Development and application of suitable criteria for the evaluation of chemical representations in school textbooks

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The study of Chemistry deals essentially with three types of chemical representations: macro, submicro, and symbolic. Research has consistently shown that students experience difficulties in understanding and interpreting the representations, in making translations between different types of representations, and in constructing them. In this study, we conducted a detailed review of existing presuppositions that define what Chemical Representations are to be included in school textbooks for the purpose of enhancing the student's understanding of Chemistry. We then conducted a detailed analysis of the Chemical Representations included in five Chemistry textbooks. The detailed analysis revealed five criteria for the evaluation of chemical representation used in school textbooks. These criteria (C1-C5) are: (C1) the type of the representation; (C2) the interpretation of the surface features; (C3) their relationship to the text; (C4) the existence and the properties of a caption; (C5) the degree of correlation between the components comprising a multiple representation. The utility of the proposed criteria was then checked against a 10th-grade Greek chemistry textbook. The five criteria cover the basic elements required for a better utilization of chemical representations in the understanding of Chemistry. The five criteria can also be used for the analysis of existing school textbooks and as an authoring tool in designing new Chemistry textbooks.

Keywords: macro, submicro, and symbolic chemical representations, chemistry textbooks, evaluation criteria

Introduction

Chemistry studies phenomena that are not available to direct experience, such as the molecular structure and the interaction between atoms, molecules, ions, etc. Thus, the understanding of chemistry is based on giving meaning to the unseen and to the untouched and in creating mental images for the corresponding molecular phenomena. To represent these phenomena chemists have invented specialized symbol systems (molecular formulas, chemical equations, molecular models, Fischer projections, etc.), which help them to communicate and visualize chemistry (Hoffmann and Laszlo, 1991; Mathewson 2005). Therefore, chemistry is a representative, symbolic and visual science (Habraken, 1996; Wu and Shah, 2004). The visualizations of chemistry through these specialized symbolic systems are external representations and, in this paper, will be referred as 'chemical representations' or 'representations', whereas mental images that are created in the mind are 'internal representations' of concepts and ideas, and they are the consequence of understanding.

Each chemical phenomenon has three aspects: the *macro*, which refers to what is observable; the *submicro*, which refers to what happens at molecular level; and the *symbolic* aspect, which refers to how a phenomenon is symbolized. Johnstone (1993) described these three equivalent levels using an equilateral triangle, each vertex of which corresponds to a chemistry level, and accordingly, chemical representations can be categorized in three equivalent types: *macro*, *submicro* and *symbolic representations*.[1]

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Macro representations depict phenomena according to human visual sense. These are direct experiences produced by laboratory experiments or by everyday life (Treagust *et al*., 2003) by watching chemical phenomena at videos, and pictures (photographs or drawings) according to photographic realism.

Submicro representations depict the structure and movement of the real, but too tiny to be observed particles of matter (atoms, molecules, ions, electrons, *etc*., Wu and Shah, 2004). The typical systems that are used for the creation of these representations are the molecular models, the most common types of which are the ball and stick-, the space filling- and the stick-structures. *Submicro* representations may be pictures, computer animations or palpable molecular models. The importance of submicro representations lies in the fact that they are the only type that depicts the particulate nature of matter, which is the base for the interpretation and understanding of chemical phenomena.

Symbolic representations include symbols, letters, numbers and signs that are used to represent atoms, molecules, ions, substances and chemical phenomena (Wu and Shah, 2004). Characteristic examples of symbolic representations are the chemical symbols, the chemical formulas, the chemical equations, the reaction mechanisms, the Newman and Fischer projections, the Lewis structures, the graphs, the algebraic equations, *etc*. They depict three-dimensional particles in a two-dimensional way. The language of chemists is constructed in terms of symbolic representations, where a symbol is the equivalent of a word (Hoffmann and Laszlo, 1991).

A full understanding of a chemical phenomenon involves the ability to move fluently between its three representations (Johnstone, 1993; Gabel, 1999). All chemists are able to visualize a phenomenon easily when they face it at any level of representation. They have developed the ability to 'see' chemistry in their minds in terms of images of molecules and their transformations (internal representations) and to construct, transform, and use a range of external representations (macro, submicro and symbolic). Hence, the role of representations and visualization is essential in developing chemical understanding.

According to the above, chemical representations are an inseparable part of various teaching materials, such as school textbooks, educational multimedia software, slides, video display, computer animation, molecular models, *etc*. However, their simple presence does not ensure that they sufficiently support students' understanding. Moreover, when they do not fulfill certain requirements, they may cause misconceptions.

Purpose of the study and research questions

This study focuses on the requirements that chemical representations should fulfill in textbooks in order to enhance understanding. We decided to examine representations in existing school textbooks, because books are the main teaching tools available to all students, and their usage is not limited by the school's material infrastructure, instructor's training *etc*. School textbooks are the educational material that students use when they study at home. Following their graduation, students continue to use their school textbooks for reference.

