

# Chemistry Education Research and Practice

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PROSPECTIVE PEDAGOGY FOR TEACHING CHEMICAL BONDING FOR  
SMART AND SUSTAINABLE LEARNING

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Abstract

As an important subject in the curriculum, many students find chemistry concepts difficult to learn and understand. Chemical bonding especially is important in understanding the compositions of chemical compounds and related concepts and research has shown that students struggle with this concept. In this theoretical paper based on analysis of relevant science education research, textbooks, and our classroom observations and teaching experiences, the authors argue that the difficulty in learning chemical bonding concepts is associated with the sequence (ionic, covalent and polar covalent bonding) in which students are taught because this sequence receives little support from constructivist theories of learning. Consequently, the paper proposes a sequence to teach chemical bonding (covalent, polar covalent and ionic bonding) for effective and sustainable learning. In this sequence, the concepts are developed with minimum reorganisation of previously learned information, using a format which is claimed to be easy for students to learn. For teaching these concepts, the use of electronegativity and the overlap of atomic orbitals for all types of bonding have also been stressed. The proposed sequence and emphasis on electronegativity and atomic orbital overlap meets the criteria for teaching and learning of concepts based on the psychology of learning including the theory of constructivism necessitating the construction of new knowledge using related prior knowledge. It also provides a better linkage between the bonding concepts learned at secondary and tertiary levels. Considering these proposed advantages for teaching, this sequence is recommended for further research into effective and sustainable teaching.

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Introduction

Researchers are deeply concerned about secondary and tertiary students' (a) perceptions of chemistry being difficult, (b) experiencing difficulty in learning the subject, (c) inadequate background content knowledge for learning advanced content, and (d) ability to apply their knowledge to real world problems (Boujaoude & Barakat, 2000; Coll & Treagust 2001, 2002; Dhindsa, 2002; Dhindsa & Treagust, 2009; Nakhleh, 1992). These authors have also stated that the large amount of content taught in a grade level, content abstractness, the traditional teaching style with emphasis on rote learning and assessment through tests and examinations are among the major factors responsible for students' poor perceptions of chemistry. For example, students' incomplete and vague answers to chemistry examination questions reflect their shallow understanding of the concepts (Dhindsa & Treagust, 2009).

To overcome such problems associated with chemistry teaching and learning, researchers have proposed improvements to the chemistry curriculum including attending to course content sequencing, staff/student relationship, students' social and cultural

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3 background, learning styles, use of technology and alternative explanations (Abilola &  
4 Dhindsa, 2012; Bodner, 1992; Dhindsa & Emran, 2006; Gabel, 1999; Kirkwood &  
5 Symington, 1996; Nahum, Mamlok-Naaman, Hofstein, & Krajcik, 2007; Taber, 2011). This  
6 report concentrates on chemical bonding content sequencing and proposes better explanations  
7 for effective teaching and learning.  
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9 Curriculum developers (experts) sequence the chemistry content knowledge that is to  
10 be taught with increasing difficulty to match the mental development of the students as their  
11 age increases. They also aim to support higher levels of content learning using previously  
12 learned content as prior knowledge. The selection of content and its organization/sequencing  
13 is based on the expertise of curriculum developers. When they are not aware of recent related  
14 science education research to guide the selection and sequencing the content, they rely  
15 heavily on the way they understand the content that is usually organised from the unknown to  
16 the known. Often this sequencing fails to satisfy the learning needs of students especially  
17 those needs described by psychological theories of learning (Abiola & Dhindsa, 2012) and  
18 hence encourages rote learning. Effective teaching requires sequencing content from the  
19 known to the unknown to support student learning (OPSU, 2010). On the other hand,  
20 metallurgy topics (say, about iron), for example, are arranged and taught from the unknown  
21 to the known (ores, extraction, properties and uses). This sequence is an expert organization,  
22 the way experts understand the content, and is not based on the students' daily experiences  
23 with iron.  
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25 Psychologically, students learn from the known to the unknown (Dunlosky, Rawson,  
26 Marsh, Nathan & Willingham, 2013). Therefore, for effective teaching, the organization of the  
27 topic about iron for example, the sequence uses, properties, ores and extraction of iron which  
28 makes sense. There has been a belief that once a student learns higher-level chemistry  
29 content, the lower level chemistry content becomes clear to him/her. This approach has  
30 encouraged teachers to oversimplify the concepts for teaching students at lower levels of  
31 schooling. However, it has been found that the oversimplified concepts taught at lower level  
32 are misconceptions which resist change even at higher levels (Coll & Treagust, 2002;  
33 Dhindsa, 2011; Taber, 2000, 2011, 2012; Wimmer & Dhindsa, 2005). Dhindsa (2011) has  
34 reported that graduate students defined an element as a substance with the same type of  
35 atoms, an oversimplified definition learned at lower secondary level. Oversimplification of  
36 concepts rather adds to students' misconceptions and frustrations (Dhindsa, 2011; Hurst,  
37 2002, Justi & Gilbert, 2002). Moreover, teachers unthinkingly follow textbook sequences and  
38 explanations which are purported to also be supported by learning theories but which are  
39 largely how the topics have been introduced over time. These sequences follow the unknown  
40 to the known pattern and the explanations often are incomplete (Abiola & Dhindsa, 2012).  
41 According to these authors, teachers use the marbles and sand analogy to explain a decrease  
42 in volume when equal volumes of ethanol and water are mixed. Based on this explanation,  
43 the volume should always decrease during liquid-liquid solution formation because often  
44 molecules are not spherical in shape and some part of the molecules can go into the spaces  
45 between molecules; however, in other cases the volume may increase or stay the same.  
46 Moreover, this explanation ignores the interaction between solvent and solute particles. Such  
47 incomplete explanations are not sustainable and require students to learn, unlearn and relearn  
48 the process over and over again. One approach to address these and other aspects of learning  
49 chemical bonding has been to present a coherent view of energy and energetics using an  
50 interdisciplinary approach (Cooper & Klymkowsky, 2013).  
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52 The authors of this study argue that chemical bonding is another topic that is not  
53 sequenced and taught to support effective and sustainable learning at all levels. Moreover,  
54 explanations are incomplete and oversimplified. This deficiency is reflected in the numerous  
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problems (including acquiring misconceptions) that students face when learning this topic (Nahum, et. al 2007; Ozmen, 2004; Taber, 2011; Wimmer, Dhindsa, Seddigi, & Khaled, 2006). These researchers also have expressed their dissatisfaction with the way in which chemical bonding is taught; however, there are only a few researchers who have proposed new teaching pedagogies and models to overcome these problems. Taber (2001) considered a progression from electron and metal cation interaction in metals to cation and anion interaction in ionic compounds and proposed that metallic bonding should be taught before ionic bonding. Thereafter covalent bonding in giant covalent structures followed by covalent bonding in simple molecules should be taught. We argue that concept of multiple bonding of an atom with a number of other atoms is a difficult concept for students to understand. Also, as discussed later in the paper, progression from ionic to covalent bonding might be difficult for students to understand. More recently, Taber (2011) proposed an alternate explanation for teaching chemical bonding based on electrostatic attraction; in all bonds, the length of the bond depends on the magnitude of attractive and repulsive forces between the bonding atoms. Nahum, Mamlok-Naaman, Hofstein and Taber (2010) summarized research on chemical bonding and covered various aspects of it including the way it is taught, misconceptions, bonding models and other factors. They also described recent research on this topic by Nahum, et al. (2007) and Nahum, Mamlok-Naaman, and Hofstein (2008). Nahum, et al. (2008) proposed the use of Coulomb's law in explaining chemical bonding and further stated that (a) the chemical bonding section should be sequenced based on bond strength for teaching and (b) there are no pure ionic or covalent bonds; all bonds have ionic and covalent bonding components (based on the valence bond theory).

