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Proposed pedagogies for teaching and learning chemical bonding in secondary education

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Abstract:
In a preceding publication (Tsaparlis, G., Pappa, E. T., & Byers, B. (2018). Teaching and learning chemical bonding: Research-based evidence for misconceptions and conceptual difficulties experienced by students in upper secondary schools and the effect of an enriched text. *Chemistry Education Research and Practice*, *19*(4), 1253–1269), we reviewed previous studies on students' misconceptions and conceptual difficulties with the topic of chemical bonding and tested the knowledge of tenth-grade Greek students on certain key aspects of bonding. In addition, we presented an enriched teaching text on this topic for the tenth grade and examined its effectiveness with regard to the same aspects of bonding. In the present study, we review earlier studies, which made proposals concerning the teaching of this topic, and provide some proposals of our own, based on the findings of our previous study. We recommend that a spiral curriculum spanning all three upper-secondary grades should be adopted. A learning progressions approach, employing lower and upper anchors of relevant scientific knowledge is considered, and a proposed list of potential core concepts, lever concepts, and stepping-stones are presented. Finally, the pros and cons of a modern qualitative quantum mechanical approach to bonding are considered.

Keywords: chemical bonding, learning progressions, misconceptions, spiral curriculum, teaching and learning
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Introduction

Although the concept of chemical bonding is fundamental to the teaching of chemistry at both the secondary and the tertiary levels, the topic has proved difficult to organize and approach for curriculum designers, teachers, and students alike. It requires both appreciation of many critical details and some sophisticated reasoning, making it complicated and hard for a large majority of the general student population. The many types of bonding (metallic, ionic, covalent, polar and non-polar bonding, intermolecular bonding) cause conceptual difficulties and lead to the formation of numerous misconceptions.

In a preceding publication (Tsaparlis, Pappa, & Byers, 2018), we reviewed previous, mainly recent, studies concerning students' conceptual difficulties with the topic of chemical bonding and, in addition, reported our own findings from a research study with upper-secondary level students (tenth grade, age 15–16) in Greece, which set out to examine their knowledge about basic bonding concepts and issues that have been identified in previous relevant research. The students generally displayed weak knowledge and possessed a number of misconceptions. In addition, we carried out a quasi-experimental research study with tenth-grade students from a prestigious Greek private school, some who were taught from, and used for their study the standard Greek chemistry textbook (the control group), and others (the treatment group), who were provided with a modified/enriched teaching text. English translations of both standard and enriched texts on chemical bonding are available through the preceding publication (Tsaparlis et al. 2018: Appendices 1 and 2).[1]

In this paper, which can be considered as a follow-up to the preceding publication, we review previous studies containing proposals for the prospective teaching of bonding, with emphasis on the secondary level, taking account of the following facts:

1. the topic of chemical bonding is taught at both the (mainly upper) secondary and the tertiary level, so there is an overlap of concepts, instructional tools and approaches (a *communality* of problems) between the secondary and the first-year undergraduate level,

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2. understanding of chemical bonding is an on-going continuum of developing complexity that runs through both secondary and tertiary education.

We believe that it is important for secondary teachers to be aware of what might be needed subsequently when students move on to tertiary education. For this reason, in our review of the relevant literature, in addition to studies that deal exclusively with the secondary level, we include studies that deal with both the secondary and the (first-year) undergraduate level, and also some studies that deal only with the undergraduate level. For the latter two cases, we make clear the level being referred to. If no level is indicated, the secondary level is implied. In addition, and in the same spirit, we provide proposals of our own.

A summary of diagnostic studies on chemical bonding

The conceptual difficulties that students encounter when studying the topic of chemical bonding lead many of them to resort to rote memorizing and the formation of misconceptions (e.g. Levy Nahum, Mamlok-Naaman, Hofstein, & Krajcik, 2007), many of which prove resistant to instruction. Taber (1998) has suggested that an 'alternative conceptual framework' for chemical bonding prevails, according to which the 'octet rule' is used by students as an explanatory framework for chemical stability and reactivity and this can then lead to "the development of a spread of 'misconceptions'". On the other hand, according to Talanquer (2007), 2013) students fail to recognize leading causal agents or any other type of causal mechanism, when building their explanations about chemical substances, reactions and bonding and demonstrate a cognitive bias toward teleological explanations, as represented in school textbooks and in teaching, which are often heavily influenced by assessment procedures (Levy Nahum, Mamlok-Naaman, Hofstein, & Taber, 2010). This can also contribute to the development of a number of misconceptions. There is clearly a need to close the gap between current educational research and school textbook writers (Bergqvist, Drechsler, De Jong, & Chang Rundgren, 2013).

Working with high-school physical science and chemistry students, and general chemistry university students, Luxford and Bretz (2014) identified misconceptions regarding four themes: (i) periodic trends; (ii) electrostatic interactions; (iii) the octet rule; and (iv) surface features associated with the representations (for instance, lines indicate bonds or spacing of the dots between atoms indicates equal sharing). From a study with undergraduate students enrolled in a first-semester organic chemistry course, Burrows and Reid Mooring (2015) concluded that a lack of understanding of electronegativity may lead to a misunderstanding of polar covalent bonding. On the other hand, in a study with upper-secondary students in Sweden and first-term undergaduate students in Sweden and South Africa, Nimmermark, Öhrström, Mårtensson, and Davidowitz (2016) reported that only about 20 % of the students had a clear grasp of the concept of bond energetics and endothermic processes. In addition, an emphasis on ball and stick models can lead to students having difficulty with visualization of the correct shape of molecules, while students who had encountered the VSEPR model in secondary school tended to have a better grasp of molecular shapes. Ballester Pérez et al. (2017) found the following misconceptions among secondary-school pupils and first-year undergraduate chemistry and pharmacy students: attributing macroscopic properties to particles; incorrect prediction of boiling points; perceiving ionic compounds as being formed by molecules; misunderstanding the nature of the hydrogen bond and assuming that it is present in any molecule containing hydrogen together with nitrogen, oxygen or fluorine, regardless of whether the hydrogen atom is directly bonded to these atoms or not; confusing the geometry of a molecule with the distribution of electron pairs around the central atom; and incorrectly predicting the polarity of molecules. Table 1 gives a list of the misconceptions and conceptual difficulties identified in our own study (Tsaparlis et al. 2018).

