimes students do seem to explicitly suggest that bonds are made of *some kind of material* that connects the particles. It is likely that a number of factors encourage this:

- Our teaching models often comprise of roughly spherical balls, either (visibly) glued together or connected with sticks or springs: if the models are interpreted too literally they may be understood to imply something similar (i.e., material linkage) occurs at the submicroscopic level;
- The lack of familiarity with the nature of matter at the submicroscopic scale means that learners rely upon their understanding of how things are at more familiar scale – when *generally* we need to glue, rivet, weld, etc materials together. (There are

examples where we 'bond' materials using their inherent adhesive properties that might offer more suitable analogies);

- It is documented (Andersson, 1990) that in learning particle models of matter, learners commonly pass through a stage where they conceptualise the particles (that are meant to be the matter at the scale represented) as embedded in matter – of the material itself, or in terms of having air between particles – so learners at this stage may readily consider other material to be available to form the bonding;
- References to 'bonds' may imply material entities, rather than an interaction or process (bonding) and it has sometimes been suggested that the term 'bond' itself should be avoided, although that might be difficult given its ubiquity in chemistry (Pauling, 1960). Where students learn that '*everything* is made of tiny particles', then that can seem to imply that bonds must be made of particles, like everything else.

Teaching learners from the start that the 'particles' from which mater is made up at a scale well below that is directly visible have an inherent stickiness raises the question of mechanism, but may help avoid students developing alternative conceptions about bonds as material links. The nature of that mechanism can be understood at different levels. For much of secondary level, the notion that bonding is primarily an electromagnetic ('electrical') effect should suffice, although research has often found that many learners may fail to appreciate this, suggesting it should be emphasised more in teaching.

The Nature of Atomic Structure

The introduction of atomic structure as a notion represents a major shift in modelling matter at submicroscopic level. Amorphous particles previously considered much like ball bearings or billiard balls are now presented as something quite different and indeed largely 'empty space' – a nuclear atom where nearly all the mass is located in a tiny volume at the centre, and tenuous electrons orbit at (relatively) vast distances from the nucleus. This shift from seeing the 'particles' from which matter is said to be composed as *atomos*, fundamental and indivisible, to more complex entities that not only have structure, but are themselves composed of even more fundamental particles (nucleons, electrons) presents a major challenge in chemistry teaching (Taber, 2003). Learners generally accept the new teaching, but there is a clear issue relating to whether this new account can supplement previous teaching (of the billiard-ball type account), or will be seen by learners are *replacing* earlier flawed teaching. This complication may have been previewed if students have met the topic of thermal expansion prior to being taught about atomic structure. Often teaching about how some key properties of solids (rigidity, regular shapes for example) depend upon the close packing of the constituent particles, is followed by being taught about thermal expansion of solids in terms of increases in the separations of those same particles: those rigid solids are now said to be comprised of well-spaced particles which cannot be in contact because they vibrate about their lattice positions.

From the expert perspective, there is no real contradiction here, as the nature of contact at the submicroscopic scale cannot be taken to have our familiar everyday meaning. Contact is understood in terms of electrical fields (and quantum rules), and not in terms of two discrete surfaces becoming adjacent to each other. However, such an understanding is not going to be immediately available to the learner asked to use seemingly contrary explanations, and many retain the notion of ball-like particles, but invoke thermal expansion *of the particles themselves* to explain the changes at the macroscopic scale (cf. Figure 3).

A fundamental feature of the model of atomic structure needed to support chemistry teaching about chemical bonding (and some other important topics such as shapes of molecules, patterns of ionisation energy, reaction mechanisms, etc.) is that the atom is bound by the electrical attraction between the positively charged nucleus and the negatively charged electrons, which repel each other. However there are clear limitations to this level of description. On an electrical basis, there is no reason why the neutrons would be bound in to the nucleus, and indeed good reasons to reject the notion that all the positively charged protons will be collected together at one location. That learners often fail to raise this objection, suggests that they are not primarily conceptualising the structure in electrical terms.