However, chemical bonds are still taught as pure ionic and covalent; as well, the role of electronegativity in bonding is often not made clear in ionic bonding. There are four limitations in this teaching approach: (a) the bonding concepts are arranged on the basis of bond strength - a concept that students find difficult to understand, (b) the proposed teaching order is still the traditional ionic, covalent, polar covalent (partly covalent and partly ionic), hydrogen bonds and van der Waals bonds (strong to weak), (c) if the proposed teaching order is low strength to high strength (as commonly understood by students) then the proposed sequence (ionic to van der Waals) of concepts for teaching and expected bond strength (weak to strong) is not in line with each other, and (d) the concept of electronegativity is introduced when polar covalent bonds are introduced. Moreover there are no explanations given to support how an electron pair will move between  $A^+B^-$ ,  $AB$  and  $A^-B^+$  states. It also lacks visual representation of bonding concepts. The literature is silent about the requirement of overlap of atomic orbitals to occur for electrons to transfer in all types of bonding. Also a continuous spectrum for bonding from covalent to ionic is not demonstrated visually. In summary, the problems associated with difficulty, misconceptions and lack of understanding of the chemical bonding topic might be associated partly with the way the subtopics of chemical bonding are sequenced and taught to the students. Therefore, in this article the chemical bonding topic has been selected to evaluate its sequence of teaching. According to Watson and Mason (2006), researchers, curriculum developers and teachers can assist students to make connections between prior knowledge and new content by using carefully sequenced examples, including examples of students' own solution strategies, to illustrate key ideas.

#### Valence Bond Theory

Valence bond theory (VBT) is based on the Lewis structure of molecules and assumes that the electrons in a molecule occupy atomic orbitals of individual atoms. Therefore, in VBT, the picture of an individual atom during bond formation is retained. The covalent

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bond is formed by an overlap of atomic orbitals of bonding atoms (e.g. two 1s orbitals of two H atoms overlap to form the H<sub>2</sub> molecule). The overlap means two orbitals share a common region in space. There is a high probability for the shared electron pair(s) to be found in the common region but the bonding pair may leave this region. VTB suggests that a valence bond is a linear combination of covalent and ionic states.

$$\Psi_{VB} = \Psi(A - B) + a\Psi(A^- B^+) + b\Psi(A^+ B^-)$$

However, contributions from ionic and covalent states to form the valence bond may be different. Furthermore, the contribution of each of two ionic states (see a & b in the above equation) is also different and depends on the nature of the atoms involved in bonding. Hence, every valence bond involves some component of a covalent bond that requires overlap of atomic orbitals. Therefore the concept of orbital overlap as suggested by VBT also can be applied to ionic and metallic lattices.

### Chemical Bonding: Teaching Sequence and Explanations

The analysis of secondary and tertiary (First Year) textbooks (Brown, Murphy, Lemay Jr., Langford, Bursten, & Sagatys 2009; Chang 1987; Hill, McCreary & Kolb 2010; Timberlake 2010; Zumdahl 1998) as well as our O- and A-level classroom observations in Brunei and teaching experiences in Australia have revealed that the chemical bonding topic is taught in the order of ionic, covalent, non-polar covalent, metallic and inter-molecular bonding. Tsaparlis and Pappa (2011) reported that 10 out of 14 textbooks followed the above order. Only a few authors have considered a sequence different from the above for teaching these concepts (Johnstone, Morrison & Reid 1981; Tsaparlis & Pappa 2011). A recent analysis of upper secondary level textbooks in Sweden demonstrated that the way models of chemical bonding are presented might cause students to have alternative conceptions and difficulties in understanding chemical bonding (Bergqvist, et al. 2013).

Ionic bonding is described as an electrostatic force of attraction between ions of opposite charges. Ions are formed from atoms by the transfer of one or more electrons from one atom to another. The maximum number of electrons transferred can be three thus giving rise to +3 and -3 charge on the cations and anions, respectively. Some anions consisting of more than one atom [eg in NaCN, (C-N)<sup>-</sup>] do have covalent bonds. These covalent bonds are not broken when ionic solids are melted or dissolved. The ionic bond exists between atoms of metals (from groups 1, 2 and 3 in the periodic table) and non-metals (from groups 6 and 7). The octet rule (noble gas configuration) is used to explain the stability of the electronic configuration of ionic states of atoms involved in ionic bonds. All these books gave an example of ionic bonding in sodium chloride formation. The books have also shown graphically the transfer of an electron (jumping electron) from sodium to chlorine using Lewis electron-dot symbols.

Covalent bonding is described as sharing of electron pairs between two atoms of the same or different elements to complete the octet of each atom to attain the stable noble gas configuration. The books use molecules of hydrogen, chlorine and/or fluorine as examples of diatomic covalent bonding and Lewis electron-dot symbols are used to show the sharing of electrons graphically. Often no example is given that involves the sharing of electrons between two atoms of different elements. These examples assume/reflect that bond formation occurs when an equal contribution of electrons from both bonding atoms occurs that leads to equal sharing of bonding pair(s) of electrons. This bond is rarely called a non-polar covalent bond in the textbooks.

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Polar covalent bonding is often taught as a separate entity under unequal sharing of bonding electron pairs. It is taught as a covalent bond that involves unequal sharing of bonding pair or pairs of electrons that are equally contributed by the bonding atoms. The basic idea of stability through attaining noble gas configuration following the octet rule is stressed. Electronegativity values of bonding atoms are used to justify that the bonding pair is shared more by one of the bonding atoms than the other. An atom with a higher electronegativity value will share the bonding electron pair more than the one with lower value. As a result, one electron is partially lost by one atom and gained by the other, thus giving rise to partial negative and positive charges on the bonding atoms. This bond is classified as a polar covalent bond. The partial charge on bonding atoms is represented as delta positive ( $\delta^+$ ) and delta negative ( $\delta^-$ ). The atom with a higher electronegativity value receives  $\delta^-$  and the other receives  $\delta^+$ . The magnitude of the charge depends upon the difference in electronegativity values of the bonding pair of atoms. A coordinate covalent/dative bond is often not discussed in the textbooks.