Table 1: List of identified misconceptions and conceptual difficulties in the Tsaparlis et al. (2018) study.

– A 'chemical bond' may be conceived as different from either an ionic bond or a covalent bond
– 'Ions' are involved in both ionic and covalent bonding (deriving from the knowledge that a polar covalent bond possesses some ionic character)
– The concept of 'molecule' is relevant to both ionic and covalent bonding (not only to the latter)
– Coulomb forces are only associated with ionic bonding, apparently because of the attractions between ions (but students generally accept that 'attractive forces' are involved in both types of bonding)
– 'Repulsive forces' are not relevant to chemical bonding
– A 'full' valence electron shells (usually octets of electrons) leads to stability
– The 'octet rule' could be used to predict whether atoms will form ionic or covalent bonds
– 'Electronegativity', 'bond polarity', and 'Lewis structures' are assumed by many students to be of relevance only to covalent compounds

– Failure to connect the concepts of 'group', 'period', 'melting point', 'boiling point', and 'solubility' to chemical bonding

In conclusion, the prevailing approach to teaching chemical bonding continues to lead to learning difficulties and misunderstandings for many students. The following are some typical examples (that were also cited in the preceding publication):

a. The ionic bond is referred to as just a transfer of electrons between separate atoms in order to acquire full valence shells.

b. The model of the covalent bond is described as an electron pair that is shared between two atoms.

c. The octet rule is often used by the students as an explanatory framework for chemical stability and as a prerequisite for a 'proper' bond.

d. Covalent and ionic bonds are often presented in isolation, as bonds that share electrons and bonds that transfer electrons respectively.

e. Bond polarity is directly linked to the covalent bond.

f. Covalent and ionic bonds are described as 'real' chemical bonds, while most intermolecular bonds are simply referred to as forces.

The enriched text and its effectiveness

The treatment group in our preceding publication was taught using a modified/enriched text, which was based on the standard Greek text, and was written, by one of the authors (GT). The following are the basic differences between the standard and enriched texts (for a complete comparison, see Appendix 3 of the previous publication[2]): The enriched text was significantly longer (by ca. 50 %). It includes a more detailed discussion about the octet rule, with emphasis on the fact that the rule does not mandate formation of an ionic bond, though it is able to explain the charges on the ions and the stoichiometry of ionic compounds. Also, the enriched text gives a more detailed coverage of electronegativity, including the use of a quantitative scale (the Pauling scale) to this topic, and stressing its importance to the understanding of the continuum between ionic and covalent bonding. Finally, the enriched text pays particular attention to features that characterize both the covalent and the ionic bond.

Although the treatment group from the private school was found to display high levels of performance (usually over 80 %) in a large majority of the tested concepts and knowledge elements, pronounced weaknesses were still apparent for a few concepts: the importance of non-metallic elements to both types of bonding, repulsive forces, solubility, and the octet rule as explanation for chemical bond formation (ionic or covalent). The treatment group also demonstrated statistically significant differences for several concepts/knowledge elements (electrostatic interactions, electronegativity, and bond polarity), but not for other (valence electrons, the octet rule, Lewis structures or criteria for bond formation), when compared to the control group.

Rationale of the present study

The diagnostic part of our preceding research study revealed that students held misconceptions to a varying extent, dependent on the sample being studied. The intervention introduced with the treatment group was shown to have resulted in high levels of performance for a large majority of the concepts and knowledge elements tested. However, weaknesses with some key concepts clearly remained. The extent of the problem with the octet rule and its resistance to change was considered a significant, major finding of the study: students tended to treat the octet rule as a simple predictive algorithm even when the teaching specifically contradicts this approach, as was the case with our treatment group. [See also the study by Joki and Aksela (2018), which reported that an earlier proper understanding of the electrostatic-interactions model at the lower-secondary level did not prevent the development of misconceptions when the octet rule was taught to the same students in upper-secondary school (tenth grade).]

While considering the results of this preceding study, we asked ourselves whether the enriched text would be advantageous in dealing with fundamental student misconceptions concerning bonding in general. Taking into account that the intervention was carried out at a prestigious private school, whose students demonstrated high performances in school courses, including chemistry, one might well expect lower performances and higher persistence of misconceptions with less able students. So we concluded that while the answer to the above question might be yes, it could also be no. This conclusion is re-enforced by the findings of a study by Wang and Barrow (2013) with undergraduate general chemistry students, according to which high content knowledge students differed in some important aspects from low content knowledge students. For instance, while the first group was comfortable with exceptions to the octet rule, the second group tended to possess more misconceptions and be uncomfortable with such exceptions.

