Teaching and learning the concept of *chemical bonding*

Ensenyar i aprendre el concepte *enllaç químic*

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abstract

The knowledge of chemical bonding is essential to the understanding of almost every topic in chemistry. However, it is very difficult to learn, and students have a lot of misconceptions regarding this concept. In order to improve students' understanding of this concept, it is essential to revise the scientific content, the pedagogical approach and the assessment methods regarding this concept. In this paper, we will review two studies. The first one will refer to aspects that have influenced students' misconceptions regarding the topic of chemical structure and bonding, and the other one referring to new methods for teaching the concept of *chemical bond*, as well as assessment tasks.

keywords
Chemical structure and bonding, learning goals, learning performances, organization principles.

resum

El coneixement de l'enllaç químic és essencial per comprendre gairebé qualsevol tema de química. Tanmateix, és molt difícil d'aprendre i els estudiants tenen una gran quantitat de concepcions alternatives en relació amb aquest concepte. Amb l'objectiu de millorar la comprensió dels estudiants entorn d'aquest concepte, és essencial revisar el contingut científic, l'enfocament pedagògic i els mètodes d'avaluació. En aquest article, revisem dos estudis. El primer es refereix als aspectes que han determinat les concepcions alternatives dels estudiants respecte del tema de l'estructura i l'enllaç químic, i l'altre es refereix als nous mètodes d'ensenyar el concepte *enllaç químic*, així com a les activitats d'avaluació.

paraules clau
Estructura i enllaç químic, objectius d'aprenentatge, resultats d'aprenentatge, principis organitzadors.

Introduction

The theoretical content of chemistry is best seen as a set of models. Gilbert (1998) claims that models play a major role in all science disciplines; nevertheless, they seem to be particularly problematical to chemistry students. Students live and operate in the macroscopic world of matter. Unfortunately, they do not perceive chemistry as related to their surroundings. Moreover, they do not easily follow shifts between the macroscopic and microscopic levels (Johnstone, 1991; Gabel, 1996; Tsaparlis, 1997; Pabuçcu & Geban, 2012). Chemical concepts are very abstract and students find it difficult to explain chemical phenomena by using these concepts. The study of students' alternative conceptions and conceptual frameworks has been an active field among science educators for more than two decades. According to Gabel (1996, p. 43):

> The theoretical content of chemistry is best seen as a set of models

> The complexity of chemistry has implications for the teaching of chemistry today. We know that chemistry is a very complex subject from both the research on problem solving and misconceptions […] and from our own experience […] students possess these misconceptions not only because chemistry is complex, but also because of the way the concepts are taught.

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In this paper, we will review two studies that were done regarding teaching the concept of *chemical bond*, as well as assessment tasks.

First study: several aspects that have influenced students' misconceptions regarding the topic of chemical structure and bonding

This study focuses on several aspects that have influenced students' misconceptions regarding the topic of chemical structure and bonding. In Israel, although there has been a serious effort to overcome this problem, the same misconceptions arise each year. We assume that most of these difficulties derive from the characteristics of chemistry learning, such as the central role of models, the linguistic cues and phenomena explained through the sub-microscopic level. Nevertheless, we suggest that there are also external misleading factors, namely, the way the teachers teach (pedagogy, contents and textbooks) and the way students learn, which lead to students' misconceptions.

In this study, we reviewed the analyses of the results of fourteen years of chemistry matriculation examinations (Hofstein, 1991-1994; Bar-Dov, 1995-2003) regarding this topic. Based on these results, we investigated the sources for these misconceptions through further research with students, teachers and scientists. Our assumption was that one of the main factors, which is significant regarding this problem, is the way students are evaluated. In this study we indicated that teaching and learning of this particular topic are very much influenced by the obligatory matriculation examination. Moreover, we suggest that these examinations, in their present form, in fact amplify students' misconceptions.