Metallic bonding is described as bonding due to valence electrons that are delocalised throughout the solid. The metallic bond is described as an array of metal positive ions immersed in a sea of delocalised valence electrons. A cross section of a metal is shown representing equal amounts of negative charge for electrons and positive charge for metallic kernels; the overall charge is zero. The strength of the metallic bond is associated with the number of delocalised valence electrons, e.g., one for sodium (example of a soft metal) and six for chromium (example of a hard metal). This is an old model that is not in line with recent developments in the area of metallic bonding. More details are discussed in a later part of this article.

#### Analysis of Teaching Sequence and Explanations

The major problems associated with this order of teaching are that the students learn that all types of bonding are independent of each other and there is no association between them. They also learn that electronegativity can explain polar covalent bonding and it does not have a role in ionic bonding. The students gain the notion that during ionic bonding formation electrons can jump from one atom to another under normal conditions, which is not an acceptable conception.

When covalent bonding is taught after ionic bonding, teachers often fail to establish the link between ionic and covalent bonding because these are extreme ends of the bonding spectrum based on differences in the electronegativity values of the bonding atoms. Hence the actual link between ionic and covalent bonding is relatively weak because these ideas are still to be connected by teaching polar covalent bonding. The students, therefore, might develop the notion that covalent bonding is also an independent identity and has nothing to do with ionic bonding. Teaching polar covalent bonding after covalent bonding follows an acceptable order because the concepts are well connected and teachers can establish a link between them using valence bond theory and Lewis dot symbols. The students can also understand the link. However, analysis of textbooks and our school teaching experiences revealed that textbooks and teachers spend very little or no time to show the students that polar covalent bonding is a link that connects ionic and covalent bonding; for the teacher who would like to establish such a link, the teaching order is reversed. This means that after teaching polar covalent bonding, teachers have to go back to ionic bonding that was taught before the covalent bonding. When metallic bonding is taught after polar covalent, teachers often fail to establish a link between polar covalent bonding and metallic bonding and so metallic bonding is taught as an isolated concept.

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5 Teachers and textbooks establish polarity of the polar covalent bond using differences  
6 in electronegativity of the bonding atoms, whereas they place very little emphasis on  
7 electronegativity data while teaching ionic and covalent bonding. The students therefore often  
8 may develop the notion that electronegativity has no role to play in covalent and ionic  
9 bonding, despite electronegativity values of bonding atoms playing a significant role in all  
10 types of bonding. Covalent bonding occurs between atoms of the same (or slightly different)  
11 electronegativity values and ionic bonding between atoms with extremely large differences in  
12 electronegativity values. Scientists have agreed to these differences as  $\leq 0.4$  for covalent  
13 bonding and  $>1.7$  for ionic bonding (The electronegativity values for all atoms on the Linus  
14 Pauling scale range from 0.7 to 4.0 (Chang, 1987; p. 318)). Between these values lies the  
15 polar covalent bond. These boundaries are fuzzy. The students learn that the electronegativity  
16 difference can change the position of the bonding electron pair from the middle to one side.  
17 Moreover, the number of examples given in the textbooks and used during classroom  
18 teaching is limited to support students' learning of these concepts.

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22 Teachers often use NaCl as an example to teach ionic bonding and use a visual model  
23 to demonstrate that an electron jumps from sodium to chlorine without realizing that an  
24 ionization energy of 496 kJ/mole is required for an electron to leave the outermost orbit of the  
25 sodium atom. This is an oversimplified explanation of ionization to establish an ionic bond  
26 and it leads to the misconception that an electron from a sodium atom jumps to a chlorine  
27 atom. The authors argue that the electron affinity of 348kJ/mol for chlorine cannot cause  
28 sodium to lose its outermost electron. A similar argument is reported by Taber, Tsaparlis and  
29 Nakiboglu (2012). Hence, the transfer of outermost electron from sodium to chlorine will  
30 require some mechanism.

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34 The major problems with the way chemical bonding is taught include:

- 35 1. The sequence of ionic, non-polar covalent and polar covalent bonding  
36 concepts for teaching is not appropriate to support effective and sustainable  
37 learning.
- 38 2. These concepts are not properly connected to show a continuity (or  
39 spectrum) of chemical bonding.
- 40 3. Electronegativity data are mainly used to describe the polar covalent bond  
41 not the other types of bonds.
- 42 4. No mechanism is described to support the electron transfer from an atom to  
43 another in ionic bonding as well as for the formation of  $A^+B^-$  and  $A^-B^+$  in all  
44 types of bonding. Electrons simply do not jump between atoms.

#### 45 46 47 48 49 50 Proposed Teaching Order

51 Consistent with the calls for learning progressions being a guide for developing meaningful  
52 learning in science (Stevens, Shin, & Peek-Brown, 2013), the authors believe that chemical  
53 bonding should be taught in three stages: (1) covalent, polar covalent and ionic bonding, (2)  
54 bonding in lattices: metallic and crystals, and (3) inter- and intra-molecular bonding. This  
55 paper concentrates on the first and second stages. During the first stage, covalent bonding  
56 should be taught first, followed by polar covalent and then ionic bonding. Hereafter bonding  
57 in metals and ionic lattices should be taught. Since this sequence is based on electronegativity  
58 values, the role of electronegativity in chemical bond formation becomes evident. Moreover,  
59 covalent bonding is explained using an overlap of atomic orbitals; teachers can stress the  
60 concept of overlap in each type of bonding as they move from covalent to ionic bonding. It

would explain the formation of  $A^+B^-$ ,  $AB$  and  $A^-B^+$  states. Hence this sequence will address the above stated problems. The advantages of using this sequence for teaching are discussed in detail in the following section.

Covalent Character	High		-Decreases→					Low
Electronegativity value	2.1	3.5	3.0	2.1	2.1	2.1	1.9	0.9
Atom 1	H	O	N	$H^{\delta+}$	$H^{\delta+}$	$H^{\delta+}$	$Ag^+$	$Na^+$
Electron pair(s) position	**	****	*****	**	**	**	**	**
Atom 2	H	O	N	$C^{\delta-}$	$N^{\delta-}$	$Cl^{\delta-}$	$Cl^-$	$Cl^-$
Electronegativity value	2.1	3.5	3.0	2.5	3.0	3.5	3.5	3.5
Ionic Character	Low		- Increases→					High

Figure 1. Continuum of bonding with bonding electrons in expected high probability areas.

