

# Challenging Misconceptions in the Chemistry Classroom: Resources to Support Teachers

El repte de les concepcions alternatives en química: Recursos per ajudar al professorat

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## abstract

Teaching and learning chemistry can be challenging, and may often be complicated by students developing misconceptions of the chemistry they are taught. This article reports a project to support teachers, undertaken for the Royal Society of Chemistry in the UK. The project developed classroom materials to support teachers in identifying and challenging misconceptions. These materials were published in the UK in 2002, and are now being made available in translation by the Societat Catalana de Química. The project was informed from a constructivist stance where the aim is not just to recognise when students misunderstand the chemistry, but also to appreciate how and why such learning errors occur. A teacher who is both familiar with common misconceptions, and who is able to anticipate where and when learning is likely to distort teaching, is well equipped to avoid some of the common learning difficulties in the subject.

## keywords

Misconceptions, alternative conceptions, constructivism, learning impediments, *quanticles*.

## resum

El fet d'explicar i aprendre química pot ser considerat un repte i és freqüent que els estudiants desenvolupin concepcions alternatives de la química que se'ls ensenya. Aquest article relata un projecte de la Royal Society of Chemistry del Regne Unit que pretén ser una ajuda per al professorat. El projecte ha desenvolupat materials d'aula per identificar i encarar aquests conceptes erronis o concepcions alternatives. Aquests materials es van publicar l'any 2002 i ara s'estan donant a conèixer a través de la Societat Catalana de Química. El projecte es basa en una visió constructivista de l'aprenentatge i pretén no només posar de manifest les concepcions alternatives en l'aprenentatge de la química, sinó també donar resposta al com i al perquè es produeix aquest aprenentatge erroni. El professorat que conegui les concepcions alternatives més freqüents i que alhora sigui capaç d'anticipar on i quan els aprenentatges dels seus alumnes no es corresponen amb el que pretén ensenyar, estarà ben preparat per evitar o modificar algunes d'aquestes concepcions alternatives de la química.

## paraules clau

Conceptes erronis, concepcions alternatives, constructivisme, dificultats d'aprenentatge, *quanticles*.

## Introduction

In 2002 the Royal Society of Chemistry in the UK published two volumes with the title *Chemical Misconceptions – prevention, diagnosis and cure* (Taber, 2002a, 2002b), as the outcome of a research and development project designed to support school and college chemistry teachers. These materials are now being republished in translation by the Catalan Chemical Society to make them more widely available to teachers. This article sets out the background to the project and the publications.

## The abstract nature of chemistry

Chemistry is a very conceptual subject, and many of its concepts are rather abstract. So whereas some chemical terms refer to materials students can see and manipulate (solution, sulfur, sodium) or at least processes they can observe directly (combustion, distillation, mixing), many refer to ideas that are not so easily demonstrated. So students cannot be directly shown atoms, electrons, covalent bonds or delocalised electron clouds. Indeed, it is arguable whether such entities actually exist in the same sense as copper electrodes or conical flasks.

The phenomena of chemistry (i. e. chemical changes) can be readily shown to students (figure 1) but the explanations depend upon highly abstract concepts, normally involving hypothetical submicroscopic entities.

Some categories have fuzzy (metals) or shifting (acids) membership, and some processes (such as oxidation) can be understood in various ways. In the latter example, progression through the education system often reflects historical shifts that move the focus from addition or removal of real substances (oxygen, hydro-

When teaching a complex new topic, the teacher needs to undertake a careful conceptual analysis of the material, to work out how the different parts of the topic link together, and to determine a logical sequence for introducing material in terms of which concepts are prerequisites for others



Figure 1. The author working with students in one of his chemistry classes when he taught at Havering College of Further and Higher Education in North East London.

gen), through the conjectured movements of submicroscopic entities (electrons), to changes in numbers that are assigned according to a formal set of rules (oxidation states). Whilst this makes the subject fascinating for some students (it makes it potentially confusing and seemingly arbitrary for many others).