Previous researches have studied science models and chemical representations included in school textbooks examining them from various points of view and classifying them by different criteria depending on the purpose of each study. For example Han and Roth (2006) studied semiotics in science, Harrison (2001) studied the abstraction and the analogy degree, and Furio *et al*. (2005) studied representations of specific issues, such as acid-base reactions. However one must question whether the simple presence of chemical representations in existing textbooks is indeed suitable for the enhancement of students' understanding of chemistry. Can we be sure that they enhance learning by their simple presence? This is the field object of the present research. What kinds of chemical representations (regarding the macro, the submicro and the symbolic level) are used, and are they properly incorporated in textbooks?

The specific questions guiding our research were the following:

1. What are the presuppositions that chemical representations included in school textbooks should satisfy in order to enhance the understanding of Chemistry?
2. How do chemical representations included in school textbooks reveal the three levels of chemistry and the links between them?
3. How are chemical representations integrated meaningfully into school textbooks?

Our study was designed around three distinct stages in order to answer the research questions. In the first stage we searched in the literature to gather the research findings concerning chemical representations and the specifications required for visual representations in text. In the second stage we analyzed representations of five Chemistry textbooks. Five criteria were generated by this analysis, and in order to examine their utility they were applied to the evaluation of the 10th-grade Greek chemistry textbook's representations (third stage).

Literature review of chemical representations

Teachers usually assume that students can understand the role of each representation's level and the relationships between them, because teachers are able to use all the levels simultaneously (Treagust *et al*., 2003). In addition, they assume that students can easily transfer from one level to another (Treagust *et al*., 2003). We question whether this is indeed true; specifically, whether or not the students are able to think in a parallel way at the three levels of chemistry and to what degree they understand the correct message transferred by a representation?

Research studies have shown that not only school students, but also undergraduates have various difficulties concerning chemical representations. Students have difficulty in becoming familiar with the language of chemistry and in understanding meaningfully the symbolic and submicro representations. It has also shown that in representations students see only objects and letters and not the underlying principles and concepts of chemistry (Krajcik, 1991; Keig and Rubba, 1993; Garnett *et al*., 1995; Kozma and Russell, 1997; Salta and Tzougraki, 2010). Students also have difficulty in representing chemical concepts and chemical phenomena at submicro and symbolic level (Gabel *et al*., 1987; Pereira and Pestana, 1991; Griffiths and Preston, 1992; Nakhleh, 1992; Nakhleh, 1993; Smith and Metz, 1996).

When students observe symbols and chemical equations they have difficulty in visualizing and understanding the particulate nature of matter they represent, and the interactive and dynamic chemistry phenomena involved (Novick and Nussbaum, 1981; Ben-Zvi *et al*., 1986; de Vos and Verdonk, 1987a; de Vos and Verdonk, 1987b; Haidar and Abraham, 1991; Krajcik, 1991; Abraham *et al*., 1992; Hesse and Anderson, 1992; Nakhleh, 1993; Abraham *et al*., 1994; Garnett *et al*., 1995; de Vos and Verdonk, 1996). In addition, it is very difficult for students to make translations between different types of representations, and they cannot link different representations to each other so they can form a deeper understanding of the underlying concepts and not on the superficial characteristics of the representations (Tuckey *et al*., 1991; Keig and Rubba, 1993; Nakhleh and Krajcik, 1994; Kozma and Russell, 1997; Furio *et al*., 2000; Treagust *et al*., 2003; Chittleborough and Treagust, 2008). Similarly, they have difficulty in creating three-dimensional mental images by observing two-dimensional symbolic representations (Rozzelle and Rosenfeld, 1985; Seddon and Shubber, 1985; Seddon *et al.*, 1985; Seddon and Eniaiyeju, 1986; Srinivasan and Olson, 1989; Shubbar, 1990; Tuckey *et al*., 1991).

In conclusion, we can summarize that students experience difficulties in understanding and interpreting the representations, in making translations between the different types, and in constructing them. To address these difficulties a lot of research has been conducted. The following suggestions arise concerning chemistry teaching: a) Chemistry teaching should be held simultaneously at macro, submicro and symbolic level. Multiple representations should be used to depict the same phenomenon. b) Students should be taught systematically the relations between different types of representations, and how the translation from one type to another can be made. Consequently, the connections and equivalences between different types of representations should be emphasized and clarified. Students should be taught the interpretation and the meaning of symbols used in chemical representations (Bodner, 1986; Paivio, 1986; Wegner and Montana, 1993; Russell and Kozma, 1994; Barnea and Dori, 1996; Russell *et al*., 1997; Ainsworth, 1999; Sanger and Greenbowe, 2000; Treagust *et al.*, 2003; Ardac and Akaygun, 2004; Ardac and Akaygun, 2005; Kozma and Russell, 2005; Chittleborough and Treagust, 2008).

The variety of roles that multiple representations can play in supporting learning has been acknowledged. Ainsworth (1999) proposed that the functions of multiple representations fall into three broad classes. Firstly, they can support learning by allowing for complementary computational processes or information. Secondly, they can be used so that one representation constrains interpretations of another. Thirdly, they can support the construction of deeper understanding, through abstraction, extension, or by teaching the relation between representations. Complex new ideas are easier to learn and absorb when presented through multiple representations. The effectiveness of multiple representations can be best understood by considering the design parameters that are necessary to learning and the functions that multiple representations serve in supporting learning.