Review of proposals for the teaching of chemical bonding

An analysis of the coverage of the topic of bonding provided by a number (fourteen) of general chemistry textbooks (Tsaparlis & Pappa, 2012) offers a useful background. Almost all the books presented covalent and ionic bonding before intermolecular bonding, with a majority of books introducing the ionic bond before discussing covalent bonding. Most books refer to the covalent and ionic bonding continuum, though some continued to treat the two topics completely separately. Electronegativity and bond polarity are discussed within covalent and ionic bonding, which most books seem to consider as the only true types of chemical bonding, with intermolecular bonds often being merely referred to as forces. While consideration of metallic bonding is included in most of these textbooks, many fail even to mention the coordinate bond. Finally, regarding intermolecular bonds, the books follow different orders of presentation, with most attention given to hydrogen bonding.

It is important in science teaching, not only to introduce concepts in ways that are authentic presentations of specific scientific topics but also to try to make them relevant and easily understood by students. To understand concepts relating to bonding and structure, such as covalent and ionic bonds, molecules, ions, giant molecules and hydrogen bonds, students must be familiar with the mathematical and physical concepts and rules associated with bond concepts, such as orbitals, electronegativity, electron-pair repulsions, polarity and Coulomb's law. Furthermore, as a result of learning about the chemical bond, students are enabled to make predictions about and explain the physical and chemical properties of substances (structure-property relationships) (Levy Nahum et al. 2010). Despite the widely accepted notion that covalent bonding, polar covalent bonding and ionic bonding are a continuum, chemistry educators and textbooks still present this information as three distinct types of bonding. Some researchers have argued that the topic of polar covalent bonding is often presented in a problematic approach, leaving students free to interpret bonding concepts in a multitude of ways (Teichert & Stacy, 2002: a study with college general chemistry students; Bergqvist et al., 2013: a study with secondary-school students).

Studies on students' understanding

The results of several studies on students' understanding of chemical bonding are summarized in Table 2. Barker and Millar (2000) carried out a longitudinal study of 250 students following the Salters Advanced Chemistry course with the aim of probing a range of chemical ideas, including the exothermicity of bond formation and the development of thinking about covalent, ionic and intermolecular bonds. It was reported that students' understanding improved as the course progressed, for instance, initially, few students described covalent bonds accurately or understood hydrogen bonding, but at the final survey, a majority gave responses in line with scientific ideas and language. On the other hand, certain aspects of bonding, including ionic bonding and intermolecular bonds other than hydrogen bonds, remained problematic for students despite explicit teaching.

Table 2: Summary of the findings of studies on students' understanding about chemical bonding.

Reference	Education level	Main finding or implications
Barker and Millar (2000)	Post-secondary (Salters)	There was improvement of student understanding as the "Salters Advanced Chemistry" course progressed
Hilton and Nichols (2011)	Secondary	Instruction about representational form and function contributed to the enhancement of representational competence and conceptual understanding of bonding
Croft and de Berg (2014)	Secondary	A historical analysis and a textbook analysis can inform several bonding conceptions and lead to recommendations for improving teaching and learning

Joki, Lavonen, Juuti, and Aksela (2015)	Secondary	There should be insistence on a teaching model of chemical bonding that emphasizes electric (Coloumbic) interactions as the basis for most types of bonding but avoids the octet framework
Bergqvist, Drechsler, and Chang Rundgren (2016)	Secondary	The teachers may use inadequate instructional strategies and be unaware of their students' comprehension of models and conceptual difficulties
Joki and Aksela (2018)	Secondary	The teaching of the octet rule at the upper-secondary level may affect students' previous understanding that was based on an electrostatic model of chemical bonding

Starting from the tenet that many alternative conceptions held by chemistry students resulted from previous teaching, Hilton and Nichols (2011) explored the contribution of explicit instruction about multiple representations to eleventh-grade students' understanding and representation of bonding. Pre-test–post-test comparisons showed an improvement in conceptual understanding and representational competence, while analysis of students' texts provided further evidence of the students' ability to use multiple representations to explain macroscopic phenomena at the molecular level. Explicit instruction about representational form and function contributed to the enhancement of representational competence and conceptual understanding of bonding in chemistry, while the scaffolding strategies employed by the teacher played an important role in the learning process.

Croft and de Berg (2014) focused on the concepts of charge, octet, electron pair, ionic, covalent and metallic bonding and selected six key student alternative conceptions of bonding to illustrate how a historical analysis and a textbook analysis can inform these conceptions and lead to recommendations for improving the teaching and learning of bonding at the secondary-school level. The authors made five recommendations regarding: (1) The concept of 'charge' and the significance of positive and negative charge; (2) The difference between balancing charges and cancelling charges; (3) The significance of the charge on an ion in terms of the *number* of protons and electrons; (4) The strengths and weaknesses of the cubic-atom model and associated trends in the periodic table; (5) An emphasis on the *electrical* nature of the chemical bond, with electron transfer and paired electron sharing being important processes. To alert teachers to the complexity of the topic of bonding and to demonstrate that scientific models are never complete, the authors also provide an account of the role of *virtual photons* in explaining what we mean when we say that something is charged, as well as considering the repulsive and attractive effects of charge. The answers to these questions arise from the relatively recent development in particle physics of the field of quantum electrodynamics, of which Richard Feynman is regarded as the father. This topic is not, of course, intended to appear in a secondary-school curriculum.