One of the widely recognised issues in teaching chemistry, indeed in teaching the sciences more generally, is that students very commonly develop alternative ideas about science topics. This means that the teacher's job is not usually to move students from a state of ignorance to a state of knowledge, but more often to shift student thinking away from existing ways of understanding the world. These alternative ideas have been given various labels by researchers (such as alternative conceptions, conceptual frameworks, intuitive theories) but they are commonly referred to as *misconceptions* (Taber, 2009b).

Interest in students' ideas in science, and especially in their misconceptions, came to prominence at the end of the 1970s and in the early 1980s. During this period research groups based at the Universities of Waikato (New Zealand/Aeotora), Leeds (UK) and Surrey (UK) undertook extensive programmes of research into children's ideas in science, and a range of seminal studies were published. These studies effectively initiated a research programme into the nature of children's ideas, how they developed and how teachers should respond (Taber, 2006). The programme was underpinned by a perspective on learning that is commonly referred to as *constructivism* (Taber, 2009b). The interest in this area of research led to a number of books on children's ideas in science.

The basis of constructivism is to view learning as an iterative process which, by necessity, occurs in small steps. In other words, learners cannot absorb

whole new areas of knowledge as unified objects, but rather have to build up their learning step by step. Moreover, the student always has to make sense of new information in terms of their existing understanding. Such ideas are based upon work in psychology, which has explored how human learning occurs. They also are strongly linked with Jean Piaget's (Piaget, 1972) findings about cognitive development that became so influential in education in the last century. However, most classroom teachers will be only too aware of both of these constraints from their daily work with students.

In effect, this perspective on learning offers two sets of challenges to teachers. The first of these was understood before constructivism became influential in science education, and relates to how material is organised for teaching. When teaching a complex new topic, the teacher needs to undertake a careful conceptual analysis of the material, to work out how the different parts of the topic link together, and to determine a logical sequence for introducing material in terms of which concepts are prerequisites for others. One technique to assist in this process of conceptual analysis is to «map out» the concepts, such as in figure 2, which shows some of the key concepts that might be drawn upon when teaching lower secondary level students about acids.

Normally a concept map includes both concept labels (figure 2) and statements linking the concepts. These links are represented by the lines joining the boxes in figure 2, and each line would represent a proposition (such as «acids react with metal oxides», for example). Usually these would be written on the map, or the links num-

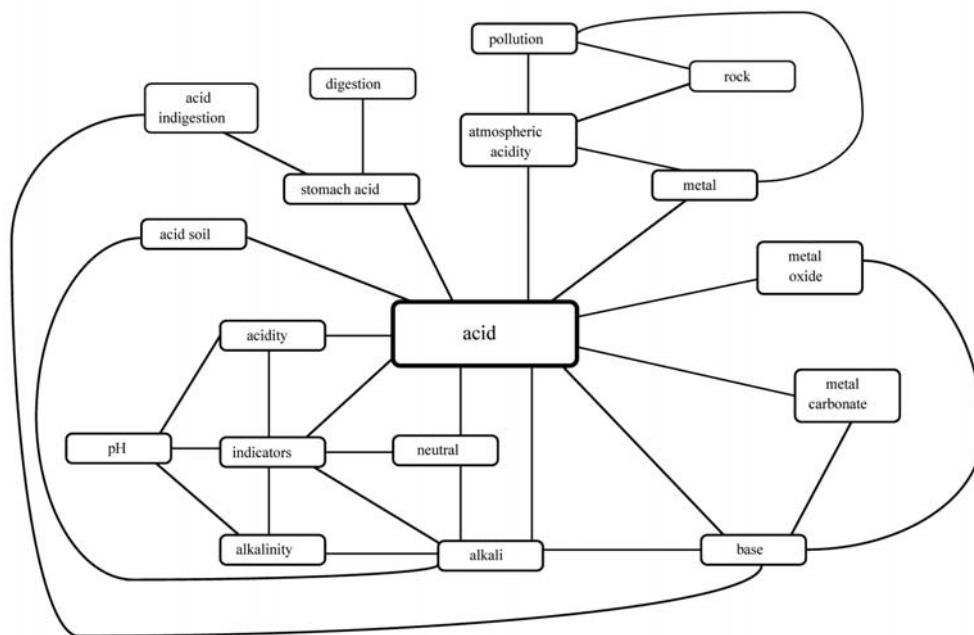


Figure 2. An outline concept map for the concept of the acids at introductory level in school science.

bered and a separate list of connections compiled.

