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A New Definition of Models and Modeling in Chemistry's Teaching

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Abstract The synthesis of new chemical compounds makes it the most productive science. Unfortunately chemistry education practice has not been driven to any great extent by research findings, philosophical positions or advances in new ways of approaching knowledge. The changes that have occurred in textbooks during the past three decades do not show any real recognition of these. Despite previously reported different types of models in this paper, from an 'empirical reliability with minimal realism' approach to realism, a new simple and broad definition, a typology of models and their relation with modeling is presented.

1 Introduction

> Chemists are a distinct people, still very few, with their own language, their laws, their mysteries, and living almost isolated in the midst of a greater people hardly curious of its business and expecting nearly nothing from its industry
>
> Diderot's *Encyclopedia*

Chemistry's teaching is in a crossroad. The number of substances made by chemists and their commercial applications has grown dramatically over the past 200 years, from a few hundred in 1,800 to over 56 million today with approximately 43 million in trade. The synthesis of new chemical compounds makes it the most productive science (Schummer 1999). Schummer (2006) indicates that in the year 2000 the number of Chemistry publications alone amounted for virtually the same number of all the other sciences' publications together. Furthermore, we recently recognized that our classroom practice is deeply embedded within philosophical approaches (Duschl 1994; Erduran and Scerri 2002; Van Aalsvoort 2004) and also the importance of technology in the chemical enterprise (Sjöström 2007; Bensaude-Vincent and Simon 2008; Chamizo 2011a). Unfortunately chemistry education practice has not been driven to any great extent by research findings, philosophical positions or advances in new ways of approaching knowledge. The changes that have occurred in textbooks during the past three decades do not show any real

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recognition of these. Here I will try to characterize the problem we are facing and to give a clue on its possible solution through what is known as "model-based view" (MBV) of science teaching applied to chemistry.

1.1 About Teaching Chemistry

> Education is a conservative enterprise, and it does not change very quickly. I think the shift in chemistry education has to come from the recognition of the fact that 99.9% of the population are not going to be chemists
>
> Roald Hoffmann

In the last 50 years many attempts have been done to change the practice of traditional school Chemistry. Following the Sputnik's launching several approaches, from *Nuffield Chemistry* and *Chem Study* to *Salters' Chemistry* and *ChemCom,* have been developed and spread to many other countries. Despite these major efforts, the results were rather disappointing (Fensham 1992; Matthews 1994); Schwab's (1962) interpretation of science teaching as a dogma or as "*a rhetoric of conclusions*" remains. For example until very recently and all around the world, Chemistry teachers provided learning experiences for students without considering their prior knowledge. Despite the huge research about misconceptions (in chemistry see Kind 2004) the problems related to conceptual change and its meaning—particularly the procedures "to face and solve it"—remains a difficult task for many teachers. One of the main results of this research recognizes the lack of time devoted for each student to think and perform experiments about the specific subject being taught. In the laboratory, for instance, students are asked to perform activities, make observations and then form conclusions. All the students must do that at the same time. They're expected to deliver conclusions both self-evident and uniform. This could only happen if each student had exactly the same prior conceptions and made and evaluated observations using identical schemes. In other words, teachers anticipate that the data will lead all pupils to the same conclusion. This does not happen in science nor does it occur in the science classroom. As Hodson (1994) advanced many years ago, in teaching labs "*less practice and more reflection*" is needed.

Despite the tradition that already have the research into nature of science (McComas 1998; Lederman 2007) many Chemistry textbooks suggest erroneously that scientific results come from the mind of a great scientist; hence teaching science requires history of science. However, neither the way these achievements were done nor the attitudes that were needed are really discussed. Since processes are ignored, there is no room to develop professional skills such as setting up experiments, evaluating experimental results, discussing alternative interpretations, professional attitudes, like open-mindedness, willingness to suspend judgment, objectivity, and so on also stay out of the picture. Addressing this issue Gilbert (2006) recognized "students can solve problems presented to them in ways that closely mirror the ways in which they were thought. They signally fail to solve problems using the same concepts when presented in different ways".

Research in school chemistry curricula suggested that an underlying, coherent structure of chemical concepts that students are supposed to learn for the purposes of explaining and predicting chemical phenomena was almost universal (De Vos et al. 1994). The authors analyzed current and post-war textbooks and syllabi representative of secondary chemistry education in most Western countries trying to find why they are so remarkably similar. Using Kuhn's (1970) approach of normal science and scientific training they interpreted dominant school chemistry as a form of normal science education. The latter has the following characteristics:

(a) Normal science education prepares future scientists for normal science.
(b) Normal science education is the dominant and normal form of science education in natural sciences at the tertiary as well as the secondary level, which means that normal science education, is paradigmatic.
(c) Normal science education contains implicit norms towards science and its philosophy and pedagogy.