Since a large part of text chemical representations are pictures, a study of the requirements of illustrations in textbooks was considered necessary. It is generally accepted that the inclusion of visual representations into text can improve learning from that text, but only under certain conditions. Visual representations are beneficial because: they bring the most critical text information to the learner's attention; they convert a 'thousand words' into a more efficient form of information; they provide a visual representation of the text content; they organize or structure the text in a more systematic fashion; they transform a complex, difficult-to-interpret text into a form easier to understand; they construct pictorial relationships between unfamiliar concepts and those already familiar to the learner; they capitalize on pictorial mnemonic techniques to make difficult-to-remember text content more memorable (Levin and Mayer, 1993).

Research studies have shown that the reading of pictorial representations is not at all trivial or straightforward, and students do in fact try hard to understand the images (Stylianidou and Ogborn, 2002). An image is worth more than a thousand words only when the reader knows the code to interpret and to design images (Pinto and Ametller, 2002). Thus, visual language should be taught to students at school, and teachers need to spend time and effort talking with students about the meaning of images and the false meanings that they may convey (Pinto and Ametller, 2002). The presuppositions under which text visual representations are likely to be helpful are the following: visual representations must be appropriate for the type of cognitive outcome that the learner is expected to have; visual representations must be related to the text, and have such characteristics that the reader can easily understand this relation. The text itself must be related to the visual representations, and the text characteristics must be compatible with the kind of visual representations provided (Levin and Mayer, 1993).

Therefore, more attention needs to be paid to the construction of images if they are to function more effectively (Levin and Mayer, 1993; Stylianidou and Ogborn, 2002). Particularly, authors should examine whether the illustrations include the specific functional characteristics required, and are of the desired quality; authors should analyze the text in order to assess whether illustrations are necessary and what kind of illustrations are suitable (Levin and Mayer, 1993). In addition, authors should be careful in mixing symbolic and real entities (students have tendency to attach greater importance to real world objects); they should highlight the elements, intended and accidental; they should encode different meanings of similar symbols in different ways; they should pay attention to wording and placing of verbal elements, and a careful layout is needed when several images are to be integrated into one diagram (Stylianidou and Ogborn, 2002). Finally, in documents with two or more types of images where the correlation is crucial, the presence of lines, such as cursors or arrows would highlight the relations and an emphasis on multi-representation in the caption might also be useful.

Development of criteria

In order to develop general criteria, and the specific characteristics of each criterion, two researchers analyzed separately the representations of five chemistry textbooks, which are: two 9th- and 10th-Grade Greek textbooks (Georgiadou *et al*., 2005; Liodakis *et al*., 2005), two textbooks used in Greek universities (McMurry, 1996; Ebbing and Gammon, 1999), and the popular American

Table 1 Criteria for the evaluation of chemical representations and their characteristics

Criterion	Typology for each criterion
C1: Type of representation	i. Macro ii. Submicro iii. Symbolic iv. Multiple v. Hybrid vi. Mixed
C2: Interpretation of surface features	i. Explicit ii. Implicit iii. Ambiguous
C3: Relatedness to text	i. Completely related and linked ii. Completely related and unlinked iii. Partially related and linked iv. Partially related and unlinked v. Unrelated
C4: Existence and properties of a caption	i. Existence of appropriate caption (explicit, brief, comprehensive, providing autonomy) ii. Existence of problematic caption iii. No caption
C5: Degree of correlation between representations comprising a multiple one	i. Sufficiently linked ii. Insufficiently linked iii. Unlinked

textbook (Moore *et al.*, 1998). Core characteristics of chemical representations, identified at the first reading, were revised after a second reading. The criteria and their relative typology were then constructed based on these core characteristics. Each researcher independently grouped the characteristics into individual criteria. Finally, to reduce bias issues, both researchers, through discussion, reconstruction and agreement, carried out an additional analysis (Stefani and Tsaparlis, 2009). The outcome of the whole analysis is the development of a fully-fledged typology specifically designed for chemical representations in textbooks (Table 1). Each criterion was correlated to literature suggestions concerning both chemical representations and pictures in order to show their usefulness for teaching. The utility of this instrument lies in the fact that can guide textbook authors to successfully incorporate chemical representations, and it can also be used to evaluate chemistry textbooks.

The developed criteria were independently used by two researchers in the analysis of the chemical representations of another chemistry textbook (Silberberg, 2008, 2nd chapter). Sixty-nine chemical representations were selected to establish the reliability of our typology. The researchers used the typology to individually evaluate twice the representations and subsequently discussed their evaluations. After discussion, each researcher evaluated the representations again, allowing for changes if she desired. Finally, an inter-rater reliability (IRR) value was 84% agreement across researchers, which is well above the 70% standard to establish reliability.

The description of each criterion follows using examples from various books.