### Advantages: Proposed Teaching Order and Overcoming the Stated Problems

#### Learning Sequence and Constructivism

This order represents a continuum (spectrum) of the bonding from equal sharing of bonding electron pair(s) in covalent bonding to the extreme case of unequal sharing of bonding electron, that is, very little sharing of the electron with the parent atom in ionic bonding. A visual representation of teaching in this order together with some characteristics is reported in Figure 1. Covalent bonding results from the attraction of the negatively charged electrons to the positively charged nuclei of the atoms of both elements. The resulting equal sharing of bonding electrons by the bonding atoms is due to the electronegativity values of the two atoms being either equal or nearly equal. Teachers should emphasise that sharing of an electron pair increases the net attraction force between the bonding atoms. As the electronegativity difference between bonding atoms increases, the extent of equal sharing of the bonding electron pair decreases as shown by a shift in the position of the electron pair from a central location between the bonding atoms (see Figure 1; readers should consider both vertical and horizontal flow of information in the figure). A shift in the position of a bonding electron pair from the middle of covalently bonded atoms results in partial charge ( $\delta^+$ ,  $\delta^-$ ) on the bonding atoms with  $\delta^+$  on the atom that shares less of the bonding electron pair and  $\delta^-$  on the atom that shares more (Example,  $H^{\delta+} : N^{\delta-}$ ). It further leads to a case when the bonding electron pair is mostly shared by one of the bonding atoms and the other gets very little opportunity to share the pair, resulting in ionic bonding. This approach does fit into our social context when we often share things equally or unequally. For example, when we go for a lunch in a group say of two, each member often contributes equally. Sometimes a member contributes more than other and there are cases when a member invites others and pays the overall bill. Teachers can use this daily life social experience to teach these concepts.



Table 1  
Some Characteristics of Chemical Bonds

Bond	Atoms type	Electron sharing	Electronegativity difference	Orbital overlap	Covalent character	Ionic character
Covalent	Same & different	High probability	None or small	Large	Maximum	Minimum
Polar covalent	Different	Intermediate probability	Small to large	Large to small	Less than covalent bonding	More than covalent bonding
Ionic bonding	Different	Low probability	Large	Small	Minimum	Maximum
Metallic	?	?	?	?	?	?

Note: ? represents questions for students to decide which of the above characteristic fits most for metallic bonding.

In this order, the concepts are well connected and build sequentially on each other as supported by the notion of constructivism. Teachers can build their teaching of polar covalent bonding on non-polar covalent bonding and also along similar lines for ionic bonding on polar covalent bonding. They can ask students to compare some characteristics of the three types of bonds such as the nature of bonding atoms (atoms of same or different elements), extent of overlap of orbitals for electron sharing as well as for electron transfer, electronegativity of bonding atoms, the role of electronegativity in three types of bonding, and changes in covalent and ionic characters from covalent to ionic bonding (See Table 1). Teachers can use these characteristics to introduce lattice (ionic and metallic) bonding. This sequence of concepts will allow the students to construct their learning using previously learned bonding concepts as prior knowledge, hence the learning process is supported by the constructivist theory of learning.

To introduce metallic bonding, teachers can ask the students about the type of bonding they expect between atoms in a metallic lattice. The teacher may guide the students to consider the characteristics of chemical bonds in Table 1 before introducing metallic bonding. A consideration of these characteristics may guide the students to think of metallic bonding as a type of covalent bonding. However, to differentiate between metallic and covalent bonds, we recommend that teachers compare the differences between these bonds in addition to the similarities. For example, a metallic atom can form multiple bonds with other atoms of its kind by overlap between spherical s-orbitals of atoms. The concept of formation of multiple bonds in metallic bonding is distinct from other type of bonds. This approach can help us support metallic bonding using VBT. The electron sea and metal kernel model does not clearly explain the concept of overlap of atomic orbitals required for the movement of electrons from one metallic atom to another. However, VBT is inclusive of explanations made by an electron sea and metal kernel model. Teachers can adopt a similar approach to teach bonding in ionic lattices.

#### Emphasis on Electronegativity

The covalent bond (non-polar) is an easy concept to teach by using simple examples of diatomic molecules such as Hydrogen, Oxygen and Nitrogen molecules. The use of these examples of non-polar covalent bonding will help the students learn single, double and triple bonds. The Lewis dot notation or overlap of atomic orbitals can be used for visual representation of covalent bonding. Also, the role of electronegativity in bonding can be

emphasized. Teachers can then use this information to teach the concept of polar covalent bonding. They can emphasise that an increase in electronegativity difference between bonding atoms, reduces the extent of overlap as more electron density is transferred to a more electronegative atom. As a result, the shared pair of electrons spends more time with the more electronegative atom. Teachers can further link teaching of ionic bonding to polar covalent bonding, with the former being a case of maximum polarity. In this sequence of teaching, teachers are required to use electronegativity data as a basis for classifying these types of bonding. Therefore, they can use the electronegativity data to explain the probability of finding electrons between the bonding atoms.

#### Ionic Bonding and Atomic Overlap

In the proposed sequence of learning these concepts, students learn the importance of overlap of atomic orbitals. They will also learn that with an increase in difference of electronegativity values of bonding atoms, bonding electrons spend more time closer to an atom with higher electronegativity than that with lower electronegativity. The probability of a bonding pair spending time close to an atom with lower electronegativity is low. Teachers can extend this concept to ionic bonding and can emphasise that in ionic bonding the bonding pair spends much more time with the more electronegative atom and least time with the less electronegative atom. However, the probability for bonding electron pair(s) to spend time with a less electronegative atom is not zero as supported by VBT, that is, the wave function of a valence bond is a linear combination of  $A^+B^-$ ,  $AB$  and  $A^-B^+$  states. This sequence can help students learn that an overlap of atomic orbitals is essential for ionic bonding and the probability of complete electron transfer from an atom to another is high but not 100%. Hence, students can visualize the importance of atomic overlap during ionic bonding.

Scientists have used the difference in electronegativities of two elements to classify the chemical bonds as: non-polar covalent, polar covalent and ionic bonds. When the difference of electronegativity is 0.4 or less, the bond is usually non-polar covalent; between 0.4 and 1.7, the bond is usually polar covalent and for  $\geq 1.7$ , the bond is usually ionic. The word 'usually' used in the above phrases is an indicator of uncertainty of cutoff points. The readers should therefore consider that there are grey areas around differences of 0.4 and 1.7 as supported by the word 'usually' that is used in the classification criteria. For example a bond can be classified as ionic with an electronegativity difference of 1.4 and covalent with difference  $>0.4$ . For example  $ZnBr$  and  $AgCl$  with electronegativity differences of 1.2 and 1.6 respectively are ionic.  $HF$  with electronegativity difference of 1.9 is polar covalent. These grey areas also suggest that there is an overlap of atomic orbitals during the formation of ionic bonds. Hence, electronegativity and overlap of atomic orbitals can be used to explain covalent, polar covalent and ionic bonding.