With these ideas, they summarized in ten statements the general nature of school Chemistry and tried to validate them with an international Forum of twenty-eight experts in chemical education. After several years of discussion, a general agreement on the core of dominant school chemistry was obtained and the results of the research published (Van Berkel et al. 2000). Van Berkel's research recognizes the dominant school Chemistry is particularly isolated from everyday life and society, history and philosophy of science, technology, and chemical research. His main conclusion concerning the international forum of experts' discussion was:

> The structure of the currently dominant school Chemistry curriculum is accurately described as a rigid combination of a substantive structure, based on corpuscular theory, a specific philosophical structure, educational positivism, and a specific pedagogical structure, initiatory and preparatory training of future chemist. (Van Berkel 2005, p. 67)

This 'manifesto' against traditional chemistry education agrees in one way or another with other research results from different countries.[1] For example the main objection of van Aalsvort is about logical positivism, on which chemical education is currently supported, because it emphasizes a conception of knowledge and holds assumptions about society and citizenship that turn it into a counterproductive undertaking when it comes to convincing our students of the relevance of Chemistry. On the other hand recently Talanquer (2011) suggests that chemistry is a transgressive science that resists the dogmatic classifications often founded in studies of nature of science. For him "explaining and modeling are just two of the many facets of chemistry. The discipline is also about making new substances, designing new synthetic and analytical processes, and analyzing and transforming material systems". Chemists do not observe nature passively; they measure to achieve transformations (Hoffmann 2007) through the chemical experiment (Chamizo 2011a, b).

Research has been done trying to recognize the factors of failure involved in science's education reform. Some of them are: misplaced goals of the curriculum (Duschl and Osborne 2002); lack of involvement of teachers in policy making (Aikenhead 1997); lack of a learning theory (Novak 1977), epistemological (Van Aalsvoort 2004; Talanquer 2011) and last but not least, resistance of teachers to change (Herron 1971). Out of this van Berkel (2005) proposed three conditions to escape from the dominant school Chemistry:

1. In order to escape, we have to know what to escape from.
2. In order to escape, we have to know where we are escaping to. That means to develop and legitimize a new coherent vision of the structure of a school chemistry curriculum.
3. In order to escape, we have to know how to escape.

[1] See for instance: Jensen (1998a, b, c), Gabel (1999), Izquierdo and Adúriz (2003), Hodson (2003), Van Aalsvoort (2004), Chamizo (2007), and Talanquer (2011).

After his research on Salters' acceptance in the UK he found that "attempts to escape could be more successful if large-scale development projects were to adopt and implement these three conditions of escape together. That is, to articulate a new vision while preventing the importation of the old one, and to plan, realize, and test the new vision by developmental research". All these ideas form the proposal of a new and 'open' curriculum are considered at the Utrecht University to be applied (De Vos et al. 2002; Bulte et al. 2006; Prins et al. 2011).

Suckling et al. explained, in the introduction of their book "*Chemistry through models*", published in 1978, the use of models in learning, understanding, and practising chemistry. They showed that professional chemists use models in their work, not only in the material sense, but also in their patterns of thought, coming to grips with chemistry and its applications through the manipulation of models. Accepting Brunner's research (1966), they agree that modeling is so natural in our thinking that we are not aware of the mechanism of the process. Besides for them inter-disciplinary interaction is most likely to be effective when it is based on an understanding of the models that the various disciplines use. But:

> … traditionally however the chemist has not been trained to cope with these requirements. Chemistry (like anatomy?) tempts its disciples to the relatively unstructured accumulation of facts. In academic courses, introductions to other disciplines are often introductions to facts rather to underlying patterns of though, which is to say to models. (Suckling et al. 1978, p. 3)

Recognizing the transgressive character of chemistry, its deep experimental roots, and the premises of van Berkel et al. and Suckling et al. another way to escape from the dominant school chemistry is through what is known as "model-based view" (MBV) of science teaching applied to chemistry. One of the aims of this work is to make explicit the relation among models, modeling and the real world.

1.2 About Models and Modeling

> It is time to rid chemistry of obstacles of every kind which retard its progress and to introduce in it a true spirit of analysis; we have proved sufficiently that this reform must be brought about by perfecting the language.
>
> A. Lavoisier

In recent years there has been intense research in philosophy of science[2] and in science education[3] using models and modeling some of them specially devoted to Chemistry (Suckling et al. 1978; Klein 2003; Erduran and Duschl 2004). This characterizes what is known as "model-based view (MBV) of science, where models and modeling are seen to take a central role in the justification and formation of knowledge" (Tapio 2007, p. 751).

For just over 50 years, both, philosophers and researchers in science education, starting from different positions and with different ambitions have led to various classifications of models. Here is important to remember Harré's words about models' classification:

> An object, real or imagined, is not a model. But it functions as a model when it is viewed as being in certain relationship to other things. So the classification of models is ultimately a classification of the way things and processes can function as models. (Harré 2004, p. 6)

[2] For example: Black (1962), Hesse (1966), Morgan and Morrison (1999), Bailar-Jones (2002), Harré (2004), Casanueva (2005), and Giere (2006).

[3] See for instance: Gilbert et al. (2000), Justi and Gilbert (2003), Matthews (2007), Clement (2008), Clement and Rea-Ramírez (2008), Schwarz et al. (2009).

Table 1 Some typologies of models

Typology	References
Scale, analogic, mathematical, theoretical	Black (1962)
Enactive, iconic, symbolic	Bruner (1966)
Scale, analog, theoretical	Giere (1991)
Mental, expressed, consensus, teaching	Gilbert and Boulter (1997)
Analogical (scale, iconic/symbolic, mathematical theoretical) and mental	Harrison and Treagust (2000a, b)
Historical and hybrid	Justi (2000)
Concrete, verbal, visual, mathematical, gestural	Boulter and Buckley (2000)
Iconic (homoemorphs and paramorphs)	Harré (2004)

Some of these classifications or typologies are shown in Table 1 where it can be recognized the complexity of the subject.