Joki et al. (2015) designed a holistic, novel way to teach bonding at the middle school level, based on research. Analysis of their interview data revealed that applying principles relating to Coulombic interactions to understand bonding requires simultaneous appreciation of several factors: electron shells in terms of energy levels, the distance between the outer electrons and the nucleus on the basis of electron shell construction, and the effective nuclear charge. According to the authors, the study introduces two new research points of view: (1) a teaching model of bonding that emphasises electric interactions as the basis for most types of bonding but avoids the octet framework; (2) a systemic approach used for the examination of students' conceptual structures.

Bergqvist et al. (2016) investigated secondary teachers' knowledge base for teaching bonding by focusing on three essential components of pedagogical content knowledge: (1) the students' understanding, (2) their representations, and (3) their instructional strategies. The results showed that the teachers were generally unaware of how representations of the models they used affected student comprehension, had trouble specifying students' difficulties in understanding, and used instructional strategies that were mostly insufficient to promote student understanding.

Finally, Joki and Aksela (2018), informed by their research reviewed above (Joki et al. 2015), carried out a case study that aimed to explore, how a student's understanding of bonding evolved from lower- to upper-secondary school when an electrostatic model of bonding was used at the lower-secondary level, and then how the students' understanding was influenced by the teaching of octets/full shells at the upper-secondary level. The same students were interviewed after lower-secondary school and again during their first year at upper-secondary school and the findings showed that the students' earlier proper understanding of the electrostatic-interactions model at the lower-secondary level did not prevent the later development of less-canonical thinking. According to the authors, there is a need for teachers to develop appropriate pedagogical content knowledge in order to promote better understanding of bonding.

Many of the above findings are crucial to our own proposals; for instance, the improvement of student understanding with course progression supports a spiral curriculum approach, while the importance of energetics and electric interaction to bonding have been our guiding principles.

Novel approaches to teaching chemical bonding

Taber (2001) identified the following four key “pedagogical learning impediments” to the effective teaching and learning of chemical bonding:

1. *An atomic ontology and the initial atomicity.* Atoms are assumed to be the only fundamental units of substances. For instance, a reaction between *elemental* sodium and *elemental* chlorine is assumed to involve a direct reaction between sodium atoms and chlorine atoms, with a consequent exchange of electrons: one sodium atom loses one electron, which is gained by a chlorine atom. In reality, of course, the reaction is much more complex, involving a final step where sodium cations and chloride anions combine together to form a sodium chloride crystal.)

2. *The over-generalization of the octet rule.* So instead of using the rule as a way of identifying likely stable species (such as O^{2-} and NH_3), it becomes a general-purpose explanation for why reactions occur.

3. *The dichotomous classification of bonding.* Covalent bonds are formed when electrons are shared between non-metal atoms, while in ionic bonding electrons are transferred from metal to non-metal atoms. Consequently, bonding is often regarded as only either covalent or ionic, while metallic bonding or the van der Waals force/bonding are not considered as “proper” bondings.

4. *The use of anthropomorphic language* [for instance, “bonds formed and reactions occurred, so that atoms could achieve full shells or octets of electrons” – so student explanations are commonly phrased in terms of what an atom might ‘want’ or ‘need’” (Taber & Adbo, 2013, p. 348)].

To tackle these impediments to learning and the associated alternative conceptions, Taber (2001) proposed a curricular model of chemical bonding, which starts with metallic structures, then goes on to ionic structures, to giant covalent structures, and finally to simple molecular structures. The model emphasizes molecules and ions (rather than atoms) as the basic unit of matter so as to avoid the assumption of initial atomicity, while the nature of bonding, structures, and properties of substances are explained in terms of electrostatic forces, but not the octet rule, nor the desires of atoms. Addressing bonding in terms of electrostatics would also serve as a good foundation for subsequently learning about electronegativity, bond polarity, hydrogen bonds, and solvent-solute interactions.

A book entitled “Teaching secondary chemistry”, edited by K. S. Taber and written for both newly qualified and experienced secondary science and chemistry teachers, includes a chapter by Taber (2012) on models of chemical bonding. This chapter, which is based on Taber’s rich relevant research, starting with his PhD thesis on exploring students’ developing understanding of bonding, provides an alternative method for approaching bonding. There are four units in this chapter (From holding power to chemical bonding/Principles underpinning the bonding concept/Modelling varieties of chemical bonding/Relating type of bonding to changes in chemistry). ‘Modelling varieties’ examines metallic lattices, ionic lattices, covalent bonding, bond polarity, and other forms of bonding in that order, while “Relating type of bonding to changes in chemistry” considers dissolving, melting and boiling, and the relationship of bonds to chemical reactions. Taber (2013) has also reviewed the topic of bonding.

Based on Taber (2001) curricular model, Lee and Cheng (2014) devised a plan for the teaching of chemical bonding to a tenth-grade chemistry class, in which they emphasized how different models of structures explained the variety of properties of different solid substances. In this teaching plan, each topic started by addressing the properties of substances at a macro level, before considering structures at the submicro level. The recommended order is given below:

1. Giant metallic structures (properties of metals and metallic bonding)

2. Giant ionic structures (properties of salts, ionic bonding and electrostatic interactions)

3. Giant covalent structures (properties of giant covalent structures, using the example of diamond, and covalent bonding)

4. Simple molecular structures (properties of simple molecular substances and the nature of the van der Waals force/bonding)

5. Molecules.

The above teaching plan was delivered to a class of tenth-grade students in Hong Kong, with teaching involving a 2 h lesson each week for a period of 8 weeks. In depth interviews were conducted with three students whose achievement in chemistry was in the first 20th, 50th, and 70th percentile of the student population in Hong Kong respectively. The three case studies revealed that the curricular model proposed by Taber (2001) was helpful in developing the students' understanding of chemical bonding from the "transfer of electrons" or "sharing of electrons" to thinking in terms of electrostatic interactions of chemical species. Although it was found that the learning of some basic Coulombic electrostatics principles presented little difficulty, applying those principles to the understanding of chemical bonding was not always successful. This was especially evident in the lowest-achieving student's learning of covalent bonding. It was postulated that while the student learned covalent bonding as electrostatic attractions, the undue emphasis on the octet rule in the curriculum and assessment might have steered the students' learning focus.