#### Discussion

The discussion is reported under three headings: Learning Science Perspective, Links to Other Chemistry Concepts, and Limitations. These headings describe how the proposed pedagogy on chemical bonding is linked to psychology of learning and to those concepts which students have learned prior to and post learning of chemical bonding. Moreover, some concerns about its limitations are also discussed.

#### Learning Science Perspective

Human learning may occur as part of education, personal development, schooling, or training. It is well recognised that learning including of chemistry concepts should build on

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3 theories and models of human cognition (information processing) and psychology of learning  
4 (see Taber, 2013). These aspects are discussed below under these two headings.  
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7 Information Processing Perspective. Human information processing involves a large number  
8 of cognitive processes and each process requires some time to complete (see Anderson &  
9 Demetrius, 1993). Each cognitive process takes time and slows down the information  
10 processing rate and increases wait time (Dhindsa, 2010). Therefore, a way to improve the  
11 information processing rate is to minimize the use of these processes. The hippocampus is a  
12 region within the temporal lobe of the cerebral cortex and it plays a significant role during the  
13 processes of coding and consolidation (Abiola & Dhindsa, 2012). However, the hippocampus  
14 is bypassed when information is meaningfully learned or permanently stored and well linked  
15 to previously stored information. Bypassing the hippocampus helps to reduce the number of  
16 cognitive processes involved in activating and transferring the desired information from long  
17 term memory to short term memory for fast interpretation of new information. It also means  
18 that when stored information is properly chunked together in a cognitive structure, it can  
19 bypass hippocampus. If we consider memory capacity in terms of Miller's magic number of  $7$   
20  $\pm 2$  (recently revised to  $4 \pm 1$ ; Mathy & Feldman, 2012), it is limited. To make effective use  
21 of it, larger and effectively linked cognitive structures (chunks of knowledge) need to be built  
22 so that students can bring larger chunks of prior knowledge to support new learning. This can  
23 help learners use memory space efficiently to learn new knowledge. Learning occurs by (a)  
24 adding completely new information to the brain without any link to existing memory (rote  
25 learning), (b) completely replacing the existing cognitive structure (replacing a  
26 misconception) (c) modifying the existing cognitive structure (correcting partial  
27 misconceptions), (d) appending new information to the existing cognitive structure (enlarging  
28 existing cognitive structure) and (e) a mixture of all four. The most effective way to learn is  
29 to append new information to the existing cognitive structure with minimum modifications.  
30 This idea is supported by Jensen (2000) who stated that new neuron connections should be  
31 established with minimum loss of existing connections. In this way, the role of the  
32 hippocampus is minimised. To achieve this outcome, teaching and learning should meet the  
33 criteria of sustainable learning (Abiola & Dhindsa, 2012, Dhindsa, 2011). The proposed  
34 sequence builds on previous concepts. For example, the concepts of covalent and polar  
35 covalent bonding are well connected and require limited modification when polar covalent  
36 bonding is taught after covalent bonding. These modifications can be mostly achieved by  
37 appending new information to the existing cognitive structure describing the covalent bond.  
38 Similarly, information on ionic bonding can be added to polar covalent bonding with little  
39 additional modifications to the above stated cognitive structure representing covalent and  
40 polar covalent bonding. The overall cognitive structure can be modified to teach lattice  
41 (metallic) bonding. Each time students can activate a larger cognitive structure to effectively  
42 append additional information to it. Hence students can use their existing small short-term  
43 memory effectively. In this way, we can increase the size of a cognitive structure with  
44 minimum modification to it.  
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53 Psychology of Learning Perspective. Learning is a lasting change in behavior that results  
54 from experience. The main assumption behind all learning psychology is that the  
55 environment, conditioning, and reinforcement affect human behavior. It is well documented  
56 that reinforcement plays a significant role in bringing permanent behavior change and its role  
57 is more prominent to support rote learning of completely new concepts that are used to  
58 support meaningful learning of more new knowledge (Ausubel, 2000). Piaget (1970/1972)  
59 emphasized the roles of assimilation, disequilibrium, accommodation and equilibration in  
60 learning. The proposed pedagogy starts with single bond formation with equal sharing of a

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3 single electron between two H-atoms of the same electronegativity value. The O-level school  
4 syllabus in Brunei shows that students (age 15+ years) learn diatomic molecules ( $H_2$ ,  $O_2$ ,  $N_2$ ,  
5  $I_2$ ) in the chapters on kinetic particle theory and atomic theory (including shells, number of  
6 electrons in shells, molecular mass and gases) prior to bonding. This means covalent bonding  
7 is not a completely new concept because there are anchors to link this information.  
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10 Teachers can activate student prior knowledge by reminding them of the existence of  
11 a stable hydrogen molecule consisting of two hydrogen atoms which they have learned  
12 previously in the above stated chapters. Students can use this information to interpret new  
13 information (assimilation). A question dealing with why two H-atoms form a stable molecule  
14 is new information and will create a state of disequilibrium because the students cannot  
15 explain it with their existing knowledge. To facilitate the accommodation process, teachers  
16 can take examples from daily life of friendships between two students that are based on  
17 sharing of some common traits between friends. The concept of sharing can now be further  
18 extended stating that hydrogen atoms have one electron to share and two H-atoms share a  
19 pair of electrons that increases the force of attraction between the two atoms and it is defined  
20 as a bond. This concept is new and students have to partly rote-learn it and partly learn  
21 meaningfully as it has been linked to their daily life experience. The students now will  
22 modify their existing knowledge about a hydrogen molecule to include a bond formation as a  
23 result of electron sharing using the accommodation process to reach a state of equilibrium.  
24 Here we would recommend teachers to introduce the concept of overlap of atomic orbitals to  
25 support sharing of electrons and activate the concept of electronegativity to support the  
26 position of bonding electrons between two atoms. When both atoms are equally sharing the  
27 bonding electron pair it is in the middle of both atoms (H-H), if one H-atom is using both  
28 electrons, the other will not be able to use them ( $H^+H^-$ ) and vice versa ( $H^-H^+$ ).  
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34 In this way teachers can lay the foundation for introducing concepts of all bonds being  
35 covalent, polar covalent and ionic as explained by the Valence Bond Theory. We will not  
36 recommend linking bonding to the octet rule as it does not apply to hydrogen and many other  
37 molecules. Rather, we recommend that while teaching electronic configuration, s, p and d  
38 orbitals should be introduced to students. Also students should be able to determine the  
39 orbital to which the last electron is added using a staircase type model as proposed by some  
40 authors (Chang, 1988; Dhindsa, 2011). Since in the case of hydrogen, the first and last (only  
41 one) electron enters the s-orbital, therefore to complete this s-orbital hydrogen requires two  
42 electrons. Hence only one pair of electrons is shared between two hydrogen atoms to form a  
43 bond. The above process will be repeated (reinforcement) to explain the formation of double  
44 and triple bonds in  $O_2$  and  $N_2$  molecules, respectively. The students will use explanations  
45 learned about the hydrogen molecule to assimilate, accommodate and equilibrate information  
46 related to  $O_2$  and  $N_2$  molecules: the overlap of atomic orbitals and the role of  
47 electronegativity to determine the position of shared electron pairs between bonding atoms.  
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52 Teachers can ask students to draw various possible ways that three electron pairs can  
53 be shared between two nitrogen atoms bonded using a triple bond ( $N:::N$ ;  $N:::N$ ,  $N:::N$ , ...).  
54 Hereafter, bonding between different atoms (polar covalent bonding) is discussed and the role  
55 of electronegativity in determining and explaining the position of the shared pair will  
56 predominate. As soon as a teacher poses a new question, for example, relating to what  
57 happens when atoms with different electronegativity form a bond such as the C-H bond, well-  
58 informed students will certainly use their prior knowledge to assimilate the position of  
59 electrons towards the more electronegative atom, whereas other students will experience  
60 disequilibrium. With the help of the teacher's explanations/activities, the concept of equal

