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Chemistry: Why the Subject is Difficult?

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ABSTRACT

One aspect common in every culture is the decreasing number of students studying chemistry. What are the barriers that prevent students from learning chemistry? The objective of this study is to explore the importance of the philosophy of chemistry and suggest strategies that can facilitate students' conceptual understanding. We can make chemistry relevant and promote students' interest, curiosity and understanding by showing that science is a human enterprise. Particulate nature of matter provides an opportunity to reveal that the changing of atomic models (Thomson, Rutherford, Bohr, Bohr-Sommerfeld) is a manifestation of the tentative nature of scientific theories. It is concluded that introducing some elements of history and philosophy of chemistry is conducive towards a better understanding of scientific progress.

KEYWORDS: philosophy of chemistry, tentative nature of scientific theories, atomic models

> Evidently there's more to seeing than meets the eye.
> To see what a chemist sees one needs to know
> what a chemist knows.
> (Bent, 1984)

Resumen (Química: ¿Por qué la disciplina es difícil?)

Un aspecto común en todas las culturas es el decreciente número de alumnos que estudian química. ¿Cuáles son las barreras que evitan que los estudiantes aprendan la química? El objetivo de este estudio es explorar la importancia de la filosofía de la química y sugerir estrategias que puedan facilitar la comprensión conceptual de los estudiantes. Podemos hacer la química relevante para ellos y promover su interés, curiosidad y entendimiento al mostrarles que la ciencia es una empresa humana. La estructura corpuscular de la materia da oportunidad de hablar que el cambio de modelos atómicos (Thomson, Rutherford, Bohr, Bohr-Sommerfeld) es una manifestación de la naturaleza tentativa de las teorías científicas. Se concluye que la introducción de algunos elementos de historia y filosofía de la química conduce hacia una mejor comprensión del progreso científico.

Palabras clave: filosofía de la química, naturaleza tentativa de las teorías científicas, modelos atómicos

Introduction

Over the past decades pupil interest and achievement in chemistry have declined (Osborne & Collins, 2000). According to Aikenhead (2003, p. 103) the reason is because "chemistry and physics are irrelevant and boring, mainly because their instruction is out of synchrony with the world outside of school". It may be interesting to consider the reasons why we are at this point and then to suggest some alternatives.

There are many reasons for students finding chemistry difficult to learn. In schools and universities, the lecture is probably the oldest and most common teaching method, considered to be an effective way to present material in a manner in which student learning is mediated by the teacher. The lecture has been described as "a grossly inefficient way of engaging with academic knowledge" (Laurillard, 2002, p. 94). Nevertheless, the lecture provides an opportunity for a very large number of students to be exposed simultaneously to a large amount of information, and it will likely play a key part in the learning experience of university students in the foreseeable future (Lowry, 1999). In the traditional lecture, the level of students' involvement in the process of learning can be quite low, and "a major problem with the lecture is that students assume a passive, non-thinking, information receiving role" (McKeachie, 1994, p. 68).

According to Johnstone and Su (1994), the common assumption that the lecture is an efficient way to transfer knowledge accurately, is wrong. In the average 50 min lecture, the lecturer delivers about 5000 spoken words, of which students record only about 10%. Students on average transcribed about the 90% of the information written by the lecturer on the blackboard. Some students do not understand the meaning of words used to teach or to test students in chemistry. According to Herron (1996) students find the following difficulties: "A lack of understanding of familiar words used to convey meaning in chemistry; a lack of understanding of technical terms introduced in the study of chemistry; ascribing a familiar meaning to a common word used in technical sense; using everyday meaning to draw incorrect inferences about chemical events; failing to learn the conventions

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applied to specialized chemical language to the level of automatization required to "read chemistry" fluently" (Herron, 1996, p. 165).

About thirty years ago a number of studies described the problems of language in the learning of science (Johnstone & Cassels, 1978; Cassels & Johnstone, 1983; Byrne, Johnstone & Pope, 1994). Johnstone and Cassels (1978) found that many low exam marks in science subjects were due to a failure to understand the language of the questions. In some cases altering only one word made a difference in the result. "The negative presentation of a question sometimes has the effect of a 'double think' and if by chance two negatives stray into a question, even the strongest candidate quails" (Johnstone & Cassels, 1978, p. 166).