Despite the previously reported types of models, this paper, recognizing many of its virtues and the reasons that were proposed (see for example Harrison and Treagust 2000a; Erduran and Duschl 2004), introduces, for its use in chemistry teaching, a new and clear definition of model, a simple and yet comprehensive typology of models that also shows their close relationship with modeling in school′s classrooms or laboratories.

Before defining what a model is, one must identify what position concerning realism is held here. Among the positions that shelter the MBV are, on one side, the *constructive realism* of Giere (1988) and in the other the *constructive empiricism* of Van Frassen (1980). Without getting too deep in the intense discussion that arises when both approaches are compared: for van Fraassen an empirically adequate model is enough, while for Giere a relation of similarity between the model, the behaviour and the structure of a real system are needed. This last realistic position—with its nuances-is shared on its basis by several authors working on educational issues[4] and agree that once there is a relation of similarity between the world and the model there would be chance to use the inferred properties of the entities of the world in the design of experiments or instruments of investigation opening the possibility of intervention (Hacking 1983). About realism, and for example, the reality of electrons, the same Hacking has said:

> If you can spray them, then they are real…What convinced me of realism has nothing to do with quarks. It was the fact that by now there are standard emitters with which we can spray positrons and electrons – and that is precisely what we do with them. We understand the effects, we understand the causes, and we use these to find out something else. (Hacking 1983, pp. 22–24)

Hacking's realism disagrees with van Fraassen's *constructive empiricism.* According to him:

> Van Fraassen continues the positivist antipathy to theoretical entities. Indeed he will not even let us speak of theoretical entities: we mean, he writes, simply unobservables entities. These, not being seen, must be inferred. It is van Fraassen's strategy to block every inference to the truth of our theories or the existence of their entities. (Hacking 1983, p. 49)

Tapio recognized that the distinction between 'observability' and 'detectability' is quite central when it has been established a difference between constructive empiricism and

[4] See for instance: Hestenes (1992), Matthews (1994), Gilbert et al. (2000), Izquierdo and Adúriz (2003), Tapio (2007).

constructive realism (2007, note 6). This was one of the reasons because he recently has coined the term "empirical reliability with minimal realism" as:

> The empirical reliability of models requires only that they produce empirically successful predictions and that the reliability is established in a methodologically accepted way. (Tapio 2007, p. 761)

Tapio initially apply his proposal in physics, but here is adapted to chemistry. Hence it can be said that the minimal assumptions we make to keep close enough to Chemistry's tradition without making unwarranted commitments to pre-conceived philosophical positions are as follows:

- Reality and its entities are ontologically independent from observers.
- Claims about the existence of entities have truth-value.
- Models (and/or theories) of Chemistry are required to be empirically reliable.
- The product of Chemistry is empirically reliable knowledge.

This empirical reliability with minimal realism accepts, as ontological realism, that physical objects exist independently of our own minds. Furthermore and coinciding with Bunge: *the frequent occurrence of error, perhaps even better than the occasional finding of truth, proves the existence of the real world* (Bunge 2006, p. 30). The empirically reliability of chemical knowledge obtained through models has been well identified by Klein (1999, 2003) and Morgan and Morrison:

> … in 1853 Dumas used his formula equation to introduce the notion of substitution, something he would later develop into a new theory about the unitary structure of organic compounds. This notion of substitution is an example of the construction of a chemical conception that was constrained by formulas and formulas equations. Acting as models these chemical formulas were not only the referents of the new conception but also the tools for producing it. Through these models the conception of a substitution linked, for the first time, the theory of proportion to the notions of compound and reaction. We see then how the formulas (models) served as the basis for developing the concept of a substitution, which in turn enabled nineteenth-century chemists to provide a theoretical representation for empirical knowledge of organic transformations. (Morgan and Morrison 1999, p. 18)

It can be said that today, millions of compounds were predicted and synthesized by organic chemists (Schummer 2006) according to this notion of substitution of Dumas, and its reliability and "reality" matches the conditions proposed by Hacking and discussed above about electrons.

This empirical reliability position with a minimal realism allows placing models as mediators between the real world and us. This position, realist about entities, allows to use the properties that we infer from them in the design of experiments, in chemical synthesis, in the production of the artificial, in intervention. As indicated by Morgan and Morrison:

> Models function not just as means of intervention, but also as means of representation. It is when we manipulate the model that these combined features enable us to learn how and why our interventions work. (Morgan and Morrison 1999, p. 12)

Model is a polysemous word; it has been used and is still used with several meanings. That is one of the difficulties we meet when used in teaching. On one side it is exemplary, it indicates things, attitudes or people worth to emulate. The courage of a warrior, the intelligence of a wise man, the solidarity of a doctor, the speed of a runner are examples of models in this regard. In this paper we expand on previous investigations (Chamizo 2009, 2010) and models are defined as follows:

> Models (m) are representations, usually based on analogies, which are built contextualizing certain portion of the world (**M**), with a specific goal

In this definition all the words are important: the representations are essentially ideas, but not necessarily as they can also be material objects, phenomena or systems (all of them constitute a certain part of the world **M**). Representations have no meaning by themselves, they come from someone (either an individual or a group, usually the latter) that identifies them as such. An analogy is made up of those features or properties that we know are similar in (m) and (**M**). That are built contextualizing certain portion of the world **M**, refers to a historically defined time and place it also frames the representation. Some portion of the world indicates its limited nature; models (m) are partial for the world (M). A specific goal, establishes its own purpose, usually but not necessarily explains (or teach) and also predict. In this sense models can be understood as cognitive artefacts or mediators constructed in order to create subjective plausibility about the target. It is important to remember that explanation is one of the most significant features of science, but in some cases when models are even completely unable to offer an explanation, much of its prestige lies in predicting.