The basic electrical model also fails to explain why electrons are found in 'shells', that moreover have the same maximum occupancy regardless of the nuclear charge, nor why electrons often seem to be found in pairs (bonding pairs, non-bonding pairs). Given the significance of quantum rules, there is a question over whether we should teach something of this idea from early in chemistry education. Traditionally quantum mechanics has been considered an advanced topic, and any treatment that was incorporated in introductory chemistry at school level would clearly only offer a very partial account of these ideas. Yet there is a potential research theme here, regarding both (i) the extent to which some notions of there being quantum rules applying to electronic arrangements in atomic/ molecular systems are inherently any more difficult or abstract than other ideas already taught at this level; and (ii) whether the increase in subject difficult necessitated by introducing additional abstract notions at this point in learning, might actually be justified by the increased potential for making otherwise arbitrary principles seem part of a more coherent account.

Basic Models of Bonding

If we adopt a basic model of the structure of matter consisting at submicroscopic scale of particles which form into various configurations due primarily to electrical (or electromagnetic) interactions then we can describe most types of bonding in terms of arrangements of atomic cores (nuclei and their associated 'inner' shells of electrons) and sufficient valence electrons to maintain electrical neutrality (Taber, 2012a). We can use this model to describe increasingly complex types of bonding interaction. So, for example, in teaching about solid structures, the main types of structures (in terms of increasing complexity, arguably a sensible teaching order) would be

- Metals: A lattice arrangement of a single type of atomic core, with delocalised electrons moving around the lattice;
- Covalent crystals: a repeating pattern of atomic cores, with localised pairs of electrons around particular cores, or between cores;
- Ionic lattice: valence electrons arranged around individual cores that are attracted into a regular lattice due to their net charges;
- Molecular solids (and also liquids); discrete arrangements of a small number of cores with localised pairs of electrons around particular cores, or between cores (i.e., molecules); that are then attracted together due to secondary interactions between the charges within these discrete molecules.

This order reflects increasing complexity from the perspective of the discipline of chemistry, but research is indicated to explore how sequencing influences the 'learning demand' (Leach & Scott, 2002) from the students' perspectives. The approach described here is however broadly consistent with the research-based scheme described by Levy Nahum, Mamlok-Naaman, Hofstein and Krajcik (2007) that starts from "the principles that are common to all types of chemical bonds".

This approach leads to four main types of bonding: between delocalised electrons and the lattice of cations (cores), or metallic bonding; pairs of negative electrons between positive cores, or covalent bonding; attractions between ions of different charges, or ionic bonding; and attractions between neutral molecules due to the asymmetrical charge distributions within them – often called intermolecular forces. When described in these terms it may not seem surprising that the latter type of intermolecular interactions tends to be weaker than the others, and indeed sometimes these types of interactions are not considered to fully 'count' as chemical bonds. However, all these interactions can be understood as primarily electrical attractions, and so fundamentally the same type of interaction. It is also important to teach that although we tend to think of bonding as being about attractions, the repulsions are equally important, as the actual structures represent an equilibrium situation where the various forces acting balance out.

These descriptions of different types of bonding refer to *models* of how we understand the 'particles' to configure, and in practice most substances do not seem to match these ideal cases. In particular no compound is known with what is considered 'pure' ionic bonding, where the actual electron distribution in the structure is thought to reflect undistorted discrete ions being attracted together. Although pure covalent bonds are considered to exist (in elements for example), the inductive effect means that not all bonds between atomic cores of the same elements can be considered completely covalent (e.g., the CC bond in $CH_3.COOH$). Many compounds have polar bonds where the bonding electrons are asymmetrically located between atomic cores: and there is a continuum from the completely symmetrical covalent bond, to the asymmetric polar bond, to the ions distorted through the directional influence of other ions, to the ideal case of a pure ionic lattice. Most metals are considered to show a degree of covalent character in their bonds, and in aromatic 'covalent compounds' such as benzene, there is a possibility of increasing the extent of delocalisation across increasing number of atomic cores, ultimately leading to graphite which is a conductor, and in effect has metallic (delocalised pi) bonding in the plane of the covalent (sigma) bonded framework. This situation is reflected in Figure 10 that suggests that most real bonds fall within the triangle, rather than at its apices.