Why some students don't learn chemistry

"A sure way to kill conversation at a party is to confess that you are a chemist" (Johnstone, 2000, p. 10). For many students, chemistry is seen as a difficult, complex and an abstract subject that requires special intellectual talents and a too much effort to be understood (Ben-Zvi, Eylon & Silberstein, 1987; Gabel, 1999; Johnstone, 1991; Nakhleh, 1992). However, "… perhaps more than other sciences, understanding chemistry relies on making sense of the invisible and untouchable" (Kozma & Russell, 1997, p. 949). The sources of students' difficulties can have at least three origins (Johnstone, 1984):

1. The nature of the science itself makes it inaccessible.
2. The methods by which we have traditionally taught raise the problems.
3. The methods by which students learn are in conflict with either or both of the above.

The specialist language that chemists use can be a barrier to understanding: "Chemists communicate in a highly elaborated alphabetic and symbolic language" (Sliwka, 2003, p. 24). According to Johnstone (1982, p. 377) chemistry can be seen at least at three levels: "There is the level at which we can see and handle materials, and *describe* their properties in terms of density, flammability, colour and so on. […] A second level is the *representational* one in which we try to represent chemical substances by formulae and their changes by equations. This is part of the sophisticated language of the subject. The third level is atomic and molecular, a level at which we attempt to *explain* why chemical substances behave the way they do." These ideas have then become the famous Johnstone's triangle (Johnstone, 1991).

In this study I propose to explore the importance of nature of science and consequently the relevance of the philosophy of chemistry. Most chemistry teachers are aware of the problems referred to by Bent (1984), Herron (1996) and Johnstone (1991). Nevertheless, there is no one way to solve the problems. Matthews (1998) suggests one alternative by pointing out that philosophy is not far below the surface in any chemistry classroom. At a most basic level, any text or scientific discussion will contain terms such as law, theory, model, explanation, cause, truth, knowledge, hypothesis, confirmation, observation, evidence and idealization. This summarizes succinctly any chemistry course or even perhaps textbook. Finally, Matthews (1998) concluded:

> Philosophy begins when students and teachers *slow down* the science lesson and ask what the above terms mean […] what things can be known and how can we know them, and about what things actually exist in the world and the relations possible between them (p. 169, emphasis added).

Indeed, the crux of the issue is how to 'slow down.' In the next section I will illustrate this approach by using atomic models in order to understand the particulate nature of matter.

Understanding the particulate nature of matter

The particulate nature of matter is fundamental to almost every topic in chemistry and this explains the reason why its understanding is so important. The particulate nature of matter is indirectly taught using some general chemistry topics: it starts with the laws of definite and multiple proportions. But "… most of the textbooks present the laws of definite and multiple proportions within an inductivist perspective, characterized by the following sequence: experimental findings showed that chemical elements combined in fixed/multiple proportions, followed by the formulation of the laws of definite and multiple proportions, and finally Dalton's atomic theory was postulated to explain the laws" (Niaz, 2001, p. 243). This is usually followed by presenting the atomic models of Thomson, Rutherford, and Bohr by emphasizing experimental details. The positivist presentation in many textbooks "leaves out what really happens, that is the 'how' and 'why' of scientific progress" (Niaz, 2008, p. 38). For example, in the case of Bohr's model of the atom, most textbooks consider the major contribution Bohr's theory the explanation of hydrogen line spectrum in the Balmer and Paschen series (Blanco & Niaz, 1997). While, according to Lakatos (1970) "… Bohr's problem was not to explain Balmer's and Paschen's series, but to explain the paradoxical stability of the Rutherford atom. Moreover, Bohr had not even heard of these formulae before he wrote the first version of his paper" (p. 147). Some scholars consider the history and philosophy of science to be the fabric of science teaching (Matthews, 1994). Most textbooks ignore the philosophical issues and the fact that progress in science evolves through competition between rival and conflicting research programme (Lakatos, 1971; Niaz, 1998).