The questions entitled «Chemical bonding and structure» that are provided each year are very similar. These questions and the students' answers were analyzed. Fourteen years of analyses revealed that students possess a variety of misconceptions regarding the *chemical bonding* concept

The questions entitled «Chemical bonding and structure» that are provided each year are very similar. These questions and the students' answers were analyzed. Fourteen years of analyses revealed that students possess a variety of misconceptions regarding the *chemical bonding* concept. Although there has been a serious effort to overcome this problem, the same crucial misunderstanding regarding the *bonding* concept has arisen each year for the last two decades. We used several methods and sources in order to explore the problem and based on the findings we suggest that students demonstrate a shallow understanding of chemical bonding not only because this topic has intrinsic complexities, but also as a result of external «misleading factors» concerning the traditional approach used for teaching the *bonding* concept. These factors are detailed in the sections that follow and supported by studies conducted worldwide.

The data analysis showed that students possess these alternative conceptions not only because this topic has its intrinsic complexities. Students' misconceptions stem also from several misleading factors. We have mentioned the content and pedagogical components, but we assume that the way students are evaluated is critical to the way this topic is taught. More specifically, we claim that the existence of the matriculation examination in its current form causes students to use slogans and declarations, explain facts by «drawers», and students demonstrate a very shallow understanding of the key concepts. According to Atzmon (1991), Birenboum (1997), and Dori (2003), this system of assessment detracts from teachers' efforts to ensure meaningful learning and the development of students' higher-level thinking abilities.

In light of this, we highly recommend making a real change in the traditional approach used for teaching this topic, abandoning the current pattern of fixative questioning and instead to form new assessment tools. Gilbert (2003) criticized the way of questioning and claimed that the teachers' role is to change this system. He suggested using completely different teaching and assessment methods. We suggest not examining a narrow range of skills, but instead to evaluate students' argumentation and thinking skills as well as the skills in creativity. Such a change requires developing a new curriculum and promoting the development of teachers' PCK. Therefore, an improvement will occur only by a systemic solution such as revising the curriculum, the assessment method as well as the teaching methods.

Second study: developing a new teaching approach for the *chemical bonding* concept aligned with current scientific and pedagogical knowledge

This study is based on the first study described above (Levy Nahum *et al.*, 2004) that we have

conducted during the academic years 2002-2004. The main goal of this study was to develop a new teaching approach for the *bonding* concept by de-construction of the traditional approach and construction of a reformed approach aligned with the scientists' views. We were looking for a more scientific and effective teaching approach in order to improve students' understanding of this topic. The main goal of this study was to develop «an outline for a new teaching approach» for high-school chemistry students in order to improve understanding of the *chemical bonding* concept. Thus, it was necessary to align the teaching of this topic with current scientific and pedagogical knowledge.

The research questions of this study were: 1) what are the key-learning goals and what is suggested as a reform approach to teaching the *chemical bonding* concept in accordance with senior scientists and with chemistry lead-teachers?, and 2) are the new assessment tasks, which were developed based on specified key-learning goals and learning performances (according to the insights raised from the previous question), more diagnostic than the traditional questions on high stakes examination with regard to students' understanding of the *chemical bonding* concept?

We adapted the «assessment-driven design» model (Reiser *et al.*, 2003) for dealing with the systemic problem that was presented above, namely, the problematic approach of teaching and assessing bonding in the last decades, worldwide. According to Reiser *et al.* (2003), the central idea of the «assessment-driven design» process is to identify the key-learning goals and to use these «big ideas» to guide all phases of the curriculum and activity design, while constantly assessing whether the tasks are aligned with the «big ideas». This idea is supported by Kesidou & Roseman (2002), who suggest that the instructional design of the curricular materials has to effectively support the attainment of the specified student learning goals. The mere presence of specific content in a curriculum material does not ensure that students will learn that content. For learning to take place, curriculum materials need to focus sound instructional and assessment strategies specifically on the ideas and skills that students are intend to learn and perform.

During the whole process of developing instructional materials, it is important to ensure that the learning goals, the pedagogical approach as well as the learning performances and the new assessment tasks are aligned in order to foster meaningful learning

During the whole process of developing instructional materials, it is important to ensure that the learning goals, the pedagogical approach as well as the learning performances and the new assessment tasks are aligned in order to foster meaningful learning. Based on the model of Reiser *et al.* (2003) and on the literature review, we designed this study process, which enabled us to re-construct a conceptual framework for teaching and assessing the concept of *bonding*.

