Asian Journal of Education and e-Learning (ISSN: 2321 – 2454)
Volume 05– Issue 01, February 2017

Student's Misconceptions on Chemical Bonding: A Comparative Study between High School and First Year University Students

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ABSTRACT— ***The aim of this paper is to investigate the students' understanding about some aspects of the chemical bond and to determine their related misconceptions. Concretely, topics such as the interpretation of some properties of substances (colour, boiling points, solubility and conductivity), intra and intermolecular forces, hydrogen bonding, covalent and molecular networks, geometry and polarity of molecules, are investigated. The research methodology used has been a questionnaire consisting on 15 multiple choice questions as a diagnostic tool. The questionnaire was applied to 79 high school students (17-18 years old) from six different secondary schools in Valencia (Spain) and 99 first-year undergraduate students of Chemistry and Pharmacy degrees at the University of Valencia (19-20 years old). In the light of the obtained results, the main misconceptions observed are: to attribute macroscopic properties to particles; incorrect prediction of boiling points; to perceive ionic compounds as being formed by molecules; misunderstanding the nature of the hydrogen bond and assuming that it is established in any molecule containing hydrogen together with nitrogen, oxygen or fluorine, regardless if the hydrogen atom is directly bonded to these atoms or not; confusing the geometry of a molecule with its distribution of electron pairs around the central atom; and, finally, a wrong prediction of the polarity of molecules. Suggestions that could be accommodated in normal classrooms, are made in order to improve learning.***

Keywords— misconceptions, chemical bonding, secondary school, undergraduate level

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1. INTRODUCTION

It is well known that during the learning process, students construct new knowledge from their previous ideas, skills and experience. Sometimes the students' ideas are not consistent with scientific conceptions and, then, misconceptions, alternative frameworks or preconceptions account. All of them negatively affect the learning and make difficult to build new concepts consistent with the accepted scientific ideas. Therefore, it is highly desirable to precisely know them for an effective teaching methodology.

One of the most powerful and productive ideas in chemical education is the fact that chemical knowledge can be generated, expressed and taught at three levels, known as macroscopic, sub-microscopic and symbolic. The macroscopic level includes the observable properties or facts that students may face in their daily lives. The sub-microscopic level includes particles (electrons, atoms, ions and molecules) and their interactions (chemical bonds and chemical reactions). The symbolic level represents the chemical processes in terms of formulas and equations. These levels are interrelated, so that the students' knowledge of each of these levels is very important to clearly understand the chemical processes (Nakhleh, 1992; Treagust et al., 2003).

However, it has been reported that not making a proper connection between these three levels leads to one of the most important reasons for the misconceptions of students (Johnstone 1982, 1993 and 2000; Nakhleh, 1992). Research of Treagust and Chandrasegaran (2009) shows that by using an alternative instructional programme designed to enhance secondary students' competence in the triplet relationship, is possible to achieve more meaningful learning of chemical representations.

The chemical concepts involving bonds between atoms and/or molecules are enough abstract and far apart from the daily experience which may explain the difficulties of understanding. These difficulties are an important source of misconceptions that must be minimized, as much as possible, given the crucial importance of the chemical bond concept in order to successfully address the study of other areas of chemistry such as chemical reactions, structure of matter, organic compounds, proteins, polymers, etc…

Up today, literature provides extensive and relevant research on students' misconceptions related to chemical bonding (Özmen, 2004). Among others, it should be worthwhile to mention the following studies in chronological order:

- Those where students cannot differentiate ionic and covalent bonding (Butts and Smith, 1987; Taber, 1994, 1997 and 2002; Boo, 1998; Tan and Treagust, 1999; Barker and Millar, 2000; Nicoll, 2001; Coll and Treagust, 2003; Kind, 2004; Othman et al., 2008; Ünal et al., 2010; Luxford and Bretz, 2013; Vladusic et al., 2016).
- Those where students poorly understand the electrostatic nature of the chemical bond (Taber 1997 and 2002; Boo, 1998; Taber et al., 2012).
- Those with misconceptions about the polarity of molecules and, also, on the geometry of molecules (Peterson and Treagust, 1989; Peterson et al., 1989; Furió and Calatayud, 1996; Birk and Kurzt, 1999; Nicoll, 2001 and 2003; Uyulgan et al., 2014).
- Those where students confuse intra- and intermolecular forces (Peterson and Treagust, 1989; Peterson et al., 1989; Tan and Treagust, 1999; Birk and Kurzt, 1999; Barker and Millar, 2000; Taber, 2002; Kind, 2004; Tarhan et al., 2008; Othman et al., 2008; Schmidt et al., 2009; Ünal et al., 2010; Vladusic et al., 2016).
- Those presenting misconceptions on melting and boiling points or on solubility and electrical conductivity of substances (Tan and Treagust, 1999; Othman et al., 2008; Schmidt et al., 2009; Ünal et al., 2010; Smith and Nakhleh, 2011; Cooper et al., 2013).
- Those where sometime students attribute macroscopic properties to particles, mixing two different levels of knowledge (Nicoll 2001 and 2003; Furió-Más et al., 2007; Othman et al., 2008; Treagust and Chandrasegaran, 2009).

For all these reasons, Nahum et al., (2007 and 2010) have analysed how the chemical bond is taught and have underlined those aspects of the traditional teaching that can contribute to the difficulties in learning. Consequently, they proposed a new approach to teach chemical bond in accordance with actual scientific and pedagogical knowledge.