Such presentations of scientific progress constitute a rhetoric of conclusions, based on immutable truths and fail to show the tentative nature of scientific theories. According to Schwab (1962), scientific topics cannot be taught as an "… unmitigated *rhetoric of conclusions* in which the current and temporary constructions of scientific knowledge are conveyed as empirical, literal, and irrevocable truths" (p. 24, original emphasis).

In actual classroom practice, science teachers are trained to transmit to their students the products of "the context of epistemological justification", that is to transmit 'what we know', rather than 'how we know what we think we know' (Monk & Osborne, 1997, p. 407). Although the importance of history and philosophy of science has been recognized for a long time (Matthews, 1994), for most chemistry textbooks, it has only served as rhetoric. This ahistoric presentation of scientific discoveries is not conducive towards a better understanding of scientific progress (Niaz, 1998; Niaz & Rodríguez, 2000) and can be the cause of chemistry's lack of relevance in chemical education (Monk & Osborne, 1997; Van Aalsvoort, 2004a, 2004b; Van Berkel *et al.*, 2000). Presentations in chemistry textbooks cannot be underestimated because this is the material students study and they influence teachers' thinking. Often, the chemistry textbooks become the curriculum of the chemistry course. According to Chiappetta, Sethna and Fillman (1991): "All of the chemistry textbooks deemphasize science as a way of thinking. Their authors do not stress the importance of how chemists discover ideas and experiment, the historical development of chemistry concepts, cause-and-effect relationships, evidence and proof, and self-examination of one's thinking in the pursuit of knowledge" (Chiappetta, Sethna & Fillman, 1991, p. 949).

Students either bring to instruction the mental models that have developed during high school, or construct new ones during instruction. To make things worse, "most students of this age (Grades 8 – 10) prefer models of atoms and molecules that depict these entities as discrete, concrete structures" (Harrison & Treagust, 1996, p. 532). In a study based on eighth-grade students' conception of the particle nature of matter, Novick and Nussbaum (1978) found that "a significant portion of the sample failed to internalize important aspects of the particle model" (p. 278). Studies on students' ideas about the particle model of matter shows that they attribute to atoms the same properties shown by bulk matter (Ben-Zvi, Eylon & Silberstein, 1986; de Vos & Verdonk, 1987; Albanese & Vicentini, 1997; Mammino & Cardellini, 2005).

Chemical reactions is another topic where students develop misconceptions, also because "Some of the major problems in teaching and learning chemistry are encountered in the very first stages of an elementary chemistry course" (de Vos & Verdonk, 1986, p. 972). Ben-Zvi, Eylon, and Silberstein (1987) have asked whether it is possible for N_2O_5 to be formed by a reaction between N_2 and O_2. Some school students in Israel have responded to this question: No; "we had N_2 and O_2. Where from did we get three additional oxygen atoms?" (Ben-Zvi, Eylon & Silberstein, 1987, p. 117). According to Treagust and Chandrasegaran (2009, p. 153), "To be able to explain chemical reactions, students will have to develop mental models of the submicroscopic particles of the substances that undergo rearrangement to produce the observed changes". Besides the concept and model of atoms and molecules, students have to understand other symbols that convey additional information. The understanding of iconic symbols is not easy for all students, and can bring additional confusion as they represent abstract concepts (Marais & Jordaan, 2000). To learn to understand and balance a chemical equation, is similar to learn a foreign language. Actually, it is even more difficult, because "the symbols and grammar of the language of chemistry are closely tied to its basic conceptual principles, and so the language of chemistry has to be constructed on an abstract and less familiar knowledge base" (Taber, 2009, p. 101).