Concept maps make good study and assessment tools as well as being used in planning teaching. A version of this figure is included in the publication *Chemical misconceptions – prevention, diagnosis and cure* (Taber, 2002b), which is discussed later in this article, where the use of concept maps to test student understanding is discussed.

The importance of undertaking some kind of conceptual analysis of the topic to be taught was familiar to chemistry educators before the explosion of interest in students' ideas in science (Herron, Cantu, Ward & Srinivasan, 1977). The need for a logical sequence of material, divided into suitable «learning quanta», was well recognised. However, the constructivist research programme has drawn attention to the way students' existing ideas complicate teaching. Where students come to class with their own alternative conceptions about science topics, this can often mean that even a

teaching presentation that is effectively planned from the perspective of the conceptual structure of chemistry, may be misunderstood because the learners interpret teaching in terms of their existing ways of thinking. Effective teaching requires the teacher to learn to see the material from the student's perspective (at the «learners' resolution») (Taber, 2002b). An early priority for the constructivist research programme was to find out a lot more about how students understood scientific concepts (Taber, 2009b).

### Students' conceptions

Over the past few decades, researchers have explored student thinking about most scientific topics, and a vast amount of material on students' ideas has accrued. An extensive bibliography of this research is freely available on the internet, due to the efforts of Professor Reinders Duit at Kiel University (Duit, 2007). Misconceptions have been reported in most topics, and across several educational levels.

Clearly, when students come to class with alternative conceptions of a topic, they will often then make sense of the teacher's explanations in terms of their existing understanding. This can lead to distortions of the teacher's intended meaning, and so compound existing misunderstandings.

This raises the question of how such misconceptions arise initially. Research suggests that some derive from intuitive understanding of the world. Children are naturally inquisitive and our brains have evolved to spot patterns and construct models to make sense of the world. Often the results do not fit with scientific understandings (but then of course the history of science offers many examples of ideas which once seemed to explain aspects of the world, but which are now discredited). As one example, it is common for students to understand heat as a material substance, as a kind of fluid. Today this would be considered as an alternative conception, but at one time it would have been the current scientific model.

A second important source of ideas is other people. Children acquire knowledge from their family and friends, from the magazines and books they read, the programs they see on television (as well as from radio, films, computer games and the internet). These sources are not always scientifically reliable. In common language, acids are necessarily dangerous, and food-stuffs should be «pure». A drink containing ascorbic and citric acids would be unlikely to sell if it was labelled as «impure solution of acids» rather than «pure orange juice». Everyday language, often used in rather imprecise and poetic ways, has commonly

been used as a source of scientific terminology, such as the 'cells' of living things, by analogy with the cells in monasteries. Unfortunately, this allows the everyday meaning of terms to be imported into students' minds. For example, particles of salt or sugar or dust are familiar to children. The «particles» of «particle theory» in chemistry are in some ways a bit like very tiny grains of salt or specks of dust. Unfortunately, these chemical particles are actually very different from everyday particles in important ways, that the use of a common term may undermine.

### Misconceptions in chemistry

Misconceptions have been identified in most topics learnt in chemistry. Interestingly, many of these misconceptions relate to the abstract entities used in chemical explanations at the level of atoms and molecules. A great deal of the explanatory framework of modern chemistry depends upon models of the structure of matter at sub-microscopic levels (in terms of atoms and molecule and electrons and bonds). Of course it is not possible to show students these entities, as they are much too small to be seen. (Data collected in such devices as tunneling electron microscopes may be used to produce images, but these are

reconstructed indirectly, not actually based on magnified vision.)