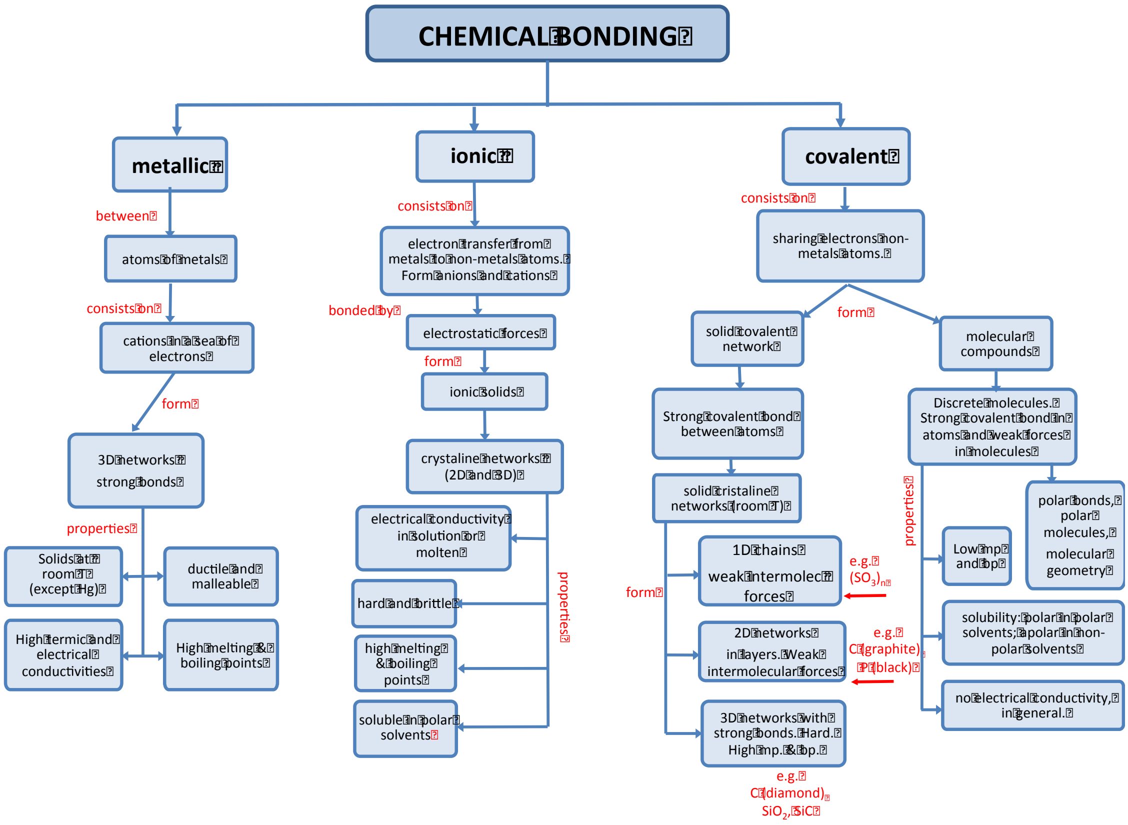
The aim of the present work is to detect and analyse the misconceptions of students regarding macroscopic and sub-microscopic levels, focusing our attention on colour, boiling points, conductivity and solubility, intra- and intermolecular forces and geometry and polarity of molecules. Furthermore, the study also pretends make a comparison between students coming from two different levels of education: last-year of secondary school and first-year undergraduate of university. Knowledge of misconceptions can help teachers to develop new teaching strategies in order to students could overcome them adequately and, also can serve for planning matters and curriculum.

2. METHODOLOGY

A questionnaire with 15 multiple choice items based on a list of misconceptions provided both from literature and from a conceptual map, has been used (see below). The questionnaire was created and tested by three experienced chemistry teachers and it is composed by some questions simple-tier type with four answers being only one of them correct (1, 2, 10, 11), and some others are two-tier multiple-choice questions, formed by two parts: one including two or three answers to select, and a second part with four possible reasons to argue the chosen response (3-9, 12-15). In these cases, students must select an answer and a reason from each part of the item.

Specifically, the conceptual areas examined in each item of the abovementioned questionnaire are as follows: colour (1); boiling points (2, 3); solubility and conductivity (4-6); intra- and intermolecular forces (7-11) and geometry and polarity of molecules (12-15). All these concepts analysed in the present work form part of the more extensive conceptual map on chemical bonding shown in Scheme 1. This scheme includes part of the contents of the curriculum of both levels studied in the present work.

The test was administered to 79 students of second year of bachelor degree coming from six high (secondary) schools of Valencia (Spain). and to 99 first-year undergraduate students at the University of Valencia (53 from Pharmacy degree and 46 from Chemistry degree). In all cases, the questionnaire was applied after the chemical bond lessons had been taught. These lessons are explained during four weeks at 4 hours/week, in the secondary school, and during weeks at 3 hours/week for undergraduate students. Both groups eight are comparable given that all the questions refer to basic concepts that are explained and/or revised in both academic levels. Both groups of students completed the test in less than sixty minutes, regardless of their respective backgrounds.



Scheme 1: Conceptual Map on Chemical Bonding

3. RESULTS AND DISCUSSION

Firstly, we show and compare the results obtained for each item as the percentage for each choice attained for secondary school students and for first-year university students. Secondly, an exhaustive analysis of figures for each question is given in order to emerge what is/are the reasons for the alternative frameworks or difficulties. The analysis has been grouped and discussed in five categories or subsections: (a) colour, (b) boiling points, (c) solubility and conductivity, (d) intra- and intermolecular forces and (e) geometry and polarity of molecules.

3.1 Colour

Item 1. *Chlorine is a yellowish-green gas. This is due to:*

1. Chlorine molecules are yellowish-green and, then, chlorine gas has the same colour.
2. The yellowish-green colour is a physical property of chlorine gas, and is due to interactions between their molecules at 1-atm pressure and 25 °C.
3. Chlorine atoms are yellowish-green and, then, chlorine gas has the same colour.
4. None of the above statements is correct.

Item 1 reveals that one of the characteristic ideas of the corpuscular model of many students consists on attribute properties of the macroscopic world to microscopic particles (Johnstone, 1982; Nakhleh, 1994; Nicoll, 2001; Kind, 2004).