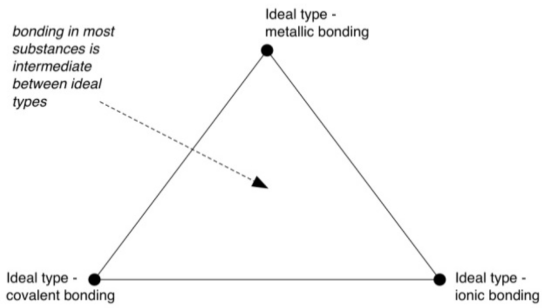


FIGURE 10. Commonly taught bonding models represent ideal types that are not generally found in nature

Understanding the more subtle features of bonding types involves going beyond the basic 'cores + valence electrons' model (and the associated shells model of atomic structure) to consider an orbital model of atoms, molecules and ions. The orbital model involves considering different symmetries of orbitals, and notions such as spin pairing of electrons, and so involves progression into more complex and increasingly abstract ideas, probably only suitable for learners who are already familiar and comfortable with the more basic models of structure and bonding. Although this shift between models is certainly a challenge for learners, there is some continuity in that the orbital level model need not be seen as completely inconsistent with what has been taught before *as long as* earlier teaching has presented the less complex ideas *as models* rather as accounts of how matter actually 'is'.

Student Learning Difficulties

As suggested above, there have been many learning difficulties identified in this topic which have been reviewed elsewhere (Levy Nahum et al., 2010; Özmen, 2004; Ünal et al., 2006). Given space limitations here only two particular examples will be discussed in any detail, but prefaced by some general observations. A key point for teachers to bear in mind is that it is likely that common teaching approaches, including the use of particular teaching models (especially when presented without their status as teaching models being made clear), must be considered as at least contributing factors in the widespread learning problems reported. Within science education more generally we find that student alternative conceptions may often be linked directly to experiences and learning outside the classroom. Yet in the case of chemical bonding it is clear that learners do not come to class with intuitive understandings of bonding (it is not something they can directly experience), and it is unlikely that many children are exposed to much extracurricular discourse about chemical bonding in their family and social lives that then influences their thinking when they meet the topic in chemistry lessons.

That is not to say that learning difficulties in this topic are *only* due to problematic teaching - for the understanding of complex abstract concepts is believed to draw at least indirectly upon our stock of intuitions of how the world works, that are themselves based on our direct experiences of the world. Learners will inevitably seek to make sense of new teaching in terms of available ideas that already make sense to them, and the models and metaphors offered by teachers may be especially influential.

The Octet Framework

Whilst research has reported a range of different common alternative conceptions relating to bonding concepts, many common student ideas derive from a particular alternative conceptual framework known as the octet framework (Taber, 1998a). This framework is discussed in more detail elsewhere (Taber, In press), but the core feature is an alternative conception that atoms seek to fill their electron shells (or obtain octets of electrons). This principle seems to have originated as an inappropriate over-interpretation of the 'octet rule', which suggests that most stable ionic and molecular structures involve atomic centres being surrounded by the same electronic configurations as found in the noble gases (see Figure 11). The octet rule is a useful heuristic, although as a 'rule of thumb' it has many exceptions, and suggests that atomic/molecular structures are inherently stable or unstable, without regard to context. Yet stability is a relative notion: so a sodium cation can be considered relatively stable when in a lattice or when hydrated, but an isolated sodium atom is more stable as a neutral atom than when its outer electron is pulled away to be separated from the ion. For many students, however, an octet structure or full outer shell implies a stable species: be that structure Na^{+}, C^{4+}, Na^{7-}, Cl^{11-} or even an excited chlorine atom with an inner shell electron promoted to fill the outer shell (Taber, 2009a).