Models (m) are representations usually based on analogies (Hesse 1966; Achinstein 1987; Clement 2008; Oliva and Aragón 2009). Clement indicated that by analogy most investigators mean a connection based on structural similarity between the target (an unknown object, a phenomena or a system, generally a problem in the context of an original situation) and a different case called the base (or the source, a familiar object, phenomena or system that helps to understand the target). It is possible to say that analogies are the originators in the construction of many models. Here is important to distinguish between abstraction (or approximation) and idealization (Portides 2007). Abstraction does not include all the objective properties that a phenomena or system implies, it involves control away from to isolate some important fact, for example the omission of intermolecular forces from the ideal gas law, or the Debye-Hückel infinite diluted salt solutions. An idealization is a characterization of an object, phenomena or system where its properties are deliberately distorted, for example the electron as a point particle, or also the ligands (ions or neutral molecules in the "crystal-field theory"). This distortion makes them unsuitable for an accurate representation of the world, it means there are not claims about real world target.

Among the many interpretations of what should be understood as a representation, the one given by Morrison and Morgan seems the most appropriate here:

> A representation is seen as a kind of rendering –a partial representation that either abstracts from, or translates into another form, the real nature of the system or theory, or one that is capable of embodying only a portion of a system. (Morgan and Morrison 1999, p. 18)

This means models can be similar to the portion of the world they represent, usually simple, but not entirely, so that predictions can be derived from it and be tested. The test results provide new information on the model. But models do not hold only a passive mirror relationship with the world as autonomous agents; they also function as research tools (Morgan and Morrison 1999) to intervene in it. And as will be shown below, they do. In this sense, Morrison and Morgan make a clarification:

> We want to caution, however, that our view of models as instruments is not one that entails a classical instrumentalist interpretation of models. To advocate instrumentalism would be to undermine the various ways in which models do teach us about both theories and the world by providing concrete information about real physical and economic systems. They can do this because, in addition to playing the role of instruments, they fulfil a representative function, the nature of which is sometimes not obvious from the structure of the model itself. (Morgan and Morrison 1999, p. 25)

In an abbreviated way: models are mediators that can be modified and their relationship with the real world is bi-directional. It means that in their relation with the real world

(Fig. 1) not only models can be altered, also that the real world becomes altered. Chemical synthesis that follows models constructions as "paper tools" (Klein 2003) by researchers in their laboratories also change and add new entities to the real world (Chamizo 2011a, b).

There are only two types of models: mental and material.

Mental models (Vosnadiu 1994; Greca and Moreira 1998; Coll and Treagust 2003; Clement 2008; Clement and Rea-Ramírez 2008) are reflected representations built by us to account (explain, predict) a situation. They are forerunners of the famous "misconceptions" (Kind 2004) and can sometimes be equivalent since they are unstable, generated in the moment and then discarded when no longer needed, making them cognitively disposable.

Material models (which may be identified as prototypes) are the ones that we have empirical access to and have been built to communicate with other individuals. Material models are expressed mental models (Gilbert et al. 2000) and can be further: symbolic, experimental or iconic.

Symbolic material models correspond to the languages of sciences, such as Mathematics or Chemistry. So those constructed mathematical equations to describe precisely the portion of the world being modelled (Malvern 2000; Mehrtens 2004) are symbolic material models. These represent the regularities that different scientific communities at various times in its history identified with some portion of the world (**M**). These models—known as laws—are the most common type, though not the only one, to offer explanations in scientific tradition (Suppe 1989). Another example of symbolic material model is the one used by chemists to represent elements, compounds and reactions (Crosland 1962; Hoffmann and Lazlo 1991).

There are several approaches of language in science characterized by different attitudes towards it. Golinski (1990) recognized three of them: the symbolic, the hermeneutical and the rhetoric. The chemical language developed in France is an example of the first approach because it studies language in relation to the objects to which it refers. Particularly since nineteenth century the chemical language promote and legitimize a new practice of chemistry followed by an impressive growth in the synthesis of new substances, particularly those that today, and from the reorganization of Chemistry done by J.J. Berzelius at the beginning of the same century, we identified like "organic". Chemist's expectation to denote unambiguously a one-to-one correspondence of word with thing (name with substance) induced Kekule to mobilize hundreds of colleagues from all Europe to the first international conference on science held in 1860 at Karlsruhe. The goal was to

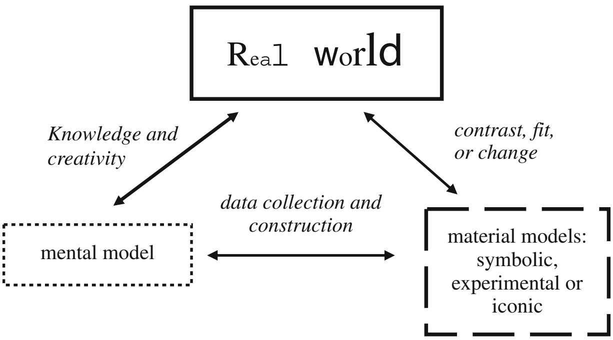

Fig. 1 The relationship between the real world, the two types of models and modeling (in *arrows*)

give each substance a name, and compounds were to be given names synthesized from the names of their parts.