1st Criterion (C1): Type of representation

The 1st criterion examines the type of each representation included in school textbooks. The following typology was used to characterize the representations: i) *Macro*, ii) *Submicro*, iii) *Symbolic*, iv) *Multiple*, v) *Hybrid* and vi) *Mixed*.

A representation is characterized as *macro*, *submicro* or *symbolic*, according to the corresponding level of chemistry represented by it. A representation is called *multiple* when it depicts a chemical phenomenon simultaneously at two or three levels of chemistry. For example, Fig. 1a is a multiple representation at macro and submicro level, because it shows macroscopically the solid, the liquid and the gas state of water, and at the same time it shows these three states submicroscopically, by molecular models. So, Fig. 1a is composed by two representations – a macro and a submicro – which are integrated into one, and each one depicts separately the same phenomenon. In a *hybrid* diagram, the representations of characteristics of two or three levels of chemistry coexist complementing each other forming one representation. For example, Fig. 1b is a hybrid representation where macro (liquid) and submicro (space filling models) characteristics coexist. The representation depicts an aqueous solution, where the solvent is depicted macroscopically, while the solute is depicted submicroscopically. The difference between multiple and hybrid representations is that multiple representations show a phenomenon at two or three levels by combining two or three representations, while hybrid representations combine characteristics of two or three levels to form one representation. A representation is termed *mixed* where characteristics of a chemistry level (macro, submicro, symbolic) and characteristics of another type of depiction, such as analogy, coexist. For example, Fig. 1c shows a mixed representation where symbolic characteristics of chemical equation and an analogy coexist.

The application of the 1st criterion can answer the questions: What is the level of chemistry that chemical representations of a school textbook are focusing on? What is the level of chemistry that the textbooks emphasize? According to literature review, teaching chemistry at all three levels is an important contributing factor to the conceptual understanding of chemical representations (Bodner, 1986; Paivio, 1986; Wegner and Montana, 1993; Russell and Kozma, 1994; Barnea and Dori, 1996; Russell *et al.*, 1997; Ainsworth, 1999; Sanger and Greenbowe, 2000; Treagust *et al.*, 2003; Ardac and Akaygun, 2004; Ardac and Akaygun, 2005; Kozma and Russell, 2005; Chittleborough and Treagust, 2008; Tsaparlis, 2009). Therefore, chemical representations included in school textbooks in support of the textual presentation of chemical concepts, should correspond to the macro, submicro and symbolic level. In 1993 Levin and Mayer argued, that pictures in textbooks, clarify, describe and/or explain text information. Thus, since chemistry has three aspects (macro, submicro, symbolic) all these aspects should be presented together to best describe, and clarify the meaning

a b c

Fig. 1 Examples of a multiple representation of the three states of water, which consists of two separate representations, a macro and a submicro one (**a**); [2, 3] a hybrid representation with macro and submicro characteristics (**b**); [2, 3] and a mixed representation with characteristics of symbolic representation (chemical word equation) and analogy (**c**). [3, 4]

of the text. For example, if a textbook presents the concept of a chemical reaction, it should include macro representation/s so that students will understand which the studied phenomenon is, submicro representation/s so thatstudents will conceptually understand the explanation of the phenomenon and symbolic representation/s so that students will learn the symbolization of the phenomenon.

2nd Criterion (C2): Interpretation of surface features

The 2nd criterion examines to what degree the meaning of a representation is clear, and specifically, to what degree the surface features of a representation are clearly labelled. By using the term ‘surface feature’ we mean the characteristics (elements) that compose the representation. For example, the representation in Fig. 2 has the following surface features: i) 2 red circles containing the symbol ‘+’, ii) 2 blue circles, iii) the symbol ‘e^-‘ and iv) 2 discontinuous elliptic lines. This representation is included in 10th-grade Greek chemistry textbook, presenting Bohr’s atomic model. Since students are taught this model for the first time, the meaning of the representation’s features should be clearly labelled to increase probability that all students will understand its content, and thus, they will create the desired mental image of Bohr’s model.

The following typology was developed to characterize the representations: i) *Explicit*, ii) *Implicit* or iii) *Ambiguous*. A representation is characterized as *explicit* when the meaning of each surface feature is clearly mentioned (Fig. 3a), as im*plicit* when the meaning of only some surface features is mentioned clearly (Fig. 3b) and as *ambiguous* when there is no indication suggesting the meaning of any surface feature (Fig. 3c). The interpretation of the surface features can be mentioned either in the text or in the captions or in the representations by internal captions. Fig. 3a is an example of an explicit macroscopic representation, because its crucial characteristics, namely the anode, the cathode, the aqueous solution and the hydrogen are clearly labeled by internal captions. Fig. 3b shows an implicit submicroscopic representation where it is declared, by internal captions, that the depicted reaction is a combustion, the reactant is a mixture of hydrogen and oxygen and the product is water, but the meaning of the space filling models is not clearly explained; namely, which