As can be seen in Figure 1a, only a 32.9 % of high school students and a 51.5% of first-year undergraduates correctly answer the item 1, indicating that the yellowish green chlorine gas is due to a physical property of the substance. In relation with the wrong answers, an 8.9% of high school students attribute the colour to the atoms or to molecules atom versus a 15.2% of college students who says that colour is a property of molecules. It is also very striking the percentage of students choosing that none of the provided statements is correct, a 17% in high school compared to 46% in college students. These results suggest that students do not distinguish between the meaning of the Cl symbol, which represents an element of the periodic table, and the Cl_2, which represents a molecule and also the chlorine substance. Therefore, an extrapolation of the macroscopic properties of matter to the submicroscopic level is clearly warned, as also found by other authors in other countries. In this sense, Treagust and Chandrasegaran (2009) observed that a 31% of high school students attributed the blue colour to individual ions Cu^{2+} instead to the aqueous solution of copper sulphate(II). Also Othman et al. (2008) found that a 54% of grade 10 students said that a sulphur atom has the same physical properties as a sample of sulphur. One reason could be that teachers do not give particular emphasis to connect the three levels: macroscopic, submiscroscopic and symbolic language, which can lead to the difficulty in distinguishing elements and substances (Johnson 2000 and 2002; Furió and Dominguez, 2007).

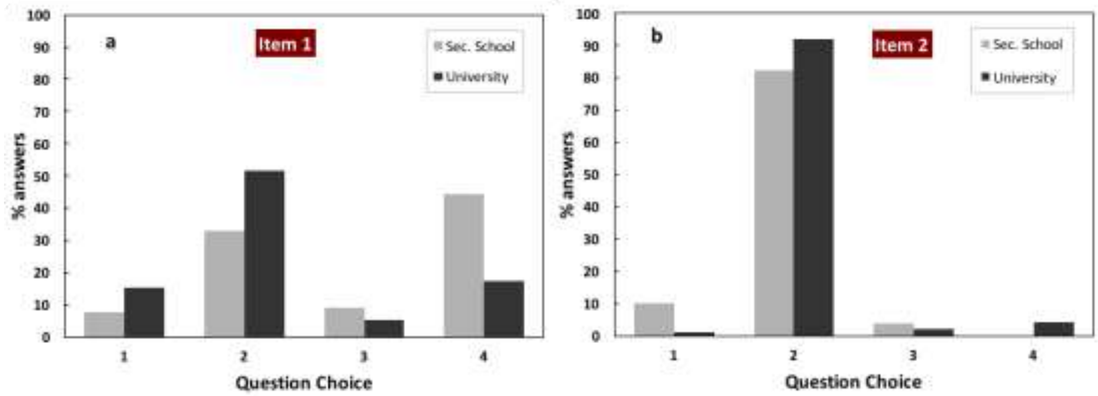


Figure 1: Comparison of Answers given by Students from Secondary School and First-year University to Item 1 (part a) and Item 2 (part b)

3.2 Boiling Points

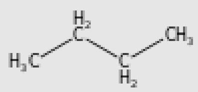
Item 2. *The boiling point of water is 100 °C. This fact is interpreted as:*

1. The water molecule has a boiling point of 100 °C at 1-atm pressure.
2. The water, a liquid substance at room temperature, has a boiling point of 100 °C at 1-atm pressure.
3. The ice has a boiling point of 100 °C at 1-atm pressure.
4. None of the above statements is correct.

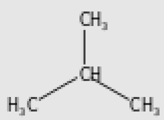
As seen in Figure 1b, the majority of both type of participants correctly answered item 2 about the boiling point of water: an 82.3% of high school and a 91.9% of undergraduates, respectively. However, there are still a 10% of students that attributed macroscopic properties to particles.

However, students have a great difficulty in predicting the boiling points of simple organic compounds as Cooper et al. (2013) pointed out for organic chemistry students that were not able to relate structure and properties. In this sense, item 3 appears as more complex since refers to the boiling point of organic compounds.

Item 3. *Which of the following organic compounds has the highest boiling point?*



***a)** Butane*



***b)** Methylpropane*

Reason:

1. Methylpropane, since it is branched and the Van der Waals forces between molecules are more intense.
2. Methylpropane, since it has higher molar mass and the Van der Waals forces between molecules are more intense.
3. Butane, since being a straight chain possess a greater contact surface, the molecules can get closer, and the Van der Waals forces are more intense.
4. Both have the same boiling point because both have the same molar mass.

In contrast to item 2, a lower percentage of students select butane compound as correct answer for item 3, revealing a major difficulty with organic compounds as said before. Specifically, the percentage of correct answer was a 44.3% for high school students and a 66.7% for first-year college, as can be seen in Figure 2a. Surprising and concernedly, one out of three of high school students believe that if a compound possesses ramifications the Van der Waals forces will be more intense. Furthermore, another important misconception observed in this item is to associate more intense Van der Waals forces at higher molar masses (8% in high school versus 23% in undergraduates).

In the proposed question, both compounds (butane and methylpropane) have the same molar mass, and then, a 12.7% of high school students answer that both will have the same boiling point. As a summary, these results evidenced two misconceptions, one is that the Van der Waals forces only depend on one factor: molar mass; and other, is that the presence of branches in an organic compound can prevent the Van der Waals forces to become fully effective. The obtained results are in agreement with those reported by Schmidt et al. (2009), who indicated that only a few percentage of students use properly the scientific model to predict boiling points of simple organic compounds.

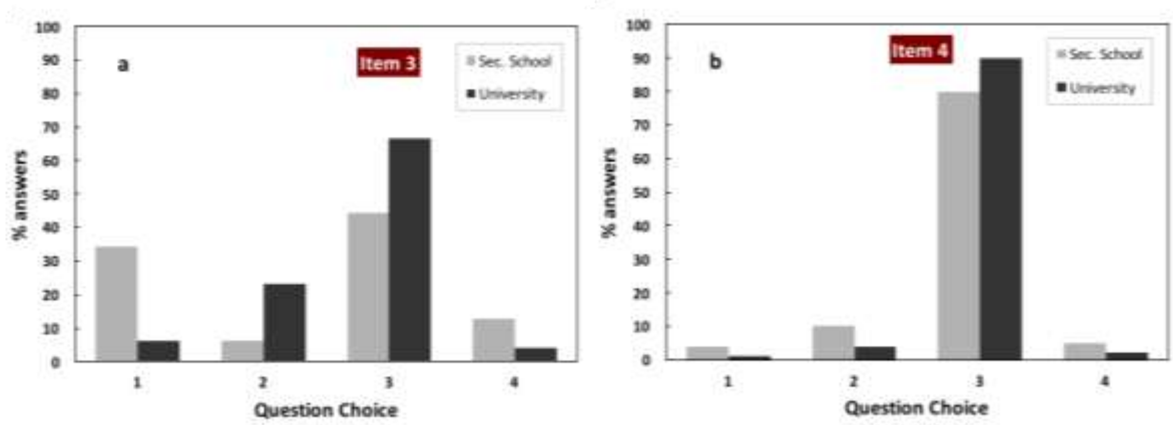


Figure 2: Comparison of Answers given by Students from Secondary School and First-year University to Item 3 (part a) and Item 4 (part b)