This means we have to offer students various representations that capture something of the conjectured nature of the molecules and ions that we want them to use as explanatory concepts. We commonly use pictures and models, but these inevitably only offer a weak representation of the ideas we are trying to teach. The molecules and atoms and electrons of science are not discretely bound objects, but rather fuzzy fields of force with no sharp edges or surfaces. They are not particles in the normal everyday sense, but something else (they have been called *quanticles*). However our teaching models made of plastic balls connected with springs (for example) cannot reflect this (figure 3). Students commonly have real difficulty understanding how the very unfamiliar nature of the molecular world is used in chemistry to explain the familiar properties of chemical substances (Taber, 2001).

In chemistry we use models to represent our ideas about aspects of the world. The models only ever reflect the target concepts to a limited extent.

The challenge of learning about the sub-microscopic models used in chemistry has been well-recognised in science education



Figure 3. The author teaching with models when he taught at Havering College of Further and Higher Education in North East London.

(Gilbert & Treagust, 2009). The abstract and unfamiliar nature of the concepts certainly increases the «learning demand» (Leach & Scott, 2002). What may be less clear is how students commonly form misconceptions about these topics (as they are unlikely to hear much about pi orbitals, hydrogen bonds, or d-level splitting before they are taught these topics in school). Yet it is clear that often students do present with alternative conceptions of these chemical models.

So, for example, consider figure 4. This shows a representation of a slice through an ionic structure (NaCl). The structure is shown as being symmetrical, with each ion closely packed with (in two dimensions) four counter ions. Students commonly interpret this as solid NaCl, comprising of a large number of NaCl ion-pairs (or «molecules»), each containing a single sodium ion bonded to a single chloride ion. These students believe that each sodium ion can only form one ionic bond, and that an ionic bond requires electron transfer to occur (Taber, 1994). Many students who make such a claim will have actually prepared NaCl in the laboratory by neutralisation followed by evaporation (a process that does not require any electron transfers and simply brings together the ions already present in the acid and alkali solutions).

Figure 5 shows two hypothetical and «opposite» processes. If students are asked which of these processes is likely to occur spontaneously, they are more likely to suggest that it is the ionisation process that is going to occur spontaneously. Students commonly expect atoms to form ions of their own accord (Taber, 2003). This is often found even after studying the topic of ionisation energies (which is explicitly and centrally about the amount of work that needs to be

Figure 4. NaCl structure (a two dimensional representation showing the symmetrical arrangement of ions).

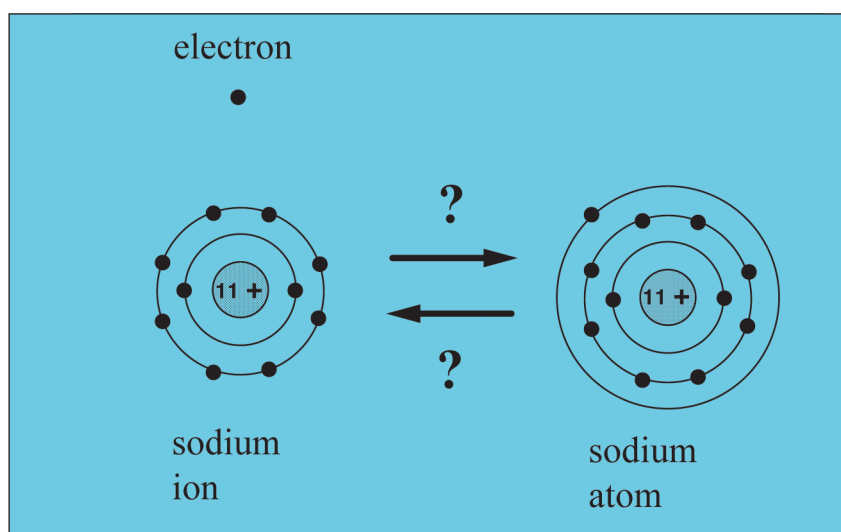
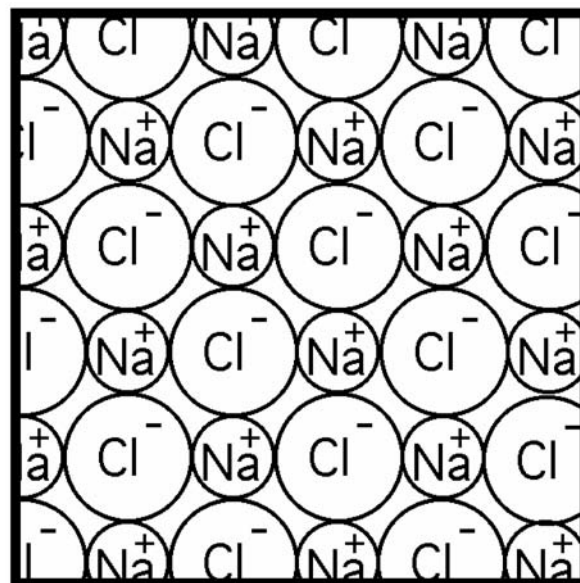