What are the models of the particulate nature of matter in the mind of our students? Maybe it can be useful to specify the meaning of a mental model. The mental models in the mind of our students derive from their descriptions in science education books and from the interactions with teachers in class. Particles of matter are generally described in science education in this way: "All matter consists of entities called particles. Individual particles are too small to be seen. They behave as hard, solid, and (except in chemical reactions) immutable objects. Their absolute dimensions and shape are usually irrelevant. In drawings the particles may be portrayed as small circles or dots" (de Vos & Verdonk, 1996, p. 659).

A review of the literature shows that students' representations of the structure of matter are rich in alternative conceptions (Haider & Abraham, 1991; Nakhleh, 1992; Wandersee, Mintzes, Novak, 1994). According to Griffiths and Preston (1992), students believe that particles are in contact and that there is no empty space between them, while Johnson (1998) in a three-year study found that matter consists of a continuous substance, and three other competing models. The perception of matter as a continuous medium is quite a common misconception (Nakhleh, 1992). Flores-Camacho *et al.* (2006) found five models of matter, with different characteristics and that "every student seems to adopt a full set of models to interpret the structure of matter, depending on the context and type of question asked" (p. 793). Often the experts use multiple representations to interpret a phenomenon. However, it is interesting to note that in the quoted study the two models most often used are incommensurable. When substances are heated and cooled, many students believe that the particles do likewise (Griffiths & Preston, 1992). This is considered a misconception, even when the copper is heated from 20 to 871°C, its atomic radius increases by 1.7% (de Vos & Verdonk, 1996).

Why the particle theory results so difficult for many students? "The particle theory is new and counter-intuitive for school students because it depends on modelling discrete and dynamic particles that are located in a vacuum" (Harrison & Treagust, 2002, p. 203). According to Gabel (2002): "What I have learned in teaching at all levels is that most students want to excel in science until they are discouraged by failing to understand it" (Gabel, 2002, p. xvii). Students are unable to integrate and connect this information with the picture they have in mind and the explanation by the teacher "is regarded by students as just another burden on the brain" (de Vos & Verdonk, 1987, p. 692).

Tentative nature of scientific theories and models

The history of the structure of the atom since the late 19th and early 20th century shows that the models of J.J. Thomson, E. Rutherford and N. Bohr evolved in quick succession and had to contend with competing models based on rival research programs. It is important to emphasize that evolving scientific models are not necessarily right or wrong, but rather increase in their heuristic and explanatory power. In other words, Rutherford's model provided greater explanatory power as compared to Thomson's model, which does not mean that Thomson was wrong. Similarly, Bohr's model provided greater explanatory power as compared to Rultherford's model. This precisely shows the tentative nature of scientific knowledge and its importance has been recognized for science education (Lederman, *et al.*, 2002). Interestingly, in a recent study Niaz and Cardellini (2011a) have asked an intriguing question: "What can the Bohr-Sommerfeld model show students of chemistry in the 21st century?"

Bohr's model of the atom successfully explained the stability of atoms, the ionization energy and the spectra of hydrogen-like ions (Balmer series), that is those having a single electron (for example, He^+, Li^{2+}, and Be^{3+}). Bohr's first model claimed to predict all the lines in the hydrogen emission spectrum. However, there was experimental evidence for a hydrogen series (anomalous Pickering-Fowler ultraviolet series), where according to Bohr there should have been none. The principal shortcomings of the Bohr model were that it could not explain the spectra of atoms containing more than one electron and the fine spectra into which spectral lines can be resolved using spectrographs of high resolving power (e.g., Zeeman effect, modification of atomic spectra by the application of a magnetic field).

Sommerfeld, however, considered Bohr's analysis of the hydrogen spectrum as only approximate as it was based on only one quantum condition, the quantization of the angular momentum. Bohr's orbits were all in a plane, which was too simple an assumption. Bohr himself also recognized that the original quantum theory was incomplete. In contrast, Sommerfeld specified not only the shape of the electron's orbit (which by analogy with planets in the solar system, could be elliptical instead of circular) but also its orientation in space. Contrary to Bohr's 1913 picture, the electrons now moved in Keplerian ellipses and during their orbits, they penetrated the region of internal electrons, thereby causing a coupling of the revolving electrons. In other words, the Bohr-Sommerfeld model, considered the two-dimensional motion of the electron in its orbital plane. Treating the problem relativistically, Sommerfeld showed that as in the case of every periodic motion under the influence of a central force, the electron with rest mass *m* describes a rosette or, more precisely, an ellipse with a slowly precessing perihelion and with one of its foci at the nucleus.