About this Klein indicated:

> In the later part of the seventeenth century and early eighteenth, chemists created a conceptual framework that encompassed concepts like chemical compound, constitution, affinity, chemical decomposition and recomposition, chemical reaction, etc. This scheme shaped the identification and classification of substances as well as experiments investigating their transformations. In the eighteenth century, chemists applied this network of concepts nearly exclusively to inorganic substances. Ordering a particular inorganic substance such as an acid, an alkali or a salt into this network required a series of experiments but was normally seen as unproblematic. However, chemists faced many problems when they began to apply this conceptual network to experiments performed with organic substances… these problems, and the way chemists solved them, by creating models of their new epistemic objects which structured the experimental phenomena in accordance with the general conceptual scheme. In order to build the models of organic compounds and reactions chemists applied chemical formulas introduced by Jöns Jacob Berzelius. (Klein 1999, p. 146)

Ever since, the so called non-existent compounds—"with structures do not offend the simpler rules of valence, but which nevertheless are characterized by a high degree of instability; in many cases the compounds in question have never been prepared" (Dasent 1963, 1966)—and many more have an existence on paper, this means they are material symbolic models (Ramberg 2001) that not simply reflect our knowledge on the substances; they also have influence on the direction taken by chemical research (Jacob 2001).

In addition to symbolic material models are experimental material models and iconic material models. Examples of experimental material models (Pérez-Tamayo 2005; Harré 2009) are male Sprague–Dawley rats used in a standardized way in biomedical research or disease modeling action for possible future remedies. Experimental material models are also devices or apparatus (Harré 2004), such as the famous Urey-Miller (recreating the atmosphere's original conditions that allowed the generation of amino acids) or the Tokomac (used to study the fission reactions that occur in stars), carrying out experiments to simulate a particular aspect of the world (**M**).

Iconic material models correspond to images, diagrams, or scale-models, like a map (Tversky 2005) or the so-called 'molecular models' (Francoeur 2001). Stereochemistry (Ramsay 1981) was constructed with iconic material models in three dimensions (De Chadarevian and Hopwood 2004). For example, in the early years of nineteenth century Dalton constructed wooden models of atoms, after him Pasteur his models of enantiomeric tartrate crystals, Hofmann his croquet ball molecular models, and van Hoff his cardboard tetrahedral models. In twentieth century the stereochemical ideas of Pauling led to the most famous example of an iconic material model, the DNA molecule by Watson and Crick.

Today, there are several million chemists all over the world writing about one million documents (papers, books and patents) a year (Schummer 2006). They intervene in the world producing new forms of matter (Hall 2000). This means chemists usually produce in their laboratories (sometimes through experimental material models), using symbolic material models or helped by iconic material models, a large variety of new substances or as Cerruti indicated (1998) 'new phenomena'.

After establishing this typology of models (mental and material, and the latter could be symbolic, iconic and experimental we must move to the second part of the model definition. The context, according to what the dictionary tells, refers to the physical environment or given situation, whether it be political, historical, cultural or any other measures considered as fact. It also establishes the meaning and value of a word sentence or fragments considered. Recently Gilbert, from the chemical education viewpoint, wrote about it:

> The everyday meanings are "the circumstances that form the setting for an event, statement, or idea, and the terms in which it can be fully understood" and "the parts that immediately precede or follow a word or passage and clarify its meaning". The word originates from the Latin language in the verb "contexere", "to weave together". In its related noun "contextus", the word expresses "coherence", "connection", and/or "relationship". Thus, the function of "context" is to describe such circumstances that give meaning to words, phrases, and sentences. A context must provide a coherent structural meaning for something new that is set within a broader perspective. These descriptions are consistent with the function of "the use of contexts" in chemical education: students should be able to provide meaning to the learning of chemistry, they should experience their learning as relevant to some aspect of their lives and be able to construct "mental maps" (or mental models) of the subject. (Gilbert 2006, p. 960, words in parenthesis are mine)

On (MBV) should clearly distinguish two contexts with different goals. The contexts are: scientific research on one hand (Giere 1999, Matthews 2007) and school science and teaching, on the other (Galagovsky and Arduríz-Bravo 2001; Izquierdo and Adúriz 2003; Matthews 2007; Viau et al. 2008, Chamizo and Garcia 2010). In both cases we have models, material models reaching consensus (Gilbert et al. 2000) in different communities (scientist and teachers) in a certain historical moment. That models are constructed in a particular historical moment with the intention of explaining and/or predicting the behavior of objects, phenomena or systems is exemplified for various chemical issues on Table 2.

Current scientific knowledge—when not surmised to secrecy restrictions that impose commercial companies or ministries of defence—is public knowledge (Ziman 1968), subject of verification by other people, usually scientists. With all the cautions acknowledged by the hermeneutic views of scientific knowledge, it is the possibility of repeating over and over experiments and observations through different conditions of time and space what validates them, what allows scientific knowledge to be presented as objective and reliable. The main way to provide information on scientific knowledge is through articles in specialized journals published for thousands month after month around the world. In the scientific context meaning is defined in terms of practices, and scientific practices, specifically its rationality, are crossed by historical time (Toulmin 1972).