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3 sharing for bonding will be modified to reach equilibration. The concept of covalent bonding  
4 will be modified meaningfully to polar covalent bonding using processes of assimilation,  
5 disequilibrium, accommodation and equilibration as proposed by Piaget as well as rote  
6 learning and meaningful learning through reinforcement as proposed by Ausubel (2000). The  
7 students will learn the concept of bond polarity and its association to electronegativity. The  
8 teachers should reinforce the concepts of atomic orbital overlap and the role of  
9 electronegativity using other examples. Lastly, teachers can extend the concept of polar bond  
10 to ionic bond, which can be defined as a maximum example of a polar bond. The above  
11 discussion supports the proposed sequence of teaching bonding that is well supported by the  
12 psychology of learning. However, when we consider the existing teaching sequence, that is  
13 teaching of ionic bonding first and then covalent bonding, the students' prior knowledge of  
14 ionic bonding concepts is not used by teachers to teach covalent bonding. Rather they start  
15 covalent bonding as a completely different/new unconnected concept; because electron  
16 transfer and sharing are distinctly different for teachers and students, students are unable to  
17 link ionic bonding to covalent bonding. The readers can realize that teaching of ionic  
18 bonding prior to covalent bonding is not as well supported as the proposed sequence by the  
19 theories of learning.

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25 In this article, the authors have suggested that the proposed order for teaching  
26 chemical bonding concepts is supported by the psychology of learning including the  
27 constructivist theory of learning. Under these circumstances, the learning of these concepts  
28 should also be linked to related concepts taught at lower grades and those to be taught at  
29 upper grades.

#### 30 31 32 Links to Other Chemistry Concepts

33 This section is divided into two parts: Links to Prior Learning and Links to Post Learning.  
34 Links to Prior Learning deals with how chemical bonding links with concepts students have  
35 learned prior to learning of this concept and Links to Post Learning deals with its links to  
36 concepts taught after the teaching of chemical bonding.

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39 Links to Prior Learning. The concept of bonding is usually taught after students have learned  
40 about atoms, molecules and ions; molecular and ionic compounds; gases; kinetic particle  
41 theory, electronic structure of the atom and the periodic table (Cambridge O-level syllabus,  
42 2014). This means students know the existence of stable diatomic molecules, molecular  
43 compounds, structure of atoms, shells, electrons in shells and their motion. Ion formation and  
44 electronegativity are introduced prior to teaching ionic and polar covalent bonding,  
45 respectively. These concepts play an essential role in explaining chemical bonding. Moreover  
46 there are a number of analogies available to extend the explanation of these concepts to link  
47 with bonding. The knowledge of these concepts can provide enough anchors for students to  
48 construct new knowledge on chemical bonding when taught using the proposed pedagogy.

#### 49 50 51 52 Links to Post Learning

53 (a) *Application of Valence Bond Theory*. In this teaching sequence, electronegativity  
54 determines the high probability area where bonding electrons can be found and an overlap of  
55 atomic orbitals is proposed for electron sharing and transfer between bonding atoms. This  
56 proposal is in line with the recent development in VBT that is the existence of covalent [AB  
57 (NaCl)] and ionic [ $A^+B^-$  ( $Na^+Cl^-$ );  $A^-B^+$  ( $Na^-Cl^+$ )] forms in each type of bonding. However,  
58 the probability of finding the bonding electron pair in regions outside the specified regions by  
59 overlapping of atomic orbitals is not zero; otherwise formation of  $Na^-Cl^+$  becomes  
60 impossible. Teachers can introduce examples (C – H; N – H) where the electronegativity

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difference between bonding atoms is small to introduce the concept that it is also possible for a bonding electron pair to move to atoms with lower electronegativity values, thus producing a reversal of change of the bonding atoms. A part of Figure 1 can be transformed to Figure 2 for visual representation of such reversal. The students can learn and observe that an electron pair can completely transfer to bonding atoms with low electronegativity. When Figures 1 and 2 are considered together, the students can visualize the existence of a cases of covalent, polar covalent and ionic bonding (also see Figure 3).

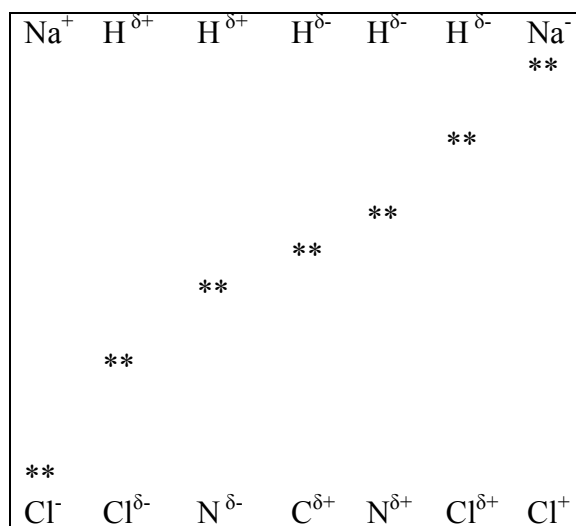


Figure 2. Continuum of bonding with bonding electrons in high and low probability areas.