Based on this basic idea of elliptical orbits, the Bohr-Sommerfeld model of the atom was widely accepted by the scientific community, as an alternative to Bohr's model.

Why has the Bohr-Sommerfeld model of the atom been ignored by general chemistry textbooks?

As a sequel to the discussion in the previous section, chemistry teachers would like to know if general chemistry textbooks present and discuss the Bohr-Sommerfeld model of the atom. In order to respond Niaz and Cardellini (2011b) analyzed 28 general chemistry textbooks published in Italy and 46 textbooks published in U.S.A. Bohr-Sommerfeld model of the atom was presented satisfactorily by five Italian textbooks and three textbooks published in U.S.A. It is plausible to suggest that most general chemistry textbooks in this study simply ignore the Bohr-Sommerfeld model of the atom, and even if they mention the model, very few consider it as a manifestation of the tentative nature of scientific theories. It is concluded that textbook authors and perhaps teachers either do not understand or do not consider the tentative nature of scientific knowledge to be important. In order to convince teachers of the importance of this model and how philosophy of chemistry can enhance our understanding we reproduce an example of a satisfactory presentation from one of the textbooks:

> Arnold Sommerfeld (1868-1951) proposed an ingenious way of saving the Bohr theory. He suggested that orbits might be elliptical as well as circular. Furthermore, he explained the differences in stability of levels with the same principal quantum number, *n*, in terms of the ability of the highly elliptical orbits to bring the electron closer to the nucleus (Figure 7-15). For a point nucleus of charge +1 in hydrogen, the energies of all levels with the same *n* would be identical. But for a nucleus of +3 screened by an inner shell of two electrons in Li, an electron in an outer circular orbit would experience a net attraction of +1, whereas one in a highly elliptical orbit would penetrate the screening shell and feel a charge approaching +3 for part of its traverse. Thus, the highly elliptical orbits would have the additional stability … The *s* orbit, being the most elliptical of all in Sommerfeld's model, would be much more stable than the others in the set of common *n* … The Sommerfeld scheme led no further than the alkali metals. Again an impasse was reached, and an entirely fresh approach was needed (Dickerson *et al.*, 1984, pp. 269-271, italics in original).

Some of the salient features of this textbook presentation, that can help in the formulation of a philosophy of chemistry are the following: a) Bohr's model of the atom despite its drawbacks could be saved; b) Sommerfeld's proposal was considered to be ingenious; c) Postulation of elliptical orbits (Bohr-Sommerfeld model) could provide additional stability and this was supported by empirical evidence; d) Despite its success, Bohr-Sommerfeld model of the atom did not go beyond the alkali metals; e) Progress in science often leads to an impasse (contradictions) and consequently a fresh approach is called for.

Conclusions

This study shows that learning chemistry is difficult for many reasons. According to Gabel (1999) "The primary barrier to understanding chemistry, however, is not the existence of the three levels of representing matter. It is that chemistry instruction occurs predominantly on the most abstract level, the symbolic level" (Gabel, 1999, p. 549). This study has shown that as atomic models change (Thomson, Rutherford, Bohr, Bohr-Sommerfeld) we need to provide our students with a scenario in which one model is superseded by another for reasons that can be presented explicitly and in a concrete fashion. Consequently, although visualizing atoms is difficult (Johnstone's triangle), we can convince our students with arguments that are closely linked to experimental evidence. In this context, content of the textbooks plays a major role as they often become the chemistry curriculum (cf. Niaz & Maza, 2011). No wonder, Bent (1984) considered that besides the textbooks, the most important models in teaching chemistry are chemistry teachers themselves. These models, of course, can be strengthened by providing teachers with an overview of the philosophy of chemistry.

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