3.3 Solubility and Conductivity

Item 4. *The compound sodium iodide can be dissolved in:*

a) *polar solvents as water* ***b)*** *nonpolar solvents* ***b)*** *whatever solvent*

Reason:

1. It does not dissolve in water, because is a network with covalent bonds between sodium and iodine atoms.
2. It dissolves in nonpolar solvents, since sodium transfers its valence electron to iodine to form a molecule of NaI.
3. It dissolves in water, since consists of a network of ions. The Na^+ cations are attracted to the negative side of the dipole of water molecules and I^- anions to the positive, weakening the ionic bonds and dissolving.
4. NaI is soluble in both polar and nonpolar solvents because it is an instantaneous process.

Fortunately, for item 4 a large number of students (80% from high school and 90% from fist year university) guess that NaI dissolves in polar solvents such as water and also choose the right reason (a.3), since this compound is a habitual example used in classrooms. These figures are quite good, but still a 10% of high school students continue associating the solubility, a macroscopic property to the molecules (see Figure 2b).

Item 5. *The statement "the compound sodium chloride (NaCl), molten or in solution, conducts electric current", is:*

a) *True* ***b)*** *False*

Reason:

1. The NaCl solid has fixed electrons in its bonds. When it is melted or dissolved, electrons are free and conduct electricity.
2. The NaCl molecule, melted or in solution, dissociates into a sodium ion and a chloride ion which are the conductors of the electric current.
3. The NaCl solid, melted or in solution, dissociates into sodium ions and chloride ions which are moving charges and then, conduct electric current.
4. NaCl is a molecular substance containing molecules which melted or in solution does not conduct electricity.

Results in Figure 3a for the item devoted to electrical conductivity of sodium chloride, shows that only one out of two of high school students (46.8%) in contrast with the 74.7% of undergraduates give the correct answer and reason (a.3), evidencing that after one year of going deeper in chemical bonding topic, students get better marks and their alternative conceptions diminish. A striking 22% of high school students and a 13% of university undergraduates still indicate that

NaCl has fixed electrons in the bond and when melted or dissolved, these electrons are free to move and to conduct electricity, as also observed by Furió et al. (2007) or Othman et al. (2008).

In this case students directly transfer the electrical conductivity model of metals to ionic compounds, believing that electrons are transferred first and then they become like a "sea of electrons" (Taber, 2003; Luxford and Bretz, 2013). In third place, high school students and undergraduates are almost equal (14%-11%) in assigning the conductivity to the sodium chloride molecule. In this case, a double mistake is produced. In one hand, they attributed macroscopic properties to particles, and on the other, indicating that NaCl contains molecules instead of ions. Regarding the last reason, only high school students (15.2%) answered that NaCl is a molecular substance and does not conduct. Therefore, after one year more of tuition, university students recognize the sodium chloride as being an ionic compound, which is a great achievement.

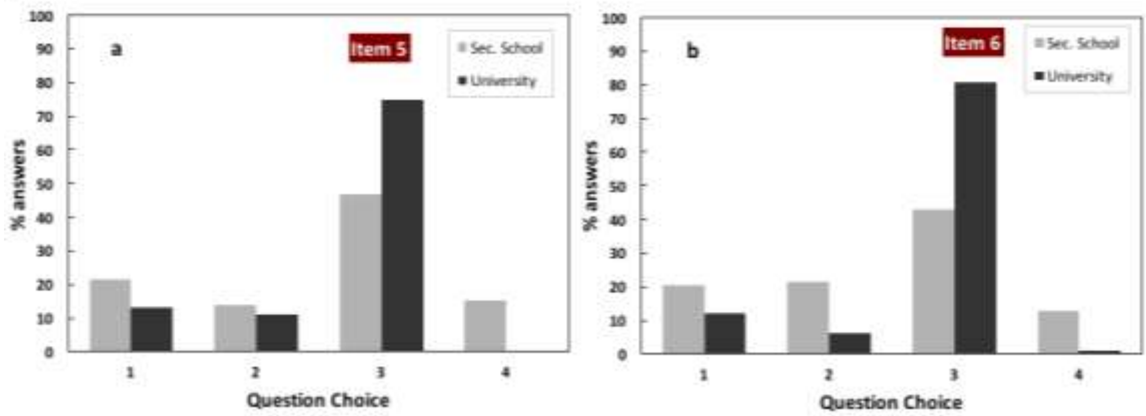


Figure 3: Comparison of Answers given by Students from Secondary School and First-year University to Item 5 (part a) and Item 6 (part b)

In summary, the misconception that ionic compounds contain molecules is detected in both items 4 and 5, as many researchers have found (Butts and Smith, 1987; Taber, 1994 and 2002; Boo, 1998; Tan and Treagust, 1999; Barker and Millar, 2000; Coll and Treagust, 2002; Othman et al., 2008; Smith and Nakhleh, 2011), although the trend is minimizing. One of the factors that contribute to this misconception could be the way as teachers illustrate the formation of an ionic bond. Usually, this process is depicted or described as a sodium atom transferring an electron to a chlorine atom, forming the respective ions attracted by electrostatic forces. Therefore, the student can incorporate the image of a discrete unit of sodium chloride. This fact could be avoided if teachers established a relationship between the formation of ionic bonds and ionic lattices.