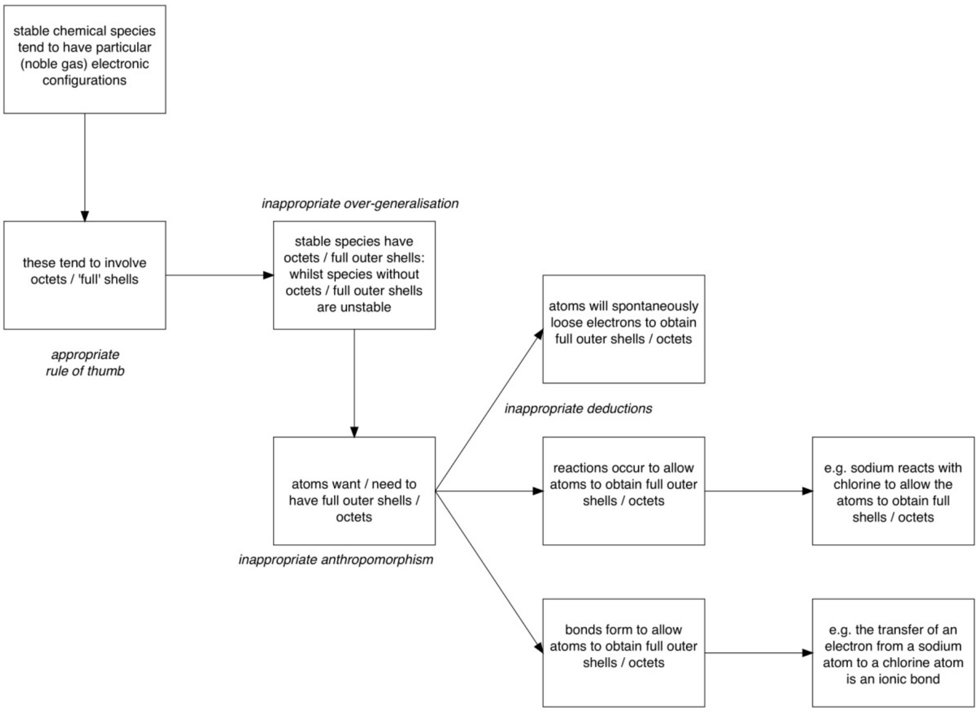