Levy Nahum et al. (2007) developed "a new teaching approach for the chemical bonding concept aligned with current scientific and pedagogical knowledge". A qualitative description that is conceptually consistent with quantum mechanics was adopted; this, according to the authors, gave a very clear, intuitive answer to the question which puzzles many students, "what really causes atoms to interact and form a chemical bond?" Based on the findings of their study, the authors suggested the so-called 'bottom up' approach for teaching the bonding concept. According to these authors, "The traditional ('top-down') pedagogical approach for teaching chemical bonding is often overly simplistic and not aligned with the most up-to-date scientific models. As a result, high school students around the world lack fundamental understanding of chemical bonding" (Levy Nahum et al., 2007, p. 579). Figure 1 provides a schematic illustration of the "bottom-up" framework (Kronik, Levy Nahum, Mamlok-Naaman, & Hofstein, 2008, p. 1682). The crux of the suggestion is that bonding should be taught based on elementary principles and by using the idea of a continuum of bond strengths. Therefore, the new framework removes the artificial dichotomous division between different types of bonding, by exposing students gradually to the main concepts and ideas, in five stages. The approach was further described in a subsequent publication: Kronik et al. (2008) [see also Levy Nahum et al. (2010) and Levy Nahum, Mamlok-Naaman, and Hofstein (2013)].

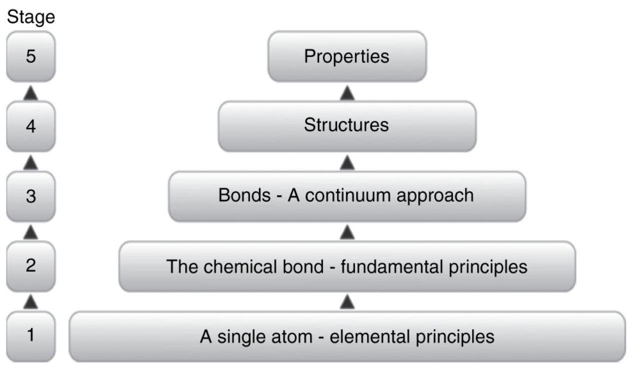

Figure 1: A schematic illustration of the "bottom-up" framework for teaching chemical bonding. Reprinted with permission from Kronik et al. (2008), p. 1682, Copyright 2008, American Chemical Society.

Dhindsa and Treagust (2014) were concerned with the psychological organization of the content of chemistry. According to these authors, curriculum developers should sequence knowledge with increasing difficulty in line with the mental development of students. In addition, higher-level content learning should be based on previously learned content as prior knowledge. Focusing on the upper-secondary and the first-year undergraduate level, the authors argue that bonding is a topic that "is not sequenced and taught to support effective and sustainable learning at all levels", and explanations are often "incomplete and oversimplified". Bonding is usually taught in the order of ionic, covalent, polar covalent, metallic and intermolecular bonding. After considering the major problems associated with this order of teaching, the authors proposed the following new teaching order: (1) covalent, polar covalent and ionic bonding, (2) bonding in lattices: metallic bonding and crystals (3) intermolecular bonding. In their paper, the focus is on the first and second stages.

Finally, in his states-of-matter approach (SOMA) to introductory chemistry teaching at the tenth grade, Tsaparlis (2000) went separately over the three states of matter, distinguishing three major units: (A) *Air, Gases, and the Gaseous State*; (B) *Salt, Salts, and the Solid State*; (C) *Water, Liquids, and the Liquid State*. Among the features of this approach was the introduction of the gaseous state first. In addition to its being the simplest and best understood by scientists, the gaseous state makes it necessary to start the study of bonding with the covalent bond (both nonpolar and polar), and this agrees with Johnstone's recommendation (Johnstone, 2000; Johnstone, Morrison, & Reid, 1980). Note that the elements and compounds which we encounter in the gaseous state, under normal conditions, tend to be small simple covalently-bonded molecules or single atoms [we work with only a few non-metals (H, O, N, halogens, and noble gases) and compounds (H_2O, O_2, NH_3, NO_x, CO, CO_2, gaseous hydrocarbons, H_2S, SO_2, HCl)], so neither ions nor the ionic bond are necessary. In the case of an ideal gas, intermolecular forces are also absent. The study of the solid state second allows for the introduction of ionic bonding and of crystal structures. The periodic table, giant covalent molecules, and metals and metallic bonding are included in this unit on solids. Finally, intermolecular forces (Van der Waals bonding, hydrogen bonding, and London dispersion forces) are introduced in the unit on liquids, which also includes the study of liquid solutions, as well as acids and bases.