Based on the finding from our first study that the examinations' demands amplify students' misconceptions and pseudo-conceptions, we began our process with discussions regarding the common questions (the high-stakes testing) that have a central influence on the way this topic is taught. In order to re-characterize the concept of *chemical bonding* we had to align the scientific content and the pedagogical approach with current scientific views and knowledge. We have based the new approach on the research participants' views. According to the research participants' views regarding the «big ideas» and their pedagogical insights we could build an outline for an alternative pedagogy. This process included the formulation of specified learning goals and learning performances with respect to the scientific practice. Based on these learning performances several assessment tasks were developed.

Accordingly, in this study, a group of ten experts was selected and assembled by the authors of this paper to discuss and comment based on their personal experience on the way that chemical bonding should be taught. We held six meetings, each of which lasted for four hours. During the workshop, the following issues were discussed and elaborated by using a focus group method:

–The common questions regarding this topic, more specifically the problematic content and structure of the high-stakes questions and the «acceptable» answers.

–The scientists' views regarding the concept of *chemical bonding* and their ideas regarding the learning goals associated with its teaching.

–The design of new assessment tasks based on decisions regarding the learning goals and the learning performances.

In all the discussions there was a continuous collaborative

exchange of ideas. The useful data produced by the interactions within the group provided the researchers with pedagogical insights that could be used for the development of a new pedagogical approach. In order to enrich the data collected, we used a unique technique during the workshop meetings in which one of the authors, as a focus group moderator, made a reference to parts of previous discussions quotations and asked the participants questions about them. During the meetings each sentence was recorded and the transcripts were analyzed.

Analysis of the discussions held during the workshop, regarding the common questions, revealed that teachers do not want their students simply repeat by rote what they had taught them; instead they want to provide them with meaningful knowledge by which they can advance. During the discussions, they mentioned the existence of the final examinations, and claimed that the type of questions asked on these examinations along with the acceptable answers lead to superficial learning. In preparing them to do well on these examinations, teachers asked their students specific questions, with the goal of successfully fulfilling the requirement of the final examinations, with little regard to students' actual comprehension of the key-concepts. Based on the results of this study, we may conclude that if students are assessed on parallel items, they can succeed in the common questions, but they may exhibit low levels of understanding regarding the new assessment tasks that we have developed during this process. We suggest that constructing the teaching and learning of a topic based on carefully specified learning goals, which are described in terms of performances, may enable educators to foster and examine much deeper levels of students' understanding.

We have developed a new experimental curriculum that is based on the suggested outline for a new approach. On the academic year 2005, the new unit was implemented in ten classes and preliminary information is provided in the next section. However, this research study was not designed to assess the effectiveness of the new teaching approach for *chemical bonding* concept. Furthermore, much work is needed to apply it in all classrooms of high-school chemistry. This appears to be an enormous challenge, since conceptual systemic change will occur only if: 1) the teachers accept and assimilate the new approach, after many years of experience in teaching according to the traditional approach, and 2) the national examinations