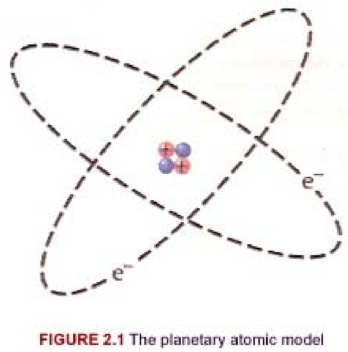
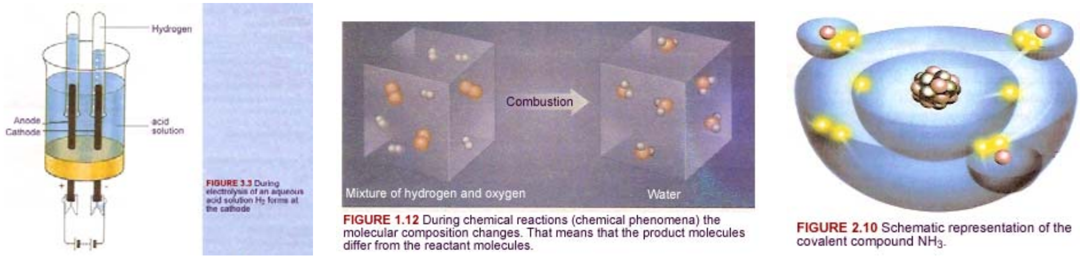


Fig. 2 A representation showing Bohr’s atomic model. [2, 3]

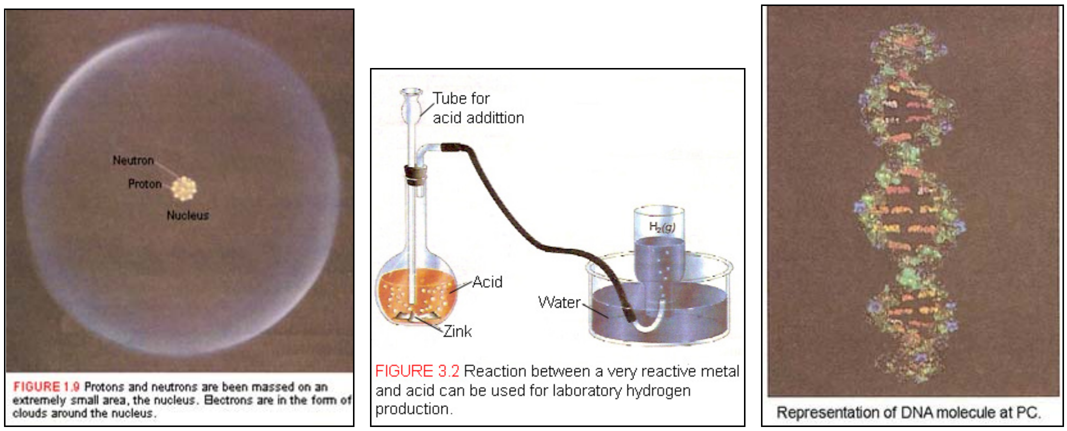
coloured sphere represents which kind of atom. Therefore, although some information is given, the interpretation of the surface features is not totally clear. Fig. 3c, is an example of an ambiguous representation, because it does not mention the meaning of any surface feature. The representation depicts the molecular compound NH_3, and its surface features are yellow, red and black spheres, and blue crusts (shells). In the representation it is not made clear which are the nitrogen and which the hydrogen atoms, neither it is mentioned that each yellow particle depicts an electron, each red sphere a proton and each black sphere a neutron. Thus, a student should have had already understood the concept of atomic bond in order to be able to interpret the representation.

The application of 2nd criterion addresses the following question: *“How can we ensure that students can understand the correct meaning of the included representations?”* It is self-evident that chemical representations are beneficial in learning only if the students can successfully interpret them. Literature findings concerning chemical representations reveal that students face considerable difficulties in receiving the correct message that representations convey (Novick and Nussbaum, 1981; Eniaiyeju and Chia, 1985; Ben-Zvi *et al.*, 1986; de Vos and Verdonk, 1987a; de Vos and Verdonk, 1987b; Haidar and Abraham, 1991; Krajcik, 1991; Seddon *et al.*, 1991; Abraham *et al.*, 1992; Hesse and Anderson, 1992; Keig and Rubba, 1993; Nakhleh, 1993; Abraham et al., 1994; Garnett *et al.*, 1995; de Vos and Verdonk, 1996; Kozma and Russell, 1997;). Thus, the



a b c

Fig. 3 Example of an explicit macroscopic (**a**),[2, 3] an implicit submicroscopic (**b**), [2, 3] and an ambiguous submicroscopic (**c**) representation.[2, 3]



a b c

Fig. 4 Example of a completely related (**a**), [2,3] a partially related (**b**),[2, 3] and an unrelated representation (**c**).[3, 4]