Item 6. *What substance is a conductor of electric current?*

a) graphite *b) diamond*

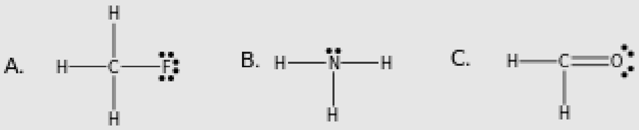
Reason:

1. Graphite, because its structure consists of layers of hexagonal rings of carbon atoms bonded by Van der Waals forces. These forces are responsible of the electrical conductivity.
2. Graphite, because the layers of hexagonal rings of carbon atoms can slide over each other explaining the conductivity.
3. Graphite, because its structure consists of layers of hexagonal carbon rings where each carbon atom is bonded to three others by covalent bonds and delocalized electrons. The mobility of electrons in the layers is responsible of electrical conductivity.
4. Diamond, because is a three-dimensional network with covalent bonds between carbon atoms. The electrons are free and can conduct electrical current.

Item 6 is devoted to the electrical conductivity of covalent substances as the two allotropes of carbon, graphite and diamond. As can be seen in Figure 3b, the percentages obtained for the correct answer and reason (a.3) in both groups of students is quite different: a remarkably low value of 43% for high school students versus a 80.8% achieved by university students that know the correct reason. Regarding the wrong reasons, a 20.3% vs. 12.1%, believe that graphite's conductivity is due to the Van der Waals forces; whereas a 21.5% vs. 6.1%, think that the sliding of the layers is the responsible of conductivity. This last misconception could be attributed to the idea of movement (of electrons or ions) here imputed to layers, in agreement with results found by Tan and Treagust (1999) and Ünal et al. (2010). Finally, a 13% of high school students answered that diamond conducts electrical current due to the free electrons in the covalent network. This incorrect answer could be due to confusion between both types of networks of graphite and diamond given that are superficially taught in secondary education (Ünal et al., 2010). Fortunately, and making the difference, almost no college students gave this answer.

3.4 Intra- and Intermolecular Forces

Item 7. *Which of the following compounds present hydrogen bonds between their molecules?*



Reason:

1. A, since there are H and F atoms in the same molecule.
2. C, since there are H and O atoms in the same molecule.
3. B, since nitrogen is bonded to hydrogen in the molecule.
4. All three molecules present H-bonds given that the condition to form H-bonds is a molecule having H atoms plus atoms of N, or O or F.

Item 7 is devoted to the prediction of formation of hydrogen bonds (H-bonds) in some molecules. As seen in Figure 4a, the correct answer and reason (B.3) is chosen by a 63.3% of high school students and by a 80.8% of college undergraduates. However, almost a 20% of both groups of students, indicate the existence of H-bonds in the three proposed compounds due to the presence of N, F, O atoms together with H atoms in the molecules. They do not mind if H atoms are or not directly bonded to the others highly electronegative atoms (N, O or F), denoting that some students do not understand how a hydrogen bond is formed. Other authors have found similar results in similar molecules. Concretely, Schmidt et al. (2009) pointed out that high school students said that dimethylether formed H-bonds because had oxygen atoms, but not the HF or CH_3F. Other study carried out by Tarhan et al., (2008) with 9th-grade students' revealed that they believe that any molecule containing hydrogen atoms can establish H-bonds.

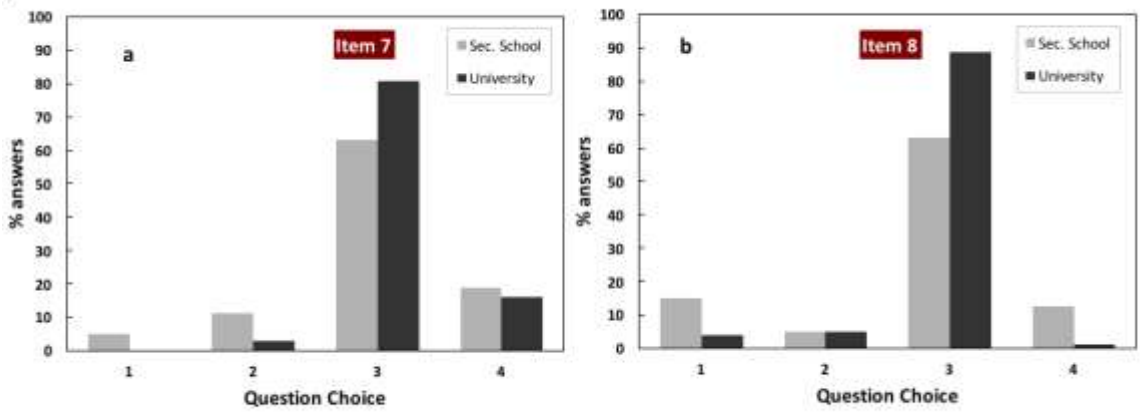


Figure 4: Comparison of Answers given by Students from Secondary School and First-year University to Item 7 (part a) and Item 8 (part b)

Item 8. *Which of the following compounds possess the strongest hydrogen bonds?*
A) *CH_3CH_2OH* ***B)*** *$CH_3CH_2NH_2$*

Reason:

1. B, because nitrogen is more electronegative than oxygen.
2. A, because its molar mass is higher.
3. A, because oxygen is more electronegative than nitrogen.
4. B, because contains more hydrogen atoms.

Regarding the intensity of the hydrogen bonds, satisfactorily, a great percentage of university students answer correctly (90%), as it is revealed in Figure 4b. On the contrary, only a 63.3% of high school students points out that H-bonds in ethanol will be more intense because the oxygen atom is more electronegative than the nitrogen one. The two main mistakes made by secondary school students are: i) saying that N atom is more electronegative than O in the ethylamine (a 15.2% of answers); and ii) attributing the H-bond strength to the quantity of H atoms in the molecule (another 12.7% of answers).

Item 9. *For which of these substances, their covalent bonds should be broken at the boiling point?*
A) *iodine* ***B)*** *diamond*

Reason:

1. A, because is a molecular substance with covalent bonds between iodine atoms.
2. B, because is a molecular substance with covalent bonds between carbon atoms.

3. A, because is a covalent substance with covalent bonds between iodine atoms.
4. B, because is a covalent solid with covalent bonds between carbon atoms.