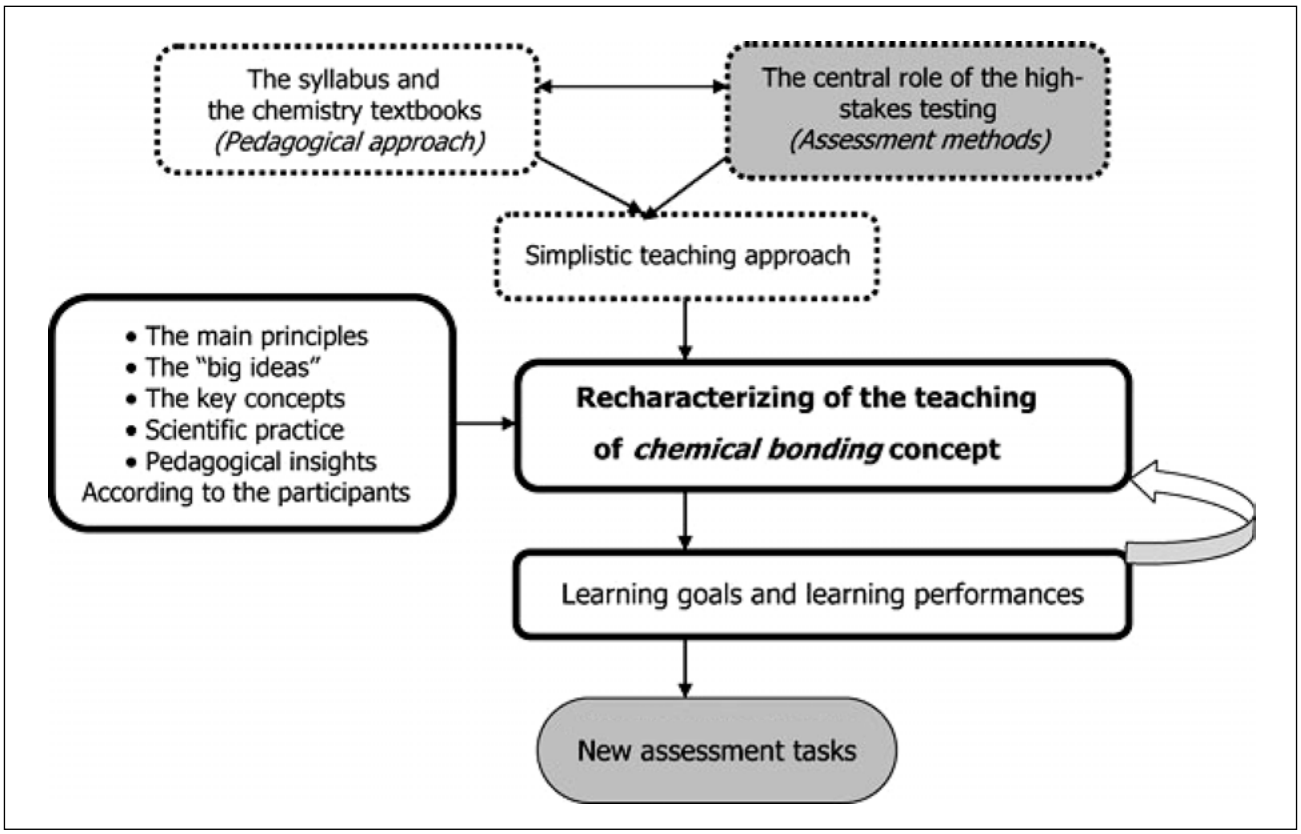

Figure 1. The research model for aligning the teaching approach with current science (Levy Nahum et al., *2007).*

will be aligned with the new curriculum. Additionally, continuous professional development for teachers is required in order to be able to implement effectively the new curriculum regarding this topic.

bonding as extreme cases of various continuum scales (stage 3). Equipped with this knowledge, students can then construct a coherent understanding of different molecular structures (stage 4) and properties (stage 5).

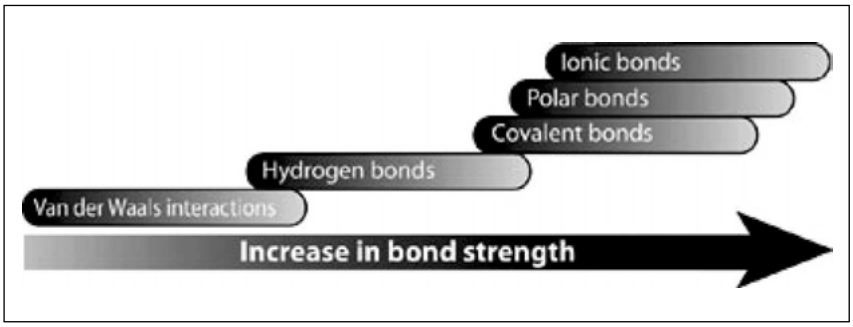

Figure 2. The continuous scale of bond strengths (Levy Nahum et al., *2007).*

Based on the long-term collaboration between prominent scientists, researchers in chemistry education and expert teachers, an innovative program aimed at teaching the *chemical bonding* concept, which follows a holistic approach to curriculum (Levy Nahum *et al.*, 2007), was developed and implemented in 11th-grade chemistry classes in Israel. Its general approach relies on basic concepts such as coulombic forces and energy at the atomic level to build a coherent and consistent perspective for dealing with all types of chemical bonds. As described by Levy Nahum *et al.* (2008, p. 1680): «It is possible to show how this diversity [of bond types] arises from a small number of fundamental principles instead of presenting it as a large number of disparate concepts». The framework proposed by Levy Nahum *et al.* (2008) introduces the elemental principles of an isolated atom (stage 1); this is followed by discussions of general principles of chemical bonding between two atoms (stage 2), and the general principles are then used to present the different traditional categories of chemical