In conclusion, concern with the psychological organization of the content of chemistry has led Dhindsa and Treagust (2014) and Tsaparlis (2000) to start with the covalent bond, with the latter authors (having both upper-secondary and the first-year undergraduate students in mind) explaining covalent bonding by means of the valence-bond quantum mechanical model. Levy Nahum et al. (2007), in their "bottom-up approach", adopted a qualitative description that is conceptually consistent with quantum mechanics, with bonding being taught from basic principles, using the idea of a continuum of bond strengths. Taber (2001), 2013) emphasized the following 'modelling varieties': metallic lattices, ionic lattices, covalent bonding, bond polarity, and other forms of bonding in that order. Taber's approach was the basis for Lee and Cheng (2014) teaching plan.

Other more specific studies

The following four studies dealt with specific approaches to teaching bonding: the effect of cooperative learning; the effect of problem-based learning; the effect of a web-based learning environment; and the effect of modelling-based teaching activities.

Acar and Tarhan (2008) investigated the effectiveness of instruction using newly developed teaching materials based on cooperative learning. When compared to a traditional approach with ninth-grade students, they reported improved understanding of metallic bonding, with the mean score obtained by students in the treatment group being significantly higher than that for the control group, with misconceptions related to metallic bonding being found less frequently in the treatment group.

Tarhan, Ayar-Kayali, Urek, and Acar (2008) examined the effectiveness of a problem-based learning (PBL) approach on ninth-grade students' understanding of intermolecular forces (dipole–dipole forces, London dispersion forces and hydrogen bonding). After the instruction was completed, a post-test and a questionnaire relating to the quality of the problem, the role of the teacher and the functioning of the group was administered. Results suggested that PBL is beneficial to students' achievement, remedying formation of alternative conceptions and developing social skills.

Frailich, Kesner, and Hofstein (2009) investigated the effectiveness of a web-based learning environment in enhancing tenth-grade high-school students' understanding of the concept of bonding. Computer-based visual models were utilised in order to demonstrate bonding and the structure of matter in a student-centered learning environment. It was reported that the treatment group significantly outperformed the comparison group on the post-test.

Cardoso Mendonça and Justi (2011) used modelling-based teaching activities for ionic bonding and introduced them in a Brazilian medium-level public-school class. From their data, they developed case studies for each of the student groups. The analysis of one of the case studies provided evidence about the way that specific elements of the teaching strategy supported students' learning.

Discussion and final proposals

According to Gilbert (2006), pp. 957–958, "throughout the world, over the past 20 years or so [that is: since the 1980s] chemical education has faced a number of inter-related problems: (1) content overload, (2) isolated facts, (3) lack of transfer, (4) lack of relevance, and (5) inadequate emphasis". High content loads lead to curricula that "are too often aggregations of isolated facts", so that students do not know how to form connections between them and "acquire a sense of how to give meaning to what they are learning". In addition, students "fail to solve problems using the same concepts when presented in different ways", and at the same time lack "a sense of why they should learn the required material". It is necessary to master the topic of chemical bonding in order to give explanations to context-based problems related to solubility, chemical reactions or molecular structure in organic chemistry. Understanding requires complex higher-order thinking (Broman & Parchmann, 2014), and it is therefore essential to take all the above problems into account when formulating a pedagogically sound approach to the teaching of the topic.

Bruner's spiral curriculum

The complexity of the subject matter relating to chemical bonding leads us to the conclusion that it is neither reasonable nor advisable for curriculum designers and textbook authors to try to cover all aspects of the topic when it is first introduced in tenth grade. A spiral curriculum spanning all three grades of upper-secondary school (see below), would therefore seem more appropriate for teaching the keystone topic of bonding. In his 1960 text "*The process of education*", Jerome Bruner opposed Jean Piaget's notion of *readiness*, and suggested that a child of any age is capable of understanding complex information: "We begin with the hypothesis that any subject can be taught effectively in some intellectually honest form to any child at any stage of development" (Bruner, 1960, p. 33). This can be achieved using the concept of the *spiral curriculum*. According to this, information should be structured so that complex ideas are first taught at a simplified level, and subsequently re-visited at more complex levels. Therefore, when teaching particularly complex topics, such as chemical bonding, we should follow levels of gradually increasing difficulty.

Teaching chemical bonding at the lower-secondary level

When designing a spiral curriculum, it is essential to consider first the lower-secondary school. In their first encounter with chemistry, students should, of course, be exposed to atoms and molecules as the basic structural units, but we suggest that it would be better to leave aside the details of atomic and molecular structure such as electrons, valence shells, the periodic table, and their relation to type of bonding until later (Tsaparlis, 1997a). Alex Johnstone has suggested the use of a kind of black box approach when first dealing with the bond concept in lower-secondary school: hydrogen makes one bond, oxygen makes two bonds, nitrogen makes three bonds, and carbon makes four bonds (Johnstone et al., 1980). With this approach, we can build a large part of elementary organic chemistry, and this should therefore be taught before inorganic chemistry, with its many chemical elements, many types of bonds, many valences, etc.

Analogical reasoning [bonding as a kind of glue sticking atoms together, or the covalent bond as a tug-of-war game between two atoms (Tsaparlis, 1984)], and anthropomorphic thinking and language might constitute a *lower anchor* (see below) of scientific knowledge at the lower-secondary level.

Taking into account the abstract, non-observable, and nondirectly-measurable character of atoms, molecules, and chemical bonds, Nelson (1994) suggested using electrical character, on the basis of the electrical conductivity of their melts and/or solutions, to distinguish between ionic and covalent compounds. Such a distinction can readily provide the basis for a formal first separation of bond type even at the lower-secondary level. This distinction and its elaborations can continue to be useful to students as they move on to upper-secondary level.