Figure 5. Two possible processes (ionisation and electron capture).

done to ionise different atoms). These topics, among others, are considered in the RSC publications (Taber, 2002a, 2002b).

#### Pedagogic «learning impediments»

What is clear in examples such as these is that the student misconceptions do not seem to derive directly from their intuitive understanding of the world (as they have no basis for building an understanding of atoms and electrons based on their own direct experience), and are unlikely to derive from everyday discourse (as few families regularly discuss ionic lattices or ioni-

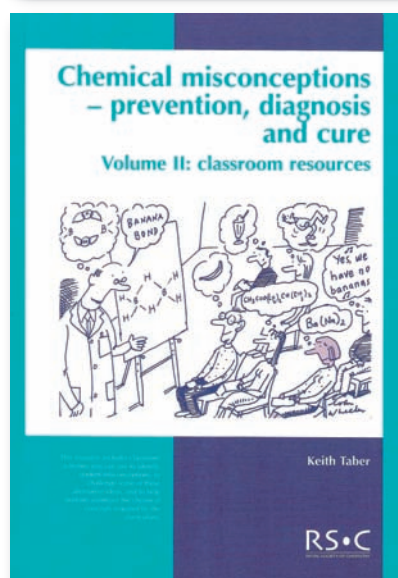
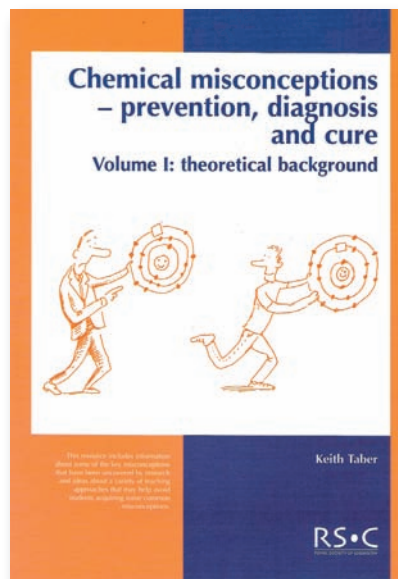
sation processes over the meal table). Yet despite this, students commonly develop strongly held, and hard to displace, misconceptions of the molecular world. For example, in one series of studies it was found that most students suggested that the hypothetical  $\text{Na}^{7-}$  ion (surely not an entity they might have learnt about in everyday life) would be more stable than a sodium atom (Taber, 2009a).

It seems clear that teaching must somehow be playing a major part in students developing many misconceptions. This is not to suggest that most teachers are setting out to teach ideas that

are misconceptions. Rather, the ways some ideas and topics are presented seems to interact with learners' existing ideas, to encourage the formation of misconceptions. So, for example, we are now beginning to understand how students' general intuitions about the world may tend to channel their interpretations of the phenomena (Taber & García Franco, 2009) and concepts (Taber & Tan, 2007) presented in school chemistry. It is also clear that many of the common misconceptions about bonding, chemical change, ionisation etc. seem to relate to a common alternative conceptual framework that students develop from their interpretation of the octet rule (Taber, 1998). A better understanding of how students come to understand chemistry in the way that they do should help us plan teaching in a way that can avoid these misconceptions developing.