Back to the articles published in scientific journals, their publication guarantees a (also provisional) validation of the depicted knowledge, as Díaz indicated:

> An investigation on the indexes of journals and titles of current scientific work shows that the word 'model' is among the ten most frequent in the titles of articles of physical, mathematical, biomedical, behavioural, social sciences and even the humanities. In addition, it is the only word on the tiny

Table 2 Some material models used in different moments in the history of chemistry

Models about	References
Chemical kinetics	Justi and Gilbert (1999)
Acid and bases	Kousathana et al. (2005)
Lewis-Langmuir-Sidwick	Chamizo (2007)
Caloric and Heat	Cotignola et al. (2002)
Alchemy	Katsiampoura (2008)
Amount of substance	Padilla and Furio-Mas (2008)
Atoms	Justi and Gilbert (2000), Taber (2003), Izquierdo-Aymerich and Adúriz-Bravo (2009)
Phlogiston	Allchin (1997)
Classical organic chemistry	Klein (1999)
Physical organic chemistry	Akeroyd (2000)

> sample of favourite words that does not design specific systems or processes, such as the words 'rat', 'human', 'cell', 'protein' or 'gene', which topped the titles of biological and biomedical articles, or the words 'child', 'family', 'language', 'work' or'social', which often specified more articles in social and behavioural sciences. The word 'model' is then, largely shared by the four corners of academic inquiry, and is a word derived from theory, in particular, methodology. (Díaz 2005, p. 11)

For scientist in everyday research, models, instead of laws, provide all the conceptual machinery (Giere 1999), as Tapio showed concerning Physics:

> On the 7249 articles published in the journal Physical Review E during 2001-2003, the word 'model' appears in 3013 articles (42%) while only 370 (5%) referred to laws. In Physical Review B for the same period there were 14 065 articles of which 4 667 (33%) mentioned models and 251 (2%) laws. The term 'law' (and experimental law) seems to have declined in Physics research. The PROLA databases of Physical Reviews shows that in the last century there has been indeed a drastic change in occurrences of the world 'model' and 'law' in physics publications. In the period 1898-1939 the relative fraction of words 'model' to 'law' was 0.4, in the 1940s it increased to 1.2 and since then steadily to a maximum value of 15.9 in the 1970s (the heyday of models, it seems). After that, the relative fraction has steadily decreased and is now 8.6. (Tapio 2007, p. 770)

In brief: scientists build models about a particular portion of the world with a specific purpose and are the material models, with their advantages and disadvantages that report to their colleagues. Contrary to usual belief, once there is no universal scientific method (McComas 1998), one of the main activities of scientists is to assess what other more competing models fit with the evidence available and consequently what is the most plausible explanation for some phenomenon in the world (Driver et al. 2000).

School science and teaching is the second context. As Oversby indicated: *Chemistry occupies a special place in science since few of the macroscopic observations can be understood without recourse to sub-microscopic representations or models* (Oversby 2000, p 227). Also in this sense, Coll and Treagust (2003) recognized that: *Chemistry teaching is dominated by the teaching of models*. School science (Izquierdo et al. 1999; Izquierdo and Adúriz 2003) belongs to the knowledge constructed and developed in the school environment, it is not science as it is for scientists, but a reconstruction of it, while lacking a reflection of the everyday knowledge of pupils. The idea here is didactic transposition:

> But teaching has never been an easy and natural business. I shall consider a little further on why so many people simply do not see things in this way. However that may be, the main reason for the hardships and vicissitudes of teaching, the source of its uncertainty and fragility, although most often overlooked, is almost self-evident. Bodies of knowledge are, with a few exceptions, not designed to be taught, but to be used. To teach a body of knowledge is thus a highly artificial enterprise. The transition from knowledge regarded as a tool to be put to use, to knowledge, as something to be taught and learnt, is precisely what I have termed the didactic transposition of knowledge. (Chevallard 1988, p. 6)

This means the processes that make scientific knowledge possible, so that students regardless of their age and socio-cultural conditions can learn it (Chevallard 1997). As these conditions are extremely diverse, so is the didactic transposition that frequently *hides the actual implications, scope, and limitations of the ideas that are being discussed as well as the true nature of the process by which the knowledge was produced* (Talanquer 2007, p. 867). However, a necessary condition is that knowledge does not cease to be rigorous and abstract. In short, didactic transposition is the transformation of scientific knowledge in a knowledge that can be taught in a specific classroom about individual students. For more detail here we should recognize two times and/or two subsets of material models built in the school context: those that belong to teaching, i.e. as presented by experts in the school environment and those with learning purposes, that are expressed by apprentices. Examples of material models built in the school context are also drawings that both, students and

Table 3 A learning progression for understanding models as generative tools for predicting and explaining (Fragment from Schwarz et al. 2009)

Level	Performances
4	Students construct and use models spontaneously in a range of domains to help their own thinking.
3	Students view models as tools that can support their thinking about existing and new phenomena. Students consider alternatives in constructing models based on analyses of the different advantages and weakness for explaining and predicting these alternative models possess.
2	Students construct and use a model to illustrate and explain how a phenomenon occurs, consistent with the evidence about the phenomenon.
1	Students do not view a model as tool to generate new knowledge, but do see models as a means of showing others what the phenomenon looks like.

teachers do, many of the illustrations shown in textbooks that usually appear as unquestioned truths, not pointing out their limitations and historically decontextualized, Justi has called these 'hybrid models' (2000). According to the above, it must be considered that there are at least two ways in which those models are interpreted once they are led and/or built by two different groups: apprentices and experts (Grosslight et al. 1991). For apprentices, the latest models are always the most correct and what best explains the object, phenomenon or system, and for the experts the replaced models can still be used if the specific model satisfies the purpose of its use, which may be even simpler. Within the educational context it is very important to make students aware of when they are working with models and when with reality.