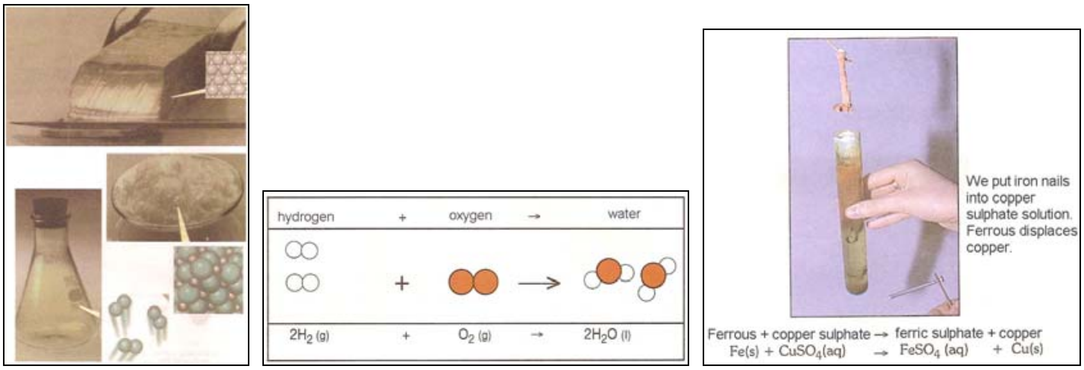
simple presence of representations in a textbook does not ensure that they enhance learning. Literature findings concerning textbooks' illustrations confirm the above conclusion that pictures are beneficial only if the reader knows the codes to interpret them and students try hard to understand them (Pinto and Ametller, 2002; Stylianidou and Ogborn, 2002). For these reasons, authors of textbooks should highlight the elements of a picture.

3rd Criterion (C3): Relatedness to text

This criterion examines the extent to which a representation is coherent and related to text content, and whether there is a direct link from the text to the representation. As *direct link* we mean phrases by which the reader is referred to the representation from the text, such as 'as can be seen in the representation', etc. The following typology was developed to characterize the representations: i) *Completely related and linked*, ii) *Completely related and unlinked*, iii) *Partially related and linked*, iv) *Partially related and unlinked* or v) *Unrelated*.

A representation is called *completely related* when it depicts the exact text content; it is called *partially related* when it depicts a familiar subject to the text but not the exact one; it is called *unrelated* when it is irrelevant to the text content. In addition, a representation is called *linked or unlinked* when the text refers to it by using a direct link or not, respectively**.** The representation shown in Fig. 4a is included in a 10th-Grade Greek chemistry textbook, in the chapter: 'Structure of the Atom'. The text describes the subatomic structure of the atom; thus, the representation is completely related to text content. The representation in Fig. 4b is included in the chapter on the properties of acids, which refers to the reaction of acids with metals and to the production of gas hydrogen. However the text does not direct the reader to Figure 3.2 so as to complete the relationship between the text and the figure. Therefore, the representation is partially related to text content. Finally, the representation showed in Fig. 4c is included in an 8th-Grade Greek chemistry textbook in the chapter of molecules. The text introduces the concept of molecules generally for the first time without any references in submicro representations of molecules and thus the representation is totally irrelevant to text and is characterized as unrelated. Additionally, the helixes of DNA, shown in 4c, are depicted with symmetry with respect to an imaginary axis rather than in the more accurate nonsymmetrical form, which can further confuse the reader.

The application of the 3rd criterion addresses the following question: Are the chemical representations included in a textbook adequately linked to the related concepts, principles or phenomena contained in the text? Previous research on chemical representations shows that students cannot easily correlate representations to equivalent concepts as they see only letters, objects and symbols, and not the underlying concepts (Eniaiyeju and Chia, 1985; Krajcik, 1991; Seddon *et al.*, 1991; Keig and



a b c

Fig. 5 Example of a sufficiently linked (**a**),[2, 3] an insufficiently linked (**b**),[3, 4] and an unlinked multiple representation (**c**).[3, 4]

Rubba, 1993; Garnett *et al.*, 1995; Kozma and Russell, 1997). In addition, research on textbook illustrations shows that students having the inclination to read only the necessary information are likely to glance over the pictures without paying the required attention, (Levin and Mayer; 1993). Therefore, textbook authors should make sure that representations are linked to the related text.

4th Criterion (C4): Existence and properties of a caption

This criterion examines whether a representation is accompanied by a caption, and whether a caption is appropriate or problematic. An appropriate caption should be *explicit, brief and comprehensive*, providing autonomy to the representation. Captions are important, because they make clear the content and the message of representations. (Bodner, 1986; Paivio, 1986; Wegner and Montana, 1993; Russell and Kozma, 1994; Barnea and Dori, 1996; Russell *et al.*, 1997; Ainsworth, 1999; Sanger and Greenbowe, 2000; Treagust *et al.*, 2003; Ardac and Akaygun, 2004; Ardac and Akaygun, 2005). Captions are also necessary in illustrations of textbooks because they point out the crucial parts of pictures (Woodward, 1993). In addition, appropriate captions make the study of a book easier, as students can understand the content of a representation without necessarily having to look at the related text.

5th Criterion (C5): Degree of correlation between the components (subordinate representations) comprising a multiple representation

The 5th criterion concerns only the multiple representations that were identified by using the 1st criterion, and examines to what extent the correlation between the surface features of the separate ‘subordinate’ representations, comprising the multiple one, is clearly indicated. The following typology was developed to characterize the multiple representations: i) *Sufficiently linked*, ii) *Insufficiently linked* or iii) *Unlinked*.