### The Royal Society of Chemistry Teacher Fellowship Project

The Royal Society of Chemistry (RSC) is both a learned society, and the UK's professional body representing chemists. It publishes a magazine for teachers (*Education in Chemistry*) and an open-access research journal in chemistry education (*Chemistry Education Research and Practice*).<sup>1</sup> For a number of years the RSC has appointed a Teacher Fellow to work on a one-year project leading to some form of teacher resources relating to primary science or school chemistry education. The Teacher Fellowship project for the 2000-2001 academic year had the theme of challenging chemical misconceptions. At the time I was appointed the Teacher Fellow for the RSC's *Challenging Misconceptions in the Classroom* project, I had recently moved into higher education after teaching in English secondary schools (11-18 year olds) and further education



(working mainly with 16-19 year olds, and adult students). During the project I worked for the RSC on secondment from Homerton College, Cambridge, and was made a Visiting Fellow at the University of London's Institute of Education where the project office was based.

The main work of the project involved identifying key areas of learning difficulty where students commonly formed alternative conceptions in chemistry, and in designing and testing simple diagnostic probes that teachers could use in the classroom to find out whether students in their classes held these misconceptions. This meant drafting probes and instructions, and finding teachers

interested in piloting the materials and offering feedback.

Teacher feedback, and returns of completed materials, allowed the different probes to be modified where this seemed advisable. The final versions of the materials (the probes, with the instructions on how to use them in the classroom) would be published as the second volume, *Classroom resources*, of the RSC publication on *Chemical Misconceptions – prevention, diagnosis and cure* (Taber, 2002a). The probes were also placed on the RSC website.<sup>2</sup>

The classroom materials were deliberately positioned in the second volume of the publication, because it was considered important for the teachers who might use the materials, that they should be presented in the context of a more detailed explanation of the rationale for identifying student misconceptions, and a review of key misconceptions in the basic topic areas covered by the classroom resources. Volume 1 was accordingly entitled *Theoretical background* (Taber, 2002b).

### Developing teachers as «learning doctors»

A particular issue raised by the project was that although there are quite a number of well-established common misconceptions found among chemistry learners (such as the examples presented earlier in this article), learners each have their own unique set of existing ideas, and so it is also common for students to develop their own idiosyncratic ideas which can also act as barriers to effective learning of school chemistry. It is clearly not possible for an organisation like the RSC to develop probes to uncover *all possible* misconceptions that any particular students may develop (and even if it were possible, the use of such materials would not be practicable in the classroom, as very few students