In the last years several educational researchers have emphasized the importance for students to build models in the school context and to show teachers how to do it[5] instead of working only with those who are provided by teachers or textbooks. It has been urging the pedagogical advantages it has, for students themselves, review the material models have been built in the school context and compare them to those built in the scientific context to explain ideas, objects, phenomena or similar systems, based on the assumption that models change as understanding increases. This can not be done by following a rigid algorithm, but rather to understand what a model is and the purpose that there is in the different steps that allow its construction in a specific context and historical time. This knowledge about models and modeling is one way of nature of science understanding (Lederman 2007) and in that direction, for example, Schwarz et al. (2009) has designed a learning progression to evaluate it (Table 3).

The construction of a model, i.e. modeling, is a compromise between the similarities and differences that they have with the portion of the world being modeled. Thus, sometimes, when the model does not fit, the empirical data can be expanded and corrected. As noted, its complexity is generally recognized over time (Justi and Gilbert 1999). Models were developed through an iterative process in which empirical evidence can review and revise their basic assumptions (Suckling et al. 1978). A model is usually one in a historical sequence (Chamizo 2007) in a particular area of knowledge, whether it is a scientific or a didactic model. The history of science is rich in examples of how scientific communities have developed models with specific objectives and how they have evolved to accommodate the empirical evidence about the observed facts (Table 2).

[5] See for instance: (Galagovsky and Arduríz-Bravo 2001; Justi and Gilbert 2002a; Acher et al. 2007; Izquierdo et al. 2007; Schwarz et al. 2009; Chamizo and Garcia 2010; Justi et al. 2011).

Briefly, as can be seen in Fig. 1, puzzling phenomenon produce questions about the real world, then comes the construction of a first model: a mental model. This activity represents private modeling with an arrow linking the two squares and has two points because it assumes that the questions depend on the individual's mental structure that performs model construction, and the other defends the position according to the empiricist representation, which depends entirely on data obtained from the perception or consensus about the world. In a specific context and historical time, usually an analogy or similarity was founded, as Giere explained:

> Anything is similar to anything else in countless respects, but surely not everything by itself represents something else. It is not the model that is doing the representing; it is the scientist using the model who is doing the representing.(Giere 2006, p. 64)

These second step in modeling is to express the mental model building a material model (symbolic, iconic or experimental). The expression material model is compared with the richness and diversity of the mental model, necessarily limited. It does consider the most important aspects of the mental model: collect data, edits, create, restart, and it is tuned up to a final version of the material model. It is usually done in two different contexts (scientific and school) with two posssible different aims and implies a two way process usually built around answering the question "What if? Or how to explain this?" Hence, the arrow linking the two boxes and that characterizes the process of modeling is also bi-directional. Finally, the material model should be subjected to the most important test: contrast between the material model and the real world according to a specific goal in each case. It is a public observation, indicated by a bi-directional arrow also because as a result of the same observation adjustments can be made to the material model so that it fits right with the real world (Tapio 2007). The assemblage prioritizes quality of explanation and predictions made by the model. Here, depending on the philosophical position of the person or the community that built the model (the context) it may be more or less strict. However, it is always necessary to evaluate the model, either against the idea, object, phenomenon or system being modeled or against the goal pursued. For example, a material model may look good to some concrete reality, as a suit can look good in a person but bad in someone else. In chemistry however, there is an important difference. As already discussed by Klein (1999, 2003) material model allows, through a chemical experiment, to built a new artificial substance (substances are for chemistry phenomena, Cerruti 1998) and thereby change the real world.

There are neither rules nor methods to learn how to construct models (Boumans 1999) but analogy is a good start (Hesse 1966; Achinstein 1987; Clement 2008). Certainly three conditions are required for modeling:

- Knowledge (to know as much as possible how is that portion of the world);
- Choosing and integrating a set of items considered important for a particular goal (like analogies);
- Imagination and creativity (to design the mental model compatible with that portion of the world setted in the target)

These conditions share what is known as abductive reasoning (Wiener 1958; Harré 1970; Good 1999). This is a process of reasoning to find a model (an explanation of given object, phenomena or system, '*perhaps with some initial plausibility*) *that makes sense of what is otherwise inexplicable, then you should conclude that the explanation is probably right* (Hacking 1983, p. 52). Abduction explains and predicts, like models and it is particularly useful in chemistry. For example as discussed above, a chemist (using symbolic material models, the chemical language that explains) may postulate the potential existence (until that moment a non-existent compound, a prediction) of a reaction product having a definite structure (another symbolic or iconic material model) before carrying out the laboratory process.

Clement (2008) recognized two epistemological meanings for the term abduction:

- A narrower sense: the formation of explanatory hypothesis (explanatory models) called by him 'generative abduction'
- A broader sense: 'generative abduction' plus evaluation and revision cycles for developing a single explanatory model, and later evaluative comparison between rival models.