A multiple representation is characterized as *sufficiently linked* when the equivalence of the surface features of the components is clearly indicated. Fig. 5a shows a sufficiently linked multiple representation at macro and submicro level, where the equivalence between the levels becomes clear by the use of arrows. A multiple representation is characterized as *insufficiently linked* when the equivalence of only some surface features is indicated clearly. For example, Fig. 5b shows an insufficiently linked representation, because the submicro and the symbolic representation are placed in parallel so that students may understand the equivalence, but it is not clearly indicated which circle and which symbol represents which chemical substance. Finally, a multiple representation is called *unlinked* when the included subordinate representations are just placed next to one another and there is no indication of the equivalence of their surface features. Fig. 5c is an unlinked representation, because the equivalence between symbolic and macro characteristics is not indicated.

The application of the 5th criterion addresses the following question: “Are there sufficient links between macro, submicro and symbolic components of a multiple representation so that students can fully understand the three levels of Chemistry? Research on chemical representations reveals that students have great difficulties in correlating the three levels of chemistry, and in transforming one level of representation into another For these reasons it has been suggested that students should be taught the relations between different types of representations in order to be able to translate one type into another, and to reach a deep and conceptual understanding of the chemical phenomena under study (Tuckey *et al.*, 1991; Keig and Rubba, 1993; Nakhleh and Krajcik, 1994; Kozma and Russell, 1997; Furio *et al.*, 2000; Treagust *et al.*, 2003; Chittleborough and Treagust, 2008; Tsaparlis, 2009).

We propose that the above criteria cover the basic elements required for a comprehensive evaluation of, or for a successful incorporation of chemical representations in, school textbooks. As an example of the applicability of the proposed criteria we present the analysis of the following representation (Fig. 6) taken from the 10th-grade Greek chemistry textbook (Liodakis *et al.*, 2005). The related text, translated by the authors, is presented below:

C1. Type of representation: *Multiple*, consists of a macro, a submicro and a symbolic representation, all of which depict a sodium chloride crystal. The macro representation is a picture, the submicro one is a ball-and-stick model and the symbolic one is a chemical formula that is mentioned in the caption.

Ions

Atoms of a particular element are electrically neutral, since, as we will study later, they have the same number of protons and electrons. However, atoms can be transformed into ions by losing or gaining one or more electrons.

- *Ions are either monoatomic, e.g.* Na^+, Ca^{2+}, S^{2-}, Cl^- *or consist of a group of charged atoms. These are known as polyatomic ions, e.g.* NH_4^+, CO_3^{2-}, $H_2PO_4^-$.

Ions that have positive electrical charge are called cations, *e.g.* Na^+, and those that have negative electrical charge are called anions, *e.g.* Cl^-. Ions are the structural particles of ionic compounds, which we shall study later on.

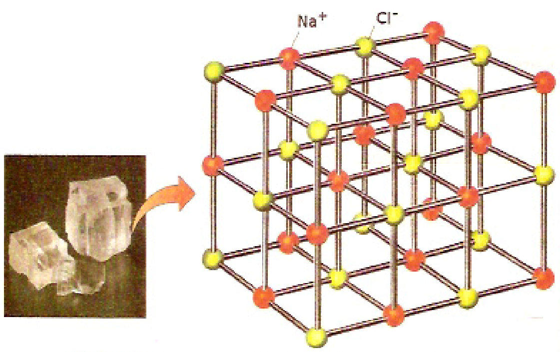


FIGURE 1.7 The crystal of NaCl consists of Na+ and Cl- ions.

Fig. 6 An example of the application of the proposed criteria.

C2. Interpretation of surface features: *Implicit*. Regarding the macro representation there is no indication for its surface features, not even for its content, and thus, it is questionable whether students can recognize what the picture depicts. Regarding the submicro representation, there are labels on the representation that demonstrate that the red balls depict sodium ions and the yellow ones depict chloride ions, but the ions are written by their symbols 'Na^+' and 'Cl^-' and not by their names. Thus, it is required from the students to interpret the symbolic representations of ions in order to understand the submicro representation. The text refers to 'Na^+' and 'Cl^-' as ions but their names are not mentioned, and the meaning of the superscripts is not explained. The symbolic representation, NaCl, appears in the caption without any explanation.

C3. Relatedness to text: *Partially related and unlinked*. The text refers generally to ions (what they are, how they are formed), without mentioning crystal lattices. In addition, there is not a direct link to the representation.

C4. Existence and properties of a caption: The caption is *brief* and provides self-sufficiency to the representation, but it is *not explicit and comprehensive*, because the included symbolic representations are not interpreted.

C5. Degree of correlation between the components comprising a multiple representation: *Insufficiently linked*. The equivalence between macro and submicro representation is pointed out by an arrow, but there is no correlation with the symbolic representation.