Teaching chemical bonding at the upper-secondary level

Ideally, the concept of bonding should be formally developed in the upper-secondary curriculum. However, considering the complex nature of the concept, it would seem unwise to attempt a head-on approach to teaching the topic. As we suggested above, a spiral curriculum approach would seem most appropriate here. In tenth grade, for example, we might be content with an elementary non-quantum mechanical treatment, more or less along the lines of the official Greek text (see Appendix 1 of the preceding publication). However, a refinement and elaboration of critical issues related to relevant student misconceptions, especially those regarding ionic bonding and the continuum approach to bonding type, along the lines taken in the enriched text used with the experimental group of our previous study should be seriously considered (see Appendix 2 of the preceding publication). The importance of *electrostatic forces*, which "are the only important force in chemistry" (Gillespie, 1997, p. 862)[3] is a fundamental aspect of all bonding. Electrical forces are essential to the understanding of both ionic and polar covalent bonding, so introducing these forces at an early stage would seem to be the appropriate way to go. Note that both the NRC Framework and the NGSS support early introduction of gravitational, electric, and magnetic forces and fields.[4]

A study on visualization of metallic bonding and the malleability of metals (Cheng & Gilbert, 2014) showed that tenth-grade students varied in terms of their appreciation of the electrostatic force which was responsible for the malleability of metals, while a clearer understanding of the electrostatic force involved can be attained when students experience visual and verbal representations simultaneously, a conclusion supported by dual coding theory. In a subsequent relevant study, Cheng and Oon (2016) reported the results of a survey of 3006 tenth to twelfth-grade students on their understandings of metallic bonding. Based on the findings, the authors suggested that a first step towards helping students to learn metallic bonding in terms of interactions is to explicitly teach that the electrostatic force is an interaction between electrons and metal cations. It is imperative for textbook authors, curriculum developers and teachers to abandon representations of bonding merely as a structure and/or a sequential process. Words and diagrams should consistently represent metallic bonding as an electrostatic force.

Special care should be taken with the continuum of bonding type, because "for students who already understand bonding in terms of the ionic-covalent dichotomy, the conceptual change needed to see bonding in terms of a continuum instead proves to be a difficult shift, perhaps in part because it requires adopting a rather different *type* of ontology of bonding" (Taber, 2008, 2013). We would suggest that the concept of electronegativity was 'invented' to help describe, understand and predict the nature and reactions of polar covalent bonds. It therefore seems to us that electronegativity has nothing to say about a non-polar covalent bond or indeed about a completely ionic bond. Although what is written about electronegativity and ionic bonding is not necessarily wrong, it can be considered as not really relevant and possibly misleading, as it appears to infer that if the electronegativity difference is large enough then ionic bonds will be formed. However, we know that it is not as simple as this and indeed this was acknowledged in the enriched text that students were given, as the difference between ionization energy to produce a cation and electron affinity to form an anion requires energy in all cases. It is in fact only the favorable contributions of lattice energies in the solid state and solvation energies in solution that enable ions to exist. To further lessen the conceptual load, it might be better to postpone, until later, a number of complicating issues, such as potential energy diagrams and the role of electron potential and kinetic energies, the nature of the covalent bond, the quantitative use of an electronegativity scale (such as Pauling's scale) and the use of electronegativity differences for predicting the percentage ionic or covalent character in a bond (see also below).

Issues relating to potential energy diagrams and the quantitative use of an electronegativity scale can profitably be introduced during the eleventh and twelfth grades. Molecular geometry as predicted by the valence-shell electron-pair-repulsion model (VSEPR) model and the various types of intermolecular bonding should also be introduced at this stage. A detailed understanding of the roles of electron potential and kinetic energies in bonding and the nature of the covalent bond, would, however, require a quantum mechanical treatment and must await tertiary education.

The need for the study of learning progressions

We suggest that the teaching of complex topics like chemical bonding would benefit from the use of *learning progressions*, a recent development based on the notion of a spiral curriculum. Learning progressions are defined as empirically validated descriptions of pathways taken by students, over extended periods of time, toward achieving an *upper anchor* of scientific knowledge and/or practice (Sevian & Stains, 2013).[5] Stevens, Delgado, and Krajcik (2010) [see also Merritt and Krajcik (2013)] emphasize that learning progressions are factors about how learning progresses and relate to the order in which ideas are presented and built upon during instruction. However, learning progressions are not tied to any particular curriculum, but rather depend on instruction. Duschl, Maeng, and Sezen-Barrie (2011) have reviewed how learning progressions are created, and how they are validated and described. They focused on four variations in approaches to studying them: (1) the subject matter of the learning progression, (2) how the boundaries (*lower and upper anchors*) of the learning progression are defined, (3) how intermediate levels can be developed and (4) the explicit or implicit model of conceptual change associated with the learning progression.

A *lower anchor* for required scientific knowledge should be achieved during tenth grade, while the shift to the desired *upper anchor(s)* can then be achieved with further studies of bonding at the eleventh and twelfth grades. It will also be useful to consider intermediate anchors. These will follow naturally once the preferred lower and upper anchors have been precisely defined. Intermediate anchors are certainly provided (especially at the eleventh grade) by the numerous applications of the bonding concepts in the study of inorganic and organic compounds, their structure, physical properties and chemical reactivity (structure-property relationships, see Table 3).

Table 3: List of proposed core concepts, lever concepts, and stepping-stones for a learning progression approach to teaching chemical bonding in the upper secondary school.