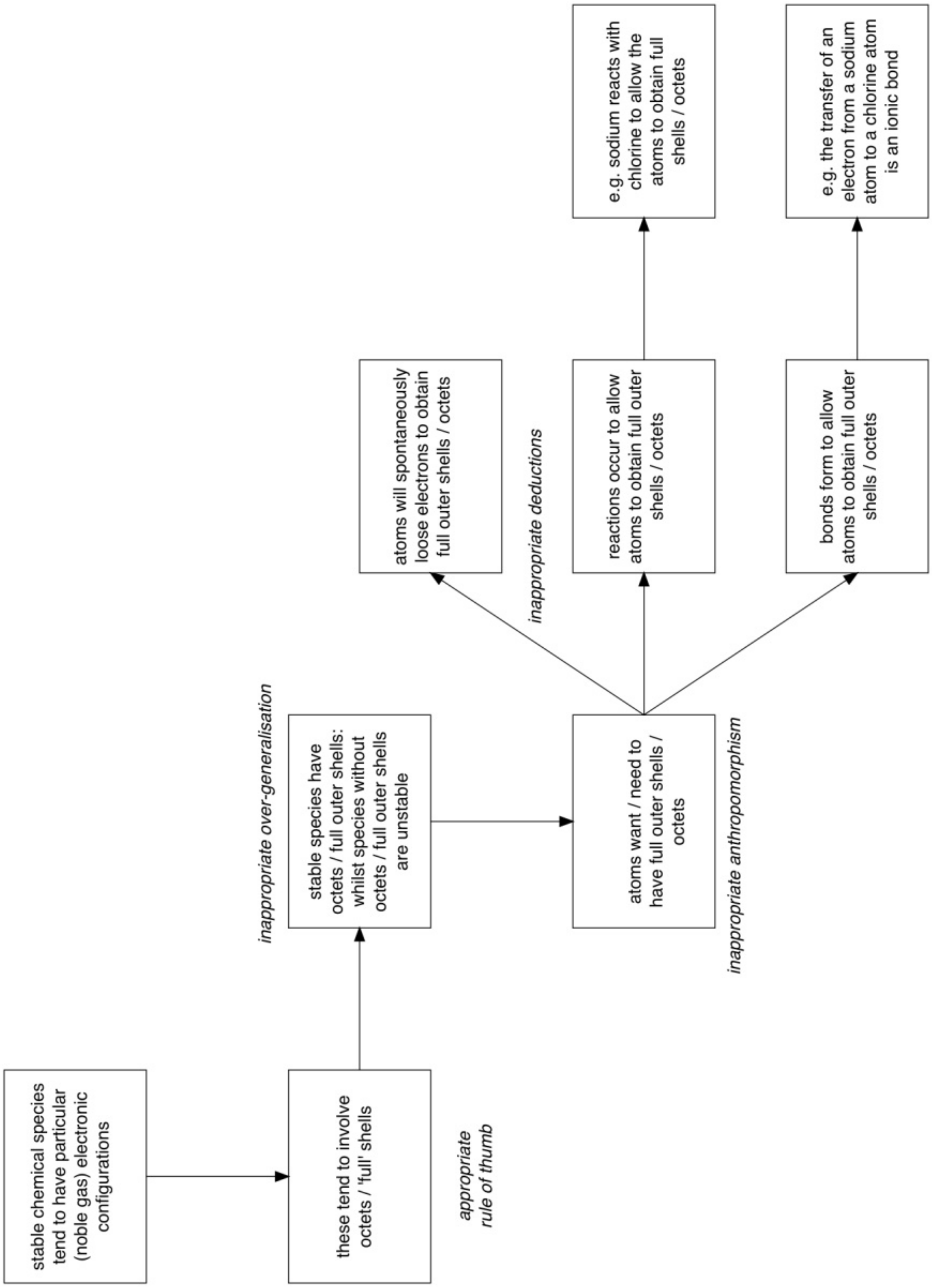