The above figure is considered as a whole representation, and by the application of the proposed criteria it emerges that there are not sufficient correlations between macro, submicro and symbolic components, which correlations are so vital in building the links between the three levels of chemistry. In addition, the characteristics of the representation are not adequately clarified and therefore its presence is decorative rather than supportive to the text.

Application of the criteria and its results

The utility of the proposed criteria was checked by their application in the analysis of a Greek chemistry textbook used by all Greek 10th-grade students in both general and technical education, where chemistry is a compulsory course. The number of the representations analyzed was 110.

The analysis shows that 23.6% of the representations included are macro, 19.1% are submicro, 23.6% are symbolic, 21.8% are multiple, 10.9% are hybrid and 0.9% is mixed representations. The majority (91.7%) of the multiple representations included correspond only to two levels of representations in chemistry, with special emphasis on the combination of macro and symbolic level (45.8%). The 29.2% of the multiple representations depict a phenomenon at submicro and symbolic level, while 16.7% at macro and symbolic level. Finally, in the whole book there is only one multiple representation at the three levels of chemistry. Counting the subordinated individual representations of the multiple as separate ones the number of all the separate representations becomes 122. The quantitative analysis shows that the symbolic representations (36.9%) are almost equal to macro ones (35.2%), while there are fewer representations for the submicro level (27.9%). This finding indicates a bias towards a macro-symbolic orientation of the textbook.

By using the 2nd Criterion (*Interpretation of surface features*) we found that only 22.7% of the representations are explicit, nearly half of them (44.5%) are implicit, while a significant number of them (32.7%) are totally ambiguous. These findings show that there is no systematic labeling for the interpretation of the representations, and thus textbook's authors overlooked the significance of this feature. It is therefore questionable whether all students can understand the correct message that the representations carry. Students may consider them as pictures that simply decorate the textbook, or they may receive false messages from them, which may cause misconceptions in learning.

Using the 3rd Criterion (*Relatedness to text*) we found that more than half of the representations (67.2%) are completely related to the corresponding concepts, principles and phenomena, while 30.0% are partially related to the text, and 2.8% have none. The partially related representations are usually examples of a general case, which is described in the text. Therefore, in order to interpret such a partially related representation, students are required to reduce a general case to a specific one, which is a very demanding task for them. By applying the 3rd Criterion we have also examined the existence of direct links from the text to the representations. For the majority of the representations (73.7%) there is no reference in the text connecting the representation with the subject under discussion. This indicates that when designing the textbook authors did not take into consideration students' difficulties in correlating chemical representations to the corresponding concepts. Therefore, it is possible that students will pass by these chemical representations without paying due attention to them, either because they will not understand what their relationship to the textual content is, or because they generally have the tendency to read only the obvious.

The 4th Criterion (*Existence and properties of a Caption*) has been used only for the representations that are not incorporated into text, because the incorporated ones are read as a part of the text that describes exactly their content, so a caption is not needed. From the 66 non-incorporated representations, 58 were accompanied by a caption, but only 37 of these captions are appropriate, namely they are clear, brief, comprehensive and provide self-sufficiency to the representation. So, about half of the representations have either problematic or no caption and thus their content is not clear, which makes their interpretation even more difficult.

The application of the 5th Criterion (*Degree of correlation between the components comprising a multiple representation* showed that more than half, (58.3%), multiple representations do not indicate the equivalence between the surface characteristics of the representations at different levels, while the remaining (41.7%) have insufficient indications for the equivalences. Usually, in the insufficiently linked representations, the individual representations are just placed side by side without any specific indication.

Conclusions and implications

Chemical representations are an inseparable part of textbooks and play an important role in helping students to understand the various chemical concepts and in supporting instructors in teaching practice.

The literature concerning chemical representations is extensive and examines them from various points of view. In this document we developed five criteria suitable for the evaluation of chemical representations used in textbooks. The five criteria, which emerged from our analysis, cover the basic elements required for a beneficial incorporation of chemical representations in school textbooks. In addition, we have identified the presuppositions that chemical representations should satisfy in order to enhance learning. During our research we confirmed the validity of the five criteria and created a single point resource document where authors of Chemistry textbooks, teachers of Chemistry, and students of Chemistry can improve their skill set in creating, transferring and absorbing the chemical representations. Authors of textbooks can make use of the criteria to select the appropriate representations, and to ensure that all representations are linked to the related texts. Teachers of Chemistry can use the criteria to select textbooks for use in their curricula. Teachers may also choose to apply the criteria in the preparation and presentation of their lecture material. Students may use the criteria in selecting supplementary reading material such as textbooks, periodicals, and other types of publications. In addition, students can improve the quality and the comprehension of their work product, whether verbal or in written format, by following the criteria of this document.

Notes

1. The terms macro, submicro, and symbolic for the three types of chemical representations were used according to suggestions of Gilbert and Treagust (2009).
2. Figure is taken from the 10th-Grade Greek chemistry textbook (Liodakis *et al*., 2005).
3. The text was translated by the authors.
4. Figure is taken from the 8th-Grade Greek chemistry textbook (Georgiadou *et al*., 2005).

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