The main requirement for the last one (which is basically the same as shown in Fig. 1) is that, if true, the abducted model would explain the phenomenon. As indicated by him the term abduction was used *to describe the process of formulating a hypothesis which, if it were true, would provide an explanation for the phenomena in question* (Clement 2008, p. 326). Here we return to the 'empirical reliability with minimal realism' approach to models discussed earlier. Abduction is not based on the supposition that truth about an independent reality can be irrefutably established, but on the idea that models have truth-value and are empirically reliable.

2 Conclusions and Implications for Teaching

> For effective teaching and learning of chemistry, classrooms need to manifest 'what chemists do' which is to model the structure and function of matter
>
> Erduran and Duschl (2004)

It is necessary to rethink the meaning of science we are teaching and how much it transforms our student's attitudes towards knowledge. As by Hodson clearly indicated:

> There is increasing recognition among science educators that science is a product of its time and place, inextricably linked with its sociocultural and institutional location, and profoundly influenced by its methods of generation and validation… Many students still do not learn much of what we intended: their scientific knowledge and their capacity to use that knowledge effectively and purposefully fall well short of our intentions; their understanding of the nature and methods of science are often incoherent, distorted and confused… Now, for the first time in history, we are educating students for life in a world about which we know very little, except that it will be characterized by substantial and rapid change, and is likely to be more complex and uncertain than today's world… The question I pose is: 'What kind of science education is appropriate as preparation for this unknown world?'(Hodson 2003, pp. 647–648)

An immediate response tells us that it is not what we have been doing. The three conditions to escape from dogmatic dominant school Chemistry (that fails to realize its own goals, it means, teaching and learning—for all pupils—the prediction and explanation of chemical phenomena) in agreement with van Berkel's proposal (knowing what we escape from, where we will escape to, and how to escape) can be achieved, as the last epigraph indicated, through MBV.

When this article was under review in this journal, an overview about models and teaching was publisheed (Seok and Jin 2011). Based on a literature review of the theoretical ideas, that science and science education philosopher's researchers have in common, models and modeling were about scrutinised according to five subtopics: meanings of a model; purposes of modeling; multiplicity of scientific models; scientific models and

Table 4 Main findings on literature review about models and modeling in science teaching (Fragment from Seok and Jin 2011)

Topic	Findings
Meanings of a model	Although definitions of a model may be diverse, a model is understood as a representation of a target. The targets represented by models can be various entities, including objects, phenomena, processes, ideas and their systems. A model is also considered a bridge or mediator connecting a theory and a phenomenon, for it helps in developing a theory from data and mapping a theory onto the natural world.
Purposes of modeling	A scientific model as a thinking and communicative device serves the purposes of describing, explaining and predicting natural phenomena and communicating scientific ideas to others. These functional roles of models are leveraged by expressing models with non-linguistic semiotic resources, using analogy and allowing mental and external simulations.
Multiplicity of scientific models	Multiple models can be developed to study the same system because scientists may have different ideas about what the target looks like and how it works. Additionally, there are a variety of semiotic resources available for constructing models which also contribute to the multiplicity of scientific models.
Change in scientific models	There are two ways to test a model in science: *empirical* and *conceptual assessments*. Empirical assessment is a way of evaluating a model in terms of the fit between the model and the actual phenomenon. In conceptual assessment, a model is evaluated according to how well it fits with other accepted models as well as with other types of knowledge The assessment of a model is conducted differently in experimental sciences, such as physics and chemistry, and historical sciences, such as earth science.
Uses of models in the science classroom	Student-centred approaches to modeling share common phases which mediate student learning in some successive cycles including exploration, expression, construction, application and revision of models. Especially, researchers emphasise that if students are allowed to build their own mental representations and present them publicly, it can result in better understanding of the targeted phenomena and processes.

change and use of models in the science classroom. The main findings of their research are shown in Table 4.

As can be seen and beyond the various theoretical positions that could be taken on the five subtopics presented in the review, the new definition and the simple and yet comprehensive typology presented here, fully comply with the revised discussion about what teachers of science need to know, about models and modeling and also shows their close relationship with modeling in school′s classrooms or laboratories.

Quite recently Clement recognized (2008, p. 2) that many of the powerful nonformal reasonings and learning processes used by experts to achieve scientific understanding are also useful in helping students to learn scientific understanding. In this direction Justi and Gilbert have shown (2002a, b) that learning to do science means that students should be able to create, express and test their own models, it means modeling. Here, as recently Prins pointed, care must be taken for students' perceptions, it means that, meaningful learning of models and modeling by students can only be achieved if students indeed feel a need for modeling and have some sense of direction in terms of a sequence of modeling activities (Prins et al. 2008, p. 1888). Besides an intensive work with teachers,[6] the

[6] As can be seen in: Van Driel and Verloop (1999, 2002), Justi and Gilbert (2002a), Drechsler (2007), Chamizo and Garcia (2010), Justi et al. (2011).

requirements to achieve that are: knowledge of specific portions of the world, choosing and integrating a set of items considered relevant for a particular goal, and creativity should be an explicit part of education at any level, understanding this, can be facilitated by the simple definition of models (recognizing them as mediators) its typology and their explicit relation with modeling, presented here.

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