FIGURE 11. The development of the 'octet' alternative conceptual framework


stable chemical species tend to have particular (noble gas) electronic configurations
these tend to involve octets / 'full' shells
appropriate rule of thumb
stable species have octets / full outer shells: whilst species without octets / full outer shells are unstable
inappropriate over-generalisation
atoms want / need to have full outer shells / octets
inappropriate anthropomorphism
atoms will spontaneously loose electrons to obtain full outer shells / octets
reactions occur to allow atoms to obtain full outer shells / octets
bonds form to allow atoms to obtain full outer shells / octets
inappropriate deductions
e.g. sodium reacts with chlorine to allow the atoms to obtain full shells / octets
e.g. the transfer of an electron from a sodium atom to a chlorine atom is an ionic bond

Given this starting point, many students not only assume that atoms will spontaneously ionise to obtain full outer shells, but that chemical reactions take place to allow atoms to fill their shells through forming bonds. Often there is an assumption of initial atomicity, so methane will be more stable than carbon and hydrogen because forming the compound allows *the atoms* to fill their shells – that is, it is assumed that the reactants are in the form of isolated carbon atoms and hydrogen atoms, rather than structures that already have noble gas electronic structures.

The metaphor of covalent bonding as 'sharing' electrons supports this way of thinking (as electrons shared 'count' for both atoms), and often ionic bonding is associated with a hypothetical electron transfer event from an isolated metal atom to an isolated nonmetal atom. This reinforces a 'molecular' conceptualisation of ionic solids as comprising of ion-pairs bound by an ionic bond (electron transfer) and only attracted together in the ionic lattice by 'just forces' due to electrical charges. This is at odds with the recommended teaching approach that bonding should be presented as primarily an electrical attraction. The misconception that ionic bonding results from electron transfer between atoms is supported by many school level textbooks. This scheme does not seem to be questioned by many learners even when they have prepared sodium chloride themselves by neutralisation and evaporation, that is from reagents that clearly already contain the ions that will be bonded together in the product.

The octet framework is not only scientifically incorrect, but impedes progression in learning. Starting from the notion that bonds form to let atoms fill their shells, usually by sharing or transferring electrons, learners go on to develop further alternative conceptions (e.g., ion-pairs remain bonded when salts dissolve) and develop obstacles to learning more advanced ideas (cf. Figure 4). Students find ways to either fit metallic and hydrogen bonds into the scheme, or discount them as genuine forms of bonding. Bond polarity may be accepted as a secondary effect, but seen as a subclass of covalant bonding rather than an intermediate category (at odds with Figure 10). Compounds such as SF_6 or even the more familiar sulphates cause problems as they do not fit the octet rule (Taber, 1998a).

Ideas linked to the octet framework and notions of atoms actively seeking to fill their shells seem to be commonly adopted by learners, and once acquired they seem to be especially tenacious (Coll & Treagust, 2003). Moreover, at least vistages of such ideas remain in the thinking of teachers (Taber & Tan, 2011), suggesting that the alternative framework is in effect being taught by one generation of learners to the next when some of them become teachers themselves.

Adopting Orbital Models

A second specific area of difficulty appears to be adopting orbital models of atomic and molecular structure. Again, a wide range of alternative conceptions and learning difficulties have been reported (Taber, 2005). One clear problem here is having adopted the ‘shell’ model of atomic structure as a precise description, rather than a model at one level of simplification. At this level of study, learners will commonly come across a range of ways of describing and modelling atomic and molecular structures (atomic and molecular orbitals, energy levels, electron density distributions etc.) which cannot be seen as consistent unless appreciated as models of different facets of something complex and abstract. Studies show how progress in acquiring these ideas may be slow (Harrison & Treagust, 2000a; Petri & Niedderer, 1998) as well as how previous learning may seem to act as a barrier to progression.

Given that even some academic chemists and chemistry educators (Sánchez Gómez & Martín, 2003; Scerri, 2000) question the precise status of some of the orbital and related models which are represented in the curriculum, it is inappropriate to teach these as accounts of how matter is actually structured, rather than as models chemists have developed to help understand evidence from their experimental work.

LOOKING TO THE NEAR FUTURE OF CHEMICAL EDUCATION

Directions for New Research

Research into teaching and learning chemistry is an active and vibrant field (Gilbert, de Jong, Justi, Treagust, & Van Driel, 2002). Some potentially fruitful directions for this research in the near future are:

* Studies of carefully designed multimedia that are properly embedded in an overall teaching approach. Overviews of the present state of the art are given by Tortosa (2012), and Chiu and Wu (2009).

* Research and development of more 'green' chemistry teaching, i.e. teaching with a strong focus on environmental issues and chemistry for sustainability. Overviews of the present state of the art are given by Karpudewan, Ismail, and Roth (2012), and Feierabend, Jokmin, and Eilks (2011).

* Studies of student learning progressions (Alonzo & Gotwals, 2012), preferably undertaken in comparable ways in different curriculum contexts;

* Explorations of the potential for supporting conceptual integration between chemistry learning and learning in physics, biology, and technology, for instance in the field of nanochemistry and nanotechnology (cf. Ambrogi, Caselli, Montalti, & Venturi, 2008; Blonder & Sakhnini, 2012)

* Development of a broader range of research perspectives and techniques applied to exploring chemistry teaching and learning, for instance more phenomenological studies, the use of lesson study (Allen, Donham, & Tanner, 2004) or design-based research (Kortland & Klaassen, 2010), and the application of repertory grid type techniques (Taber, 1994).