Issue 9 pretends to highlight whether students are able to clearly differentiate between intra- and intermolecular forces and, at the same time, distinguish between molecular and covalent substances. As seen in Figure 5a, only a 43% of high school students and a 69.7% of college ones correctly indicates that covalent bonds should be broken at the boiling point in diamond because is a covalent solid with covalent bonds between the carbon atoms (b.4). Obviously, in the hypothetical case that diamond could arrive to boil. Moreover, a worrying 34.2% of secondary school students and a 19.2% of first-year university answer that iodine (molecular substance) breaks the covalent bonds between atoms of iodine. This result reflects very clearly that students mix and confuse easily the concepts of intra- (the covalent bonds between the atoms of the molecule) and intermolecular forces (the only ones broken at the boiling point). It is also noted that another 15.2% of high school students propose iodine as a covalent substance with covalent bonds between atoms of iodine. In this case, the confusion is produced between molecular substances with only intramolecular covalent bonds and substances forming covalent networks with both intra- and intermolecular covalent bonds. After almost thirty years, our results are very similar to those obtained by Peterson et al. (1989) with grade-11 grade-12 students. One of the probably reasons may lie in the fact that textbooks or teachers not insist enough on highlighting the difference between the two pairs of concepts: intra- vs. intermolecular forces and molecular vs. covalent compounds.

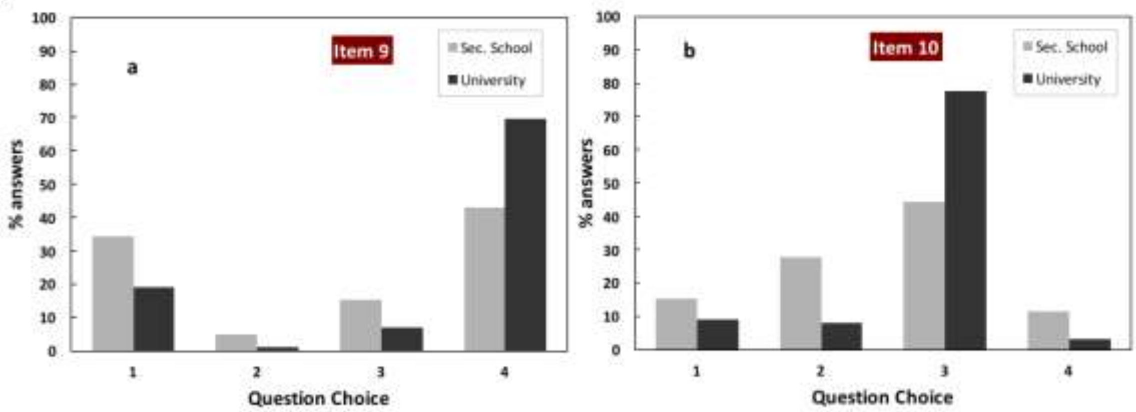


Figure 5: Comparison of Answers given by Students from Secondary School and First-year University to Item 9 (part a) and Item 10 (part b)

<u>Item 10</u>. *For the HF substance, which of the following statements is correct?*

1. HF is an ionic substance since the difference in electronegativity of H and F atoms allows establishing and ionic bond.
2. HF is a covalent substance since consists of two non-metallic elements bonded by sharing electrons.
3. HF is a molecular substance with covalent bonds between their atoms, and Van der Waals forces and H-bonds between their molecules.
4. None of the above statements is correct.

Figure 5b shows the results obtained for item 10 related to the type of substances according to their intra- and intermolecular forces. As seen, again only a 44.3% of high school students answers adequately, in contrast to a 77.8% in the case of university ones. Strikingly, a 28% of secondary students and only an 8% of undergraduates indicate that HF is covalent as is formed by two non-metals that share electrons. This misconception is quite common and it is focused only on intramolecular bonds without paying attention to the bonds between molecules, what finally leads to incorrectly classify the type of substance. Another typical and wrong criterion used to classify substances is through the difference in the electronegativity of their constitutive atoms (15.2% of high school and 9.1% of university students). Finally, an 11.4% of secondary school students are not able to discern the kind of substance according to the present bonds.

<u>Item 11</u>. *For the SiO_2 substance, which of the following statements is correct?*

1. SiO_2 is a molecular substance since it consists of two non-metallic elements linked by covalent bonds.
2. SiO_2 is a covalent substance since it consists of two non-metallic elements linked by covalent bonds.
3. SiO_2 is an ionic substance due to the difference in electronegativity between Si and O atoms that establish an ionic bond.
4. None of the above statements is correct.

As seen from Figure 6a, results are quite similar to those observed in the previous issue. A 50.6% of high school students and a 68.7% of university undergraduates selected the correct answer: SiO_2 is a covalent substance with covalent bonds between silicon and oxygen atoms forming a three-dimensional solid network. Once again, a concerning 29% of high school students and a 17.2% of first-year university, make the misconception of pointing out that SiO_2 is a molecular compound given that the bonds between atoms are covalent. In this particular case, the misconception could be attributed to the fact that students compare the chemical formulas for SiO_2 and CO_2, and then, imagine molecules in both cases.

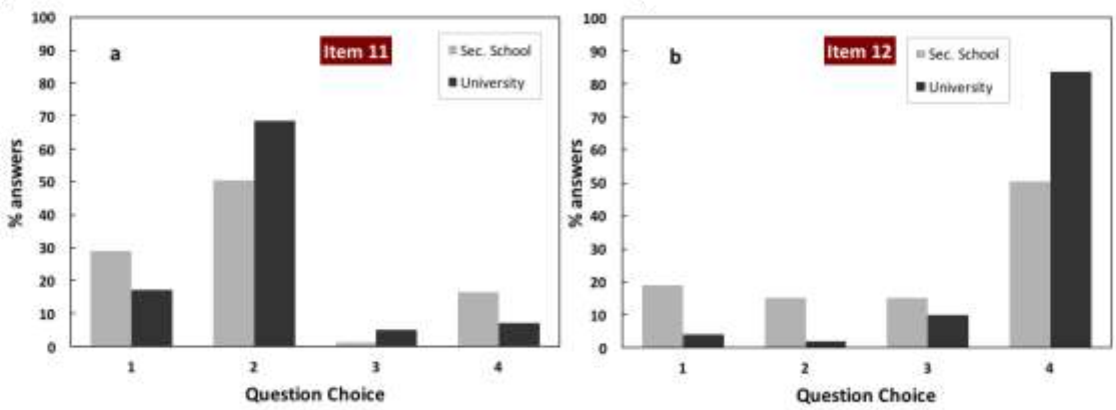


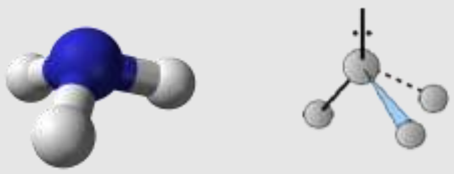
Figure 6: Comparison of Answers given by Students from Secondary School and First-year University to Item 11 (part a) and Item 12 (part b)

In summary, items 9-11 reveal a great difficulty for students, especially those coming from high school, to distinguish a covalent compound from a molecular one.