Core concepts	Lever concepts	Stepping-stones

Atom Ion Molecule Electronegativity and electropositivity Ionic bond Covalent (polar and nonpolar) bond Continuity of bond type VSEPR model/molecular geometry	Energy Metal Nonmetal Electrostatic/Coulomb (attractive and repulsive) forces Pauli exclusion principle Atomic structure Valence electrons Atomic radius Ionization energy & electron affinity Bonding and lone electron pairs	Covalent compound Ionic compound Ionic crystal Lewis structures Bond polarity Compound polarity Giant covalent structures Structure-property relationships (physical state, density, melting point, boiling point, solubility, reactivity/e.g. acidity-basicity, oxidizing and reducing power)

The theoretical construct of core *concepts* can play a key role in nurturing students' progress toward scientific understanding. According to Corcoran, Mosher, and Rogat (2009), "learning progressions in science are empirically-grounded and testable hypotheses about how students' understanding of, and ability to use, core scientific concepts, explanations and related practices grow and become more sophisticated over time, with appropriate instruction". In addition to core concepts, there is also the construct of lever concepts, which for a particular grade range represent core concepts that students already possess understanding of at the beginning of that grade range. Finally, stepping-stones are defined as learning goals for the different grade ranges (Wiser, Frazier, & Fox, 2013). Table 3 lists PROPOSED *core concepts, lever concepts*, and *stepping-stones* for a learning progressions approach to teaching chemical bonding at the upper-secondary level.

Postscript: The modern quantum mechanical model of bonding

Modern qualitative quantum mechanical descriptions of atomic and molecular structure have been taught for some time, not only in general and inorganic chemistry university courses, but also in upper secondary school, although this has met with reservations from some chemistry educators (Tsaparlis 1997a; 1997b; 2013). Focusing on the chemical bonding concept, there is no doubt that the advent and development of quantum mechanics has greatly refined our understanding. At the same time, however, quantum mechanics has "deepened the mystery of what constitutes a chemical bond" (Croft & de Berg, 2014, p. 1733). So, according to Coulson (1953), pp. 20–21, "a chemical bond is not a real thing. It does not exist. No one has ever seen one. No one ever can. It is a figment of our own imagination". Similarly, according to Gillespie and Robinson (2007), p. 97, a chemical bond is "not a real measurable object and it cannot be clearly defined". Working with tertiary students, Bouayad, Kaddari, Lachkar, and Elachqar (2014) concluded that "the quantum approach is a source of major difficulties impeding the deep understanding of the concept" (p. 4612). As a result, many chemistry educators believe that introduction to quantum theory should be postponed until the undergraduate level. For instance, Pauling (1992) proposed that beginning courses in chemistry should emphasize the simpler aspects of molecular structure in relation to the properties of substances, with concepts to be covered including the electronic structure of the atom, with emphasis on the noble-gas structure, the shared electron-pair bond, the tetrahedral carbon atom, the electronegativity scale, the partial ionic character of bonds, and the idea of resonance as applied to the benzene molecule, but molecular orbitals should be left out.

On the other hand, some researchers encourage an early introduction of a quantum mechanical approach. For example, considering upper-secondary and first-year undergraduate students, Dhindsa and Treagust (2014) used the valence-bond model of bonding to explain covalent bonding in terms of the overlap of atomic orbitals on bonded atoms, while Nimmermark et al. (2016), based on data concerning Swedish undergraduate students, suggested that it is likely to be beneficial to the understanding of bonding (and especially the covalent bond) if secondary-school students meet at least a simplified quantum model of the atom. Although the physical interpretation of atomic orbitals and the electron configurations of atoms and monoatomic ions may be useful, molecular orbitals should not be introduced at the secondary level, and only Lewis structures and the VSEPR should be used to consider molecular structures at this stage. It appears that the teaching of certain aspects of the molecular quantum mechanical model in secondary education, such as electron clouds and their overlap in bonding, could be beneficial to students and should not be ruled out. However, modern quantum-chemical concepts should only be introduced, if and where they are necessary, and with great care (Tsaparlis, 1997b).

Notes

1 Appendices 1 and 2 of the previous publication (Tsaparlis et al. 2018) are directly accessible at: www.rsc.org/suppdata/c8/rp/c8rp00035b/c8rp00035b1.pdf and www.rsc.org/suppdata/c8/rp/c8rp00035b/c8rp00035b2.pdf.
2 Appendix 3 of the previous publication is directly accessible at: www.rsc.org/suppdata/c8/rp/c8rp00035b/c8rp00035b3.pdf.
3 An explanation of the nature of the chemical bond, which goes back to G. N. Lewis (Stranges, 1981), is that it is of an electromagnetic nature: the bond is due to the attraction of the opposing magnetic fields created by the spinning electrons that form the bond. These magnetic fields do exist, but they are too weak to account for the strong chemical bond (McWeeny, 1970). Relevant here is the fact that a single electron, as in the case of the hydrogen molecule ion (H_2^+), can form a chemical bond.
4 Next Generation Science Standards (NGSS): https://www.nextgenscience.org/pe/hs-ps2-4-motion-and-stability-forces-and-interactions.
5 Related to learning progressions are the so-called *teaching-learning sequences*, which deal with theoretical approaches to the teaching and learning of scientific topics, and the deriving of principles for designing sequences and of developing empirically validated innovative sequences in various domains. Méheut and Psillos (2004, p. 516) define a teaching-learning sequence as "an interventional research activity and a product, which includes well-researched teaching-learning activities empirically adapted to student reasoning". So, a teaching-learning sequence is used to denote "the close linkage between proposed teaching and expected student learning as a distinguishing feature of such research-inspired subject oriented sequences".

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