In the academic year 2010-2011, the new program was implemented in all 11th-grade chemistry classes in Israel, which is possible because the educational system is centralized. In due course, a full-scale study assessing both teaching and learning will be conducted, aiming at reporting broader and statistically sound field results. In the framework of the new program, building on a knowledge-in-pieces perspective, Yayon, Mamlok-Naaman & Fortus (2012) describe the development and testing of a matrix that represents a systematic organization of the canonical knowledge on chemical bonding required at high-school level and a tool for representing students' knowledge of bonding. The matrix contains three strands: the structure of matter at the nanoscopic level, electrostatic interactions between charged entities, and energy aspects related to bonding. In each strand there are hierarchically ordered cells that contain fine grain concepts. The matrix, as it appeared at this stage, is available at *http://stwww.weizmann.ac.il/g-chem/the_matrix.doc*.

Discussion and summary

This research consists of all the components of a curricular process, a diagnostic study, followed by curricular development and implementation regarding the teaching of the *bonding* concept. High-school students lack a fundamental understanding regarding the key-concepts of chemical bonding. One of the goals of the chemistry teaching community is to develop more effective and scientifically aligned strategies to teach high-school students this key concept.

The traditional pedagogical approach to teaching chemical bonding and structure is often overly simplistic and thus is not aligned with the most up-to-date scientific knowledge and models. The problematic approach by which this topic is presented in many chemistry textbooks worldwide has been examined extensively in the last two decades by researchers of chemistry teaching (Ashkenazi & Kosloff, 2006; Hurst, 2002; Justi & Gilbert, 2002; Taber, 1998; Taber, 2001; Taber, 2002; Taber, 2011; Atzmon, 1991). The traditional approach, as it appears in many textbooks, is oversimplified and thus leads to overgeneralizations as well as a lack of scientific tools that may promote students' understanding. Taagepera *et al.* (2002) claim that effective comprehension and thinking require a coherent understanding of the «organizing principles». Hurst (2002) concluded his paper with the suggestion that bonding theory and related concepts need to be taught in a «uniform» manner.

The unit «Bonding» was designed to fulfill these needs. In the first stage of the study (Levy Nahum *et al.*, 2004), we used several methods and sources in order to explore the problem, and based on the findings we suggest

It should be emphasized that the chemistry teachers were deeply involved in the curricular process; they cooperated with the developers and provided their feedback and insights throughout the process. Their contribution to the design of the new approach, in all its stages, was enormous

that students display a shallow understanding of chemical bonding not only because this topic has intrinsic complexities, but also as a result of external «misleading factors» concerning the traditional approach used for teaching the *bonding* concept.

In fact, as we described based on our paper (Levy Nahum *et al.*, 2008), and as we mentioned above, the problem is with the textbooks; so in a retro-perspective view, we could have started by analyzing chemistry textbooks and based on the conclusions to develop a new framework for a new unit, but starting as we have started, from the problematic assessment approach, and the process it generated, provided us with rationalization and a deep foundation for a meaningful and detailed analysis and insights regarding the misleading factors. These factors are detailed in Levy Nahum *et al.* (2004) and supported by studies conducted worldwide. In view of that, we recommended making a real change in the traditional approach used for teaching this topic.

Based on the findings of the previous phase, we proposed a plan to eliminate the addressed problems. In the second stage (Levy Nahum *et al.*, 2007), we describe a collaborative development process with leading-teachers, researchers in chemistry teaching and senior chemists. We related to all the problematic aspects of the traditional approach and obtained a consensus regarding the organizing principles and the key concepts of this topic based on «a partnership between senior scientists and expert teachers» that follows a holistic approach to the curriculum. During this process, a conceptual framework was constructed for re-characterizing of chemical bonding, including the formulation of LG and LP.

It should be emphasized that the chemistry teachers were deeply involved in the curricular process; they cooperated with the developers and provided their feedback and insights throughout the process. Their contribution to the design of the new approach, in all its stages, was enormous. Thus, we highly recommend that any curricular development should be conducted with teachers' collaboration.

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