3.5 Geometry and Polarity of Molecules

The following items (12-15) are devoted to find out and compare the misconceptions of students in relation with geometry of molecules, and as a consequence, with their polarity.

Item 12. *Which of the following symbolic representations describes the geometry of the ammonia molecule?*



A ***B***

Reason:

1. B, because 4 pairs of electrons are located around the central atom.

2. A, because the polarity of the N-H bonds determines the shape of the molecule.

3. A, because the shape of the molecule is the spatial arrangement of the atoms around the central atom.

4. B, because the shape of the molecule is determined by the electron pairs, both lone and bonded.

In relation with geometry and their symbolic representation, we obtained shocking and surprising results as can be seen in Figure 6b. Note that a very large percentage of both groups of students, answer incorrectly, but even worse in the case of the students coming from first-year university degrees (Chemistry and Pharmacy). Concretely, a 50.6% and an 83.8%, respectively, attributed the shape of a molecule to the geometrical distribution of bonded and lone electron pairs, and for this reason wrongly selected the B.4 option. However, although the distribution of electron pairs around the central atom is a determining factor of the geometry, the misconception lies in the subtle fact of identifying the shape of the molecule (symbolically depicted with ball and stick model by drawing A) with the spatial arrangement of electron pairs (drawing B).

Other two different misconceptions are observed: i) molecular shape attributed to the number of electron pairs (19% of high school students); and ii) molecular shape attributed to the polarity of the N-H bonds (a 15.2% of high school students). Finally, it is very worrying that only a 15.2% of high school students and a 10.1% of college ones properly know that the shape of the molecule is the geometric or spatial arrangement of atoms around the central atom.

Unfortunately, our results are also in agreement with other researchers that have pointed out the existence of the abovementioned difficulties. For instance, the misconception that the shape of molecules is determined only by repulsion either of lone electron pairs or bonded electron pairs have been reported by Peterson and Treagust (1989) and Birk and Kurzt (1999). Furió and Calatayud (1996) pointed out that students usually identify the electron pairs arrangement with the shape of molecule. In addition, it has also found that molecular shape is determined by the bond polarity (Peterson and Treagust, 1989); Nicoll, 2001 and Cooper et al. 2013).

It is important to note that, most of general chemistry textbooks, explain the molecular geometry through the VSEPR theory, and, usually depict the shape of a molecule with a symbolic drawing make with lines and dots representing the electron pairs distribution around the central atom. This method could be a possible explanation for the observed difficulties in predicting the geometry of a molecule.

Item 13. *What molecule is non-polar?*

A) *CF_2Cl_2* ***B)*** *BCl_3*

Reason:

1. A, since presents tetrahedral geometry that provides a symmetrical distribution of the bond dipole moments. These are cancelled and the total dipole moment is zero.
2. B, since presents tetrahedral geometry that provides a symmetrical distribution of the bond dipole moments. These are cancelled and the total dipole moment is zero.
3. A, since presents trigonal bipyramidal geometry that provides a symmetrical distribution of the bond dipole moments. These are cancelled and the total dipole moment is zero.
4. B, since presents trigonal planar geometry that provides a symmetrical distribution of the bond dipole moments. These are cancelled and the total dipole moment is zero.

As seen in Figure 7a, a poor percentage of high school students, 43%, and a 78.8% of college ones chose properly the non-polar substance and the reason, that is, BCl_3 due to its trigonal planar geometry and symmetrical dipole moments distribution. The erroneous selection with a major percentage of answers was A.1 (21.5% of high school students and 15.2% of university one) what indicates that students believe that tetrahedral geometry is necessary and sufficient to cancel the individual dipole moments regardless of the chemical nature of the atoms bonded to the central atom, as also reported by Furió and Calatayud (1996).

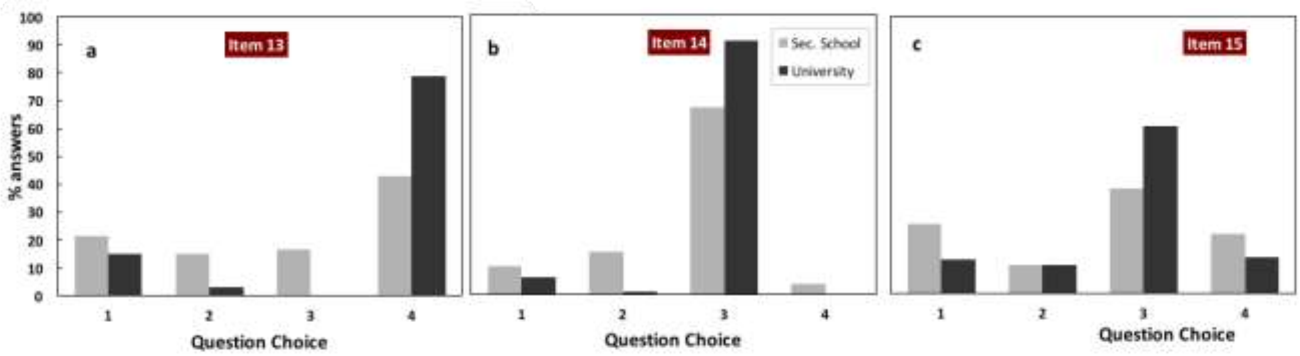


Figure 7: Comparison of Answers given by Students from Secondary School and First-year University to Item 13 (part a), Item 14 (part b) and Item 15 (part c)

Item 14. *What molecule is non-polar?*

A.  B. 

Reason:

1. B, given that the two lone electron pairs are balanced and the resultant dipole moment is zero.
2. B, since presents linear geometry providing a symmetrical distribution of the bond dipole moments. These are cancelled and the total dipole moment is zero.
3. A, since presents linear geometry providing a symmetrical distribution of the bond dipole moments. These are cancelled and the total dipole moment is zero.
4. A, since the four bonds adopt tetrahedral geometry and symmetry so that all bond dipole moments are cancelled.