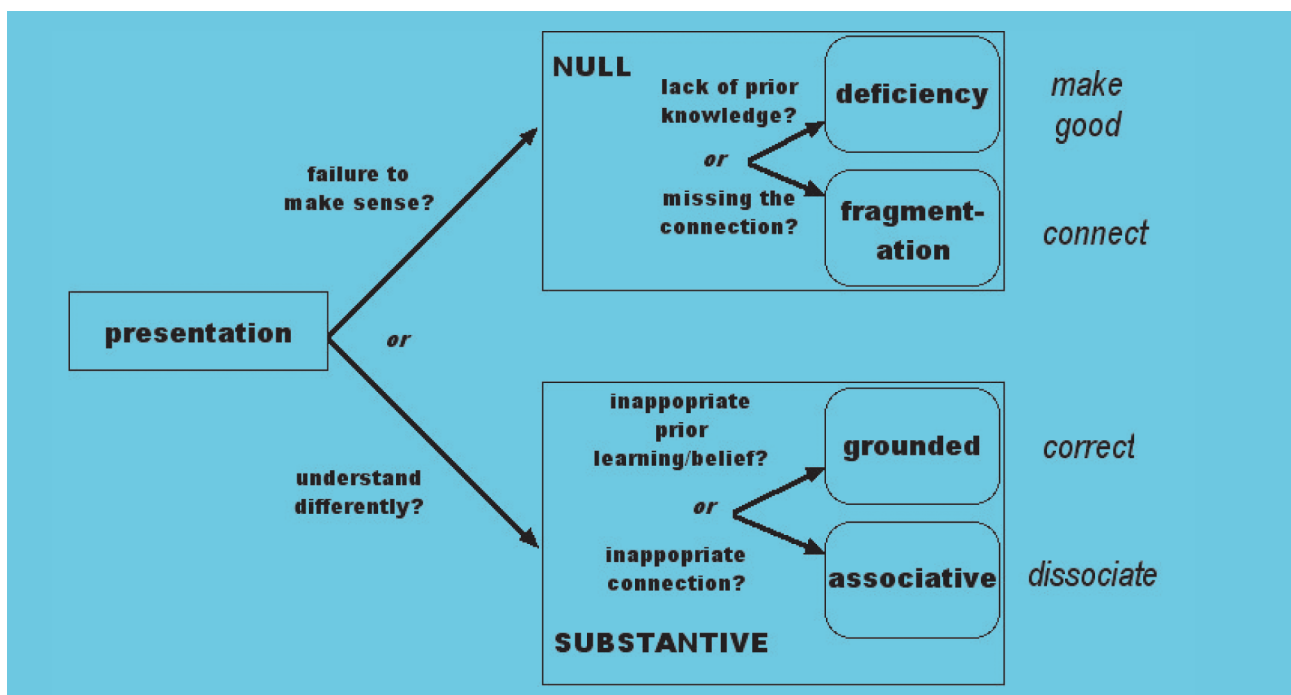


Figure 6. A typology of learning impediments. One way of thinking about how teaching can be misunderstood leading to «learning bugs» such as misconceptions, from <http://people.pwf.cam.ac.uk/kst24/ScienceLearningDoctors.html>.

The materials presented the specific probes in the context of a wider approach of encouraging teachers to see themselves as «learning doctors» who could diagnose and respond to the wide range of different ideas that might interfere with intended learning for different students

would hold each of the many conceivable misconceptions).

The materials therefore presented the specific probes in the context of a wider approach of encouraging teachers to see themselves as «learning doctors» who could diagnose and respond to the wide range of different ideas that might interfere with intended learning for different students. This was based on a model of the different ways in which learners could fail to

understand chemistry in the way the teacher had intended. Figure 6 provides a graphic illustration of a key part of this model, which is explained in more detail in the RSC Publication and on my University webpages.<sup>3</sup>

Figure 6 only acts as a model, and is a simplification of the complex interactions that lead a particular student to form a specific way of understanding chemistry (just as our balls-and-spring molecular models are only like actual molecules in limited respects). However, the model has been used as the basis of workshops with both teachers in training and teachers in service. A teachers' e-mail list is available for any science teachers who wish to use the model in their classrooms and share their experiences of being «learning doctors».<sup>4</sup>

### Conclusion

The RSC's project on challenging misconceptions in the chemistry classroom led to the publication of materials which explain the nature of common

learning difficulties and misconceptions, provide classroom probes for checking for some of the most common misconceptions, and, just as importantly, offers teachers a framework for developing their own diagnostic skills in the classroom. With the translation of the materials into Catalan, the range of teachers able to benefit from the RSC's commitment to this project will be further expanded.

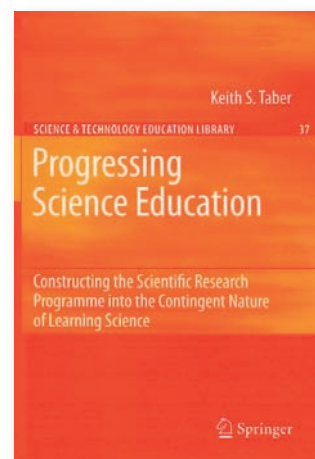
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Dr. Taber's most recent book, "Progressing Science Education: Constructing the scientific research programme into the contingent nature of learning science" looks in detail at research into learners' understandings of science. The book explores the core ideas informing the research, criticism of constructivism in science education, what we now know about student learning in science, and the priorities for further research.



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1. Available at <http://www.rsc.org/Publishing/Journals/RP/index.asp>.

2. Available at <http://www.rsc.org/education/teachers/learnnet/miscon2.htm>.

3. See <http://people.pwlf.cam.ac.uk/kst24/ScienceLearningDoctors.html>.

4. See <http://people.pwlf.cam.ac.uk/kst24/ScienceLearningDoctors.html> for details of how to join this list.