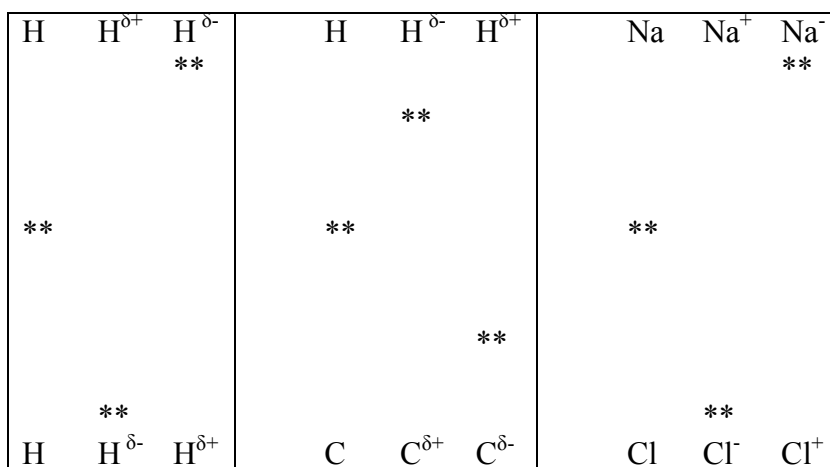


Figure 3. Continuum of bonding with bonding electrons in high and low probability areas.

Tertiary teachers can use Figure 3 and Figure 4 to demonstrate the existence of three clear bonding states for covalent, polar as well as for ionic bonds. They can also use information from Figure 4 to explain the polar covalent bonding concept in ionic bonding. This arrangement is impossible without an overlap of atomic orbitals of bonding atoms. Hence teachers can teach the mathematical concept  $\psi_{VB} = \psi(A-B) + a\psi(A^-B^+) + b\psi(A^+B^-)$  by linking it to what students have learned at school.

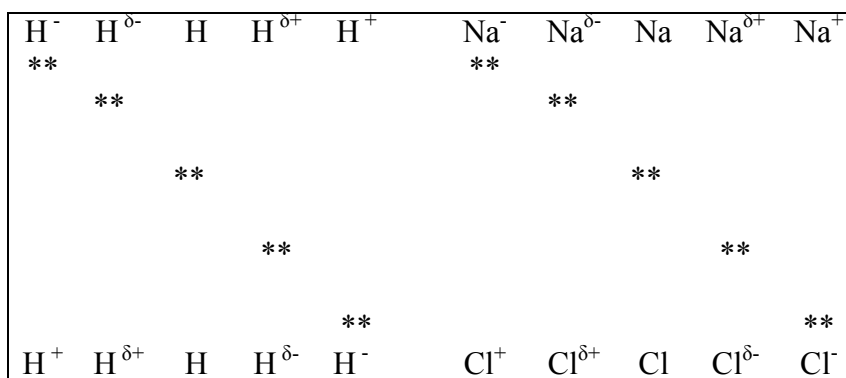


Figure 4. Possible covalent, polar covalent and ionic bonding states in H<sub>2</sub> and NaCl.

The authors of this article also believe that with the help of advanced mathematical modeling techniques and high power computers we may be able to compute solutions to more complex models and the valence bond representation may change from equation 1:

$$\psi_{VB} = \psi(A - B) + a\psi(A^- + B^+) + b\psi(A^+ + B^-) \quad (1)$$

to equation 2:

$$\psi_{VB} = \psi(A - B) + \sum_{\delta_i > 0}^1 b_i \psi(A^{\delta_i-} B^{\delta_i+}) + \sum_{\delta_i > 0}^1 d_i \psi(A^{\delta_i+} B^{\delta_i-}) \quad (2)$$

Where  $\delta_i$  is the charge at  $i$ th location between bonding atoms and its value changes from a value  $>0$  to 1.0, and  $b_i$  and  $d_i$  represent the magnitude of contributions of each function. For  $\delta_i = 1$ , the function should represent the contribution of an ionic state and all other cases ( $\delta_i$  value between 0 and 1 ends excluded) the function represents polar covalent states. A simple graphic representation of bonding between Hydrogen - Hydrogen, and, Sodium - Chlorine atoms using the above formula is given below for limited values of  $\delta_i$  (Figure 4). This graphic demonstrates a continuous spectrum for shifting a bonding pair of electrons between the bonding atoms.

#### (b) *Classifying compounds as covalent, polar covalent and ionic*

A common tradition is to classify compounds into three categories: covalent, polar covalent and ionic. Once we accept that there are no pure types of bonds, it becomes difficult to classify compounds into these categories. Since all bonds exhibit five possible characteristics as shown in Figure 4, the best way to classify a compound as covalent, polar covalent or ionic is to look for a dominant character of the bond. For example, in the case of the bond between hydrogen atoms to form H<sub>2</sub> molecule, the H : H character will be dominant, therefore hydrogen is classified as covalent. Similarly, sodium chloride is ionic as Na<sup>+</sup> Cl<sup>-</sup> predominates and HCl is polar covalent as H<sup>δ+</sup> Cl<sup>-</sup> predominates.

(c) *Resonance Structures:* In chemistry, certain molecules or polyatomic ions cannot be expressed by one single Lewis formula. Such molecules or ions are presented by more than one structure and each contributes to the actual structure. These structures are called resonance structures. Resonance is a way of describing delocalized electrons within certain molecules or polyatomic ions. This is an important topic in chemistry that students find difficult to understand. Appropriate prior knowledge is required to link this concept for effective teaching. This model of teaching chemical bonding can act as an anchor to teach resonance because the proposed model suggests teaching covalent and ionic bonding as a continuum spectrum, and students know that electrons can move to different locations during

chemical bonding. Therefore it provides an appropriate prior knowledge for tertiary teachers to develop this concept further. The university teachers may use this prior knowledge to teach contributions of each resonance structure to the overall bonding. For example the chance of obtaining  $F^+$  ion is small but not zero, hence H-F bonding is mainly contributed to by two resonance structures (H - F and  $H^+F^-$ ).

(d) *Molecular orbital theory.* Molecular orbital theory (MOT) and valence bond theory (VBT) provide two ways of support to each other. For example, overlap of atomic orbitals as proposed in the proposed model of teaching chemical bonding also has support from Molecular Orbital Theory which states that when atoms come close, a sufficient overlap must occur for actual bonding to take place and an insufficient overlap will not result in a strong bond (see Housecroft & Constable, 2010, p. 151). However, such overlap would allow electrons to flow from one atom to another.

On the other hand when teaching the MOT wave function for the hydrogen molecule, the VBT wave function can be used as an anchor. These wave functions are described below.

$$\psi_{VB} = \psi(A - B) + a\psi(A^- B^+) + b\psi(A^+ + B^-)$$

$$\psi_{MO} = \frac{1}{2}[1S_A(1) 1S_B(2) + 1S_A(2) 1S_B(1)] + \frac{1}{2}[1S_A(1) 1S_A(2) + 1S_B(1) 1S_B(2)]$$

The first part of the MO wave function consisting of two terms represents the ionic states of the molecule (Barrow, 1996). It is the same as is the case in VBT. Therefore, when teaching MOT, tertiary teachers can use the wave function of VBT as prior knowledge to develop the concept of MOT.