Much research is now being conceptualised as having as it focus *chemistry* education: research that "can and does play a role in addressing the current shortcomings in the curriculum for, and in the teaching and learning of, the ideas that constitute the subject of chemistry" (Gilbert, Justi, Van Driel, De Jong, & Tragust, 2004, p. 12). There are many important themes that are common in teaching the sciences, but increasingly researchers are identifying with chemistry education research as a distinct subfield, and investigating specific issues and problems that relate to the particular (and perhaps often the particulate) nature of chemistry as a teaching subject. Some of these specific themes have been highlighted in this chapter. Research is needed to explore how best to coordinate teaching about models and modelling so it supports learning of the scientific and curriculum models.

One particular feature of chemistry education is the extent to which learners develop alternative conceptions in areas where they have not had direct personal experience. This creates an important area for future research, as if common student alternative conceptions do not derive from direct experience with the relevant phenomena, nor from 'folk theories' that have currency in social discourse, then it seems likely that such conceptions develop due to the way in which our teaching interacts with more general aspects of a learner's cognition.

Interestingly, research into how conceptions can derive from implicit domain-general knowledge elements - a 'knowledge-in-pieces' perspective (Smith, diSessa, & Roschelle, 1993) - is already quite familiar in 'PER' – physics education research – if less well developed in 'CER' - chemistry education research. There is well established work from PER based around the idea of p-prims (phenomenological primitives) which are understood as pattern-recognition elements of cognition that are abstracted from features recognised in experience (diSessa, 2008; Hammer, 1996). As implicit knowledge elements, these p-prims do not relate to particular domains of thought (such as academic disciplines/teaching subjects), but rather are part of the general apparatus that channels how we classify and make sense of our perceptions of the world.

This perspective has not had as much attention in CER, but where it has been applied it has seemed to have potential to be fruitful (Taber & Tan, 2007). From the 'knowledge-in-pieces' perspective, students' conceptions are constructed by drawing on their repertoires of available *implicit* knowledge elements: a new phenomenon, or a new idea presented in teaching, activates what seems the most appropriate available elements and comes to be understood accordingly.

For example, commonly, when considering how removing an electron from an atom changes the system (e.g. in studying patterns of ionisation energies), students apply a 'sharing-out' notion, that the force 'given out' by the nucleus will now be shared among less electrons, so they will now be held more tightly and so become harder to remove (Taber, 1998b). That particular basic pattern is not the appropriate one to apply, but students also seem to apply a 'closer-is-stronger' pattern when considering the ease with which electrons from different shells can be removed from an atom: an intuition which *does* support learning about the scientific model. The 'knowledge-in-pieces' perspective could offer greater potential to help channel the construction of student conceptions, as it may then be possible to sequence teaching, and adopt language and teaching models that best engage the most productive 'p-prims', to support the construction of particular chemical concepts: whereas at the moment it is clear that teaching is sometimes supporting the development of tenacious but technically incorrect conceptions, such as the examples considered earlier in the chapter.

Coherent Innovations in Chemistry Education

Innovations in chemical education should be developed and implemented in a more coherent way than is currently the case. This requires the fine-tuning of at least the following components of innovations:

(i) The development and implementation of experimental instructional materials and student courses based on new insights into teaching and learning chemical topics, especially with respect to a substantiated content structure for introducing the multiple meanings of many chemical concepts,

(ii) The development and implementation of courses for chemistry teachers, to help them to acquire sufficient knowledge of new topics and appropriate competence to teach in ways that are congruent with the new approaches,

(iii) The design and execution of in-depth and longitudinal studies. The purpose of this research can be two-fold. From a theoretical point of view: to develop a better understanding of teaching and learning processes and outcomes with respect to particular chemistry. From a practical point of view: to develop guidelines for high school and college courses and courses of teacher preparation in chemical education that are informed by research.

The integration of these three innovative steps implies an important challenge for the near future of chemical education.

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