While considering metallic bonding, most metals have outermost electron/s in a s-orbital - a spherical space. The spherical nature of the orbital facilitates overlap between multiple atoms depending upon the atomic size, though restricted by number of other factors. Similarly, in ionic lattices, the outermost orbitals of non-metals can establish an overlap with the s-orbital of outermost metal atoms, and electronegativity can guide the movement of electron density between bonding atomic identities.

#### Limitations

This section is divided into four sections: Octet Rule, Teaching Atomic Orbitals Prior to Chemical Bonding Teaching, Ionic, Covalent and Polar Covalent Sequence and Misconceptions.

Octet Rule. The octet rule has been widely used in textbooks as well as by teachers to explain chemical bonding (see Chang, 1987; Housecroft & Constable, 2010; Zumdahl, 1998), but this rule has limited application to explain the formation of some molecules. However, there are many exceptions to this rule which have been linked to students' misconceptions. Considering exceptions, the octet rule cannot explain bonding of some elements in electron deficient compounds (see  $H_2$ ,  $BeCl_2$  and  $BCl_3$ ), with elements following the octet rule in some compounds and not following the rule in other compounds. For example, sulfur in  $SF_2$  has 8 valence electrons, whereas in  $SF_4$  and  $SF_6$  sulfur has 10 and 12 valence electrons, respectively. Similarly, the octet rule is unable to explain bonding in stable free radicals such as Nitrogen (IV) oxide ( $NO_2$ ). Moreover, some researchers have highlighted misconceptions



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3 associated with the use of the octet rule (Dhindsa & Treagust, 2009; Taber, 1995, 2000). We  
4 therefore decided against its use.  
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7 Teaching Atomic Orbitals Prior to Chemical Bonding Teaching. It is true that the secondary  
8 school curriculum does not require teaching atomic orbitals before teaching chemical  
9 bonding because the O-level curriculum does not need this information to define chemical  
10 bonding. We know that science information is dynamic in nature. New knowledge is  
11 generated and outdated knowledge is discarded at a fast rate. Therefore this information can  
12 be accommodated in its simplest form such that originality of the information is not changed;  
13 otherwise students may oversimplify information as a hybrid model which can lead to  
14 misconceptions (Justi & Gilbert, 2002). To use this model introduction of 1s, 2s and 2p  
15 orbitals is required. The first shell is renamed as 1s, hence only 2s and 2p orbitals are to be  
16 taught. Teaching of these concepts is not difficult and it can be further facilitated by the use  
17 of ICT. We therefore do not consider it as a serious limitation.  
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21 Ionic, Covalent and Polar Covalent Sequence. In this article we proposed the covalent, polar  
22 covalent and ionic bonding sequence for effective teaching and have demonstrated that it is  
23 well supported by the constructivist psychology of learning. However, readers may think that  
24 the existing sequence can also be supported by learning theories, given that proper care is  
25 taken to explain the crucial aspects such as covalent and ionic bonds mainly produce covalent  
26 and ionic compounds, respectively. We do agree with the above statement, because  
27 chemistry concepts of bonding are highly interlinked. However, for effective teaching we opt  
28 for a sequence that can be easily explained using multiple teaching modes such as  
29 visualization of the position of bonding electrons in the proposed model. Moreover, if we link  
30 the covalent and ionic molecules, we are comparing the product of bonding aspect rather than  
31 the process aspect of bonding. Therefore we believe, the proposed order is better supported  
32 that other sequences.  
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36 Misconceptions. There is extensive research associated with misconceptions about chemical  
37 bonding concepts (Dhindsa & Treagust, 2009; Justi & Gilbert, 2002; Taber, 2000; Taber &  
38 Coll, 2002). These studies have highlighted a number of sources for the misconceptions  
39 including the teachers' content knowledge, the way information is presented to students and  
40 oversimplification of the content. Taber (2000) stated that teaching models should reflect  
41 optimum level of simplifications without losing authenticity of scientific content. He further  
42 added that it can be achieved and if proper care is not taken, teaching may impede learning  
43 and add misconceptions. We believe these factors will also have an impact on the teaching of  
44 this proposed sequence. Misconceptions can be minimized by teaching authentic scientific  
45 content with the use of information communication technology (Barke, Hazari & Yitbarek,  
46 2009). Moreover, we need to revisit the process of identifying the misconceptions.  
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51 In the past, all our identification tools were based on the fact that we taught all  
52 bonding types as distinct: ionic bonding has been associated with electron transfer and  
53 covalent bonding with electron sharing. There has been little or no emphasis on teaching that  
54 all bonds are covalent, polar covalent and ionic to varying extents in nature. Emphasis on all  
55 bonds being covalent, polar covalent and ionic will increase with the adaptation of the  
56 proposed pedagogy. We acknowledge that the proposed sequence according to Taber and  
57 Coll (2002) may cause other student difficulties: for instance, to teach covalent bonding  
58 before ionic bonding may cause students to see an ionic lattice and all bonded materials as  
59 containing molecules. It will be interesting to see the impact of the proposed pedagogy on  
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3 students' and teachers' misconceptions when their knowledge and understanding is evaluated  
4 in the above context.  
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#### 6 Future Research Directions

7 The proposed model is a theoretical model based on its sound foundation in the psychology  
8 of learning and human information processing models and theories. However, its actual  
9 success in classroom situations needs to be evaluated. Future research therefore needs to be  
10 directed to evaluating the impact of the proposed pedagogy on students' actual learning and  
11 understanding of the bonding concepts as well as on their overall achievement. There is also  
12 need to ascertain whether or not the proposed pedagogy helps to minimize students'  
13 alternative conceptions. Moreover, research into explanations of intermolecular attraction  
14 forces and bonding in lattices is also warranted.  
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#### 17 Conclusions

18 This study proposes a sequence to teach chemical bonding (covalent, polar covalent and ionic  
19 bonding) for effective and sustainable learning. The use of electronegativity and overlap of  
20 atomic orbitals for all types of bonding has also been stressed. The proposed sequence and  
21 emphasis on electronegativity and atomic orbital overlap meets the criteria for teaching and  
22 learning of concepts of learning theories of psychology including constructivism. This  
23 sequence not only provides a better link between the bonding concepts at school but can also  
24 be easily linked to what students will learn at the tertiary level. The authors have considered  
25 some limitations for the proposed order. Therefore, the proposed teaching model details the  
26 advantages of a different approach to teaching chemical bonding to the one currently used in  
27 the classroom. When using this teaching model, we recommend that teachers explicitly make  
28 students aware of the range of tools such as models, representations of various kinds and  
29 metaphors that are used to explain different kinds of bonds. Future research in applications  
30 of the model is recommended.  
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