Regarding the polarity of CO_2 and H_2S, Figure 7b points out that a 67% of secondary school and a very satisfactory 91% of university students correctly indicate that the CO_2 is nonpolar due to its linear geometry that provides a symmetrical distribution of the individual dipole moments that leads to a null total dipole moment. Fortunately, the observed misconceptions are, quantitatively speaking, quite low: a 10% of high school students believe that H_2S is apolar as a consequence of the balance of the two lone electron pairs; a 15% of high school students identify the planar Lewis structure of H_2S with the shape of the molecule saying that presents linear geometry and as a result the total dipole moment should be zero by symmetry, as also pointed out by Furió and Calatayud (1996); and, finally, a negligible percentage of students considered the molecule of CO_2 to be not linear, in according to the reported by Nyachwaya et al. (2011).

Item 15. *According to the symbolic representation of the molecule, the XeF_4 is?*
***A)** polar* ***B)** apolar*

Reason:

1. It is polar because the existence of lone electron pairs leads to a total dipole moment different from zero.
2. It is polar because its square-plane geometry does not allow the bond dipole moments to be cancelled.
3. It is apolar because its square-plane geometry leads to a symmetrical distribution of the bond dipole moments that cancel each other being the total dipole moment equal to zero.
4. It is apolar because the six electron pairs adopt octahedral geometry and symmetry so that all bond dipole moments are cancelled.

Based on the symbolic representation of the distribution of lone and bonded electron pairs around the central atom, students answer adequately in a very low and worrying percentage, a 38% in the high school group; and roughly the double, a 60.6%, for the college sample (see Figure 7c). Again, the results highlight the above mentioned misconceptions: i) assign a total dipolar moment by the mere presence of lone electron pairs, a 25.3% in secondary education vs. 12.1% in undergraduates (see also Peterson et al. 1989; Furió and Calatayud, 1996); and ii) attribute octahedral geometry because there are six electron pairs around the central atom, regardless if are bonded or lone pairs (21.5% vs. 13.1%).

In order to summarize and better compare the results obtained for both groups of students, Figure 8 shows the percentage of participants who correctly answered each item of the proposed questionnaire.

As can be seen, in general after one year of tuition at the university, students get better results for the questionnaire than those obtained by high school students, with an exception in item 12 where the trend of the data was exchanged. These data evidenced that go back and repeat at first year of university some contents with special difficulty as chemical bond, is a good strategy, despite of some teaching ideas that promote that contents should not be repeated. However, in both populations, the lower results or the main misconceptions were observed for items 1, 3, 5, 6, 9-12 and 15, meaning that much more effort has to be done in teaching them. It is also worth mentioning that the percentage of students who do not answer any of the items is quite low, particularly in secondary 4% and a low 1% in college. This fact shows that students generally prefer to answer above all, even if not being completely sure of the answer.

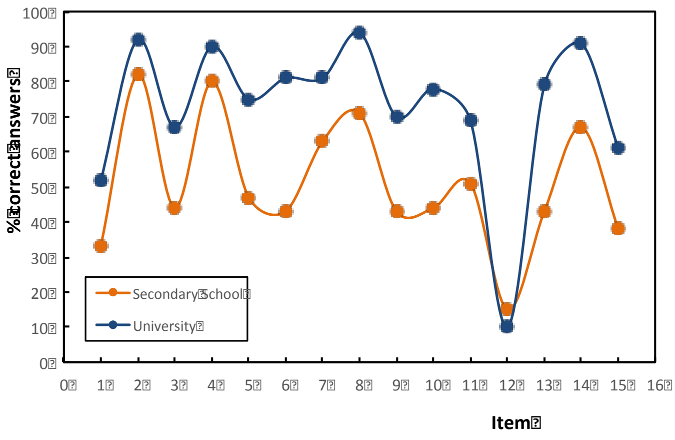


Figure 8: Comparison of Percentages of Correct Answers given by Students from Secondary School and First-year University to the Questionnaire

Finally, as a summary, Table 1 lists all the found misconceptions that reached at least an 8% of responses in whatever group of students, specifying the item where appeared. The wrong statements are grouped in the same categories as discussed: (a) colour, (b) boiling points, (c) solubility and conductivity, (d) intra- and intermolecular forces and (e) geometry and polarity of molecules.

Table 1. Misconceptions, item and percentages obtained for both groups of participants (*n* is the number of students)

Misconceptions	**Item**	**Secondary School** (*n*= 79)	**University** (*n*= 99)
Colour			
1. The yellowish green colour of chlorine is due to chlorine atoms.	1	8.5	0.0
2. The yellowish green colour of chlorine is due to the chlorine molecules.	1	8.5	15.2
Boiling Points			
3. The water molecule has a boiling point of 100 °C at 1-atm pressure.	2	10.0	0.0
4. Van der Waals forces are more intense in branching organic compounds.	3	34.0	0.0
5. Van der Waals forces are more intense as molar mass increases.	3	8.0	23.0
Solubility and Conductivity			
6. The NaI molecules can be dissolved in nonpolar solvents.	4	10.0	0.0
7. NaCl solid, molten or in solution, has free electrons that conduct electricity.	5	22.0	13.0
8. NaCl molecule, molten or in solution, dissociates into a sodium ion and a chloride ion which are the conductors of the electric current.	5	14.0	11.0
9. Graphite conducts electricity because the layers of hexagonal carbon rings can slide over each other.	6	22.0	0.0
10. Graphite conducts electricity because the layers of hexagonal carbon rings are bonded by Van der Waals forces.	6	20.0	12.0
11. Diamond conducts electricity because is a three-dimensional network with covalent bonds between carbon atoms. Electrons are free and can conduct electrical current.	6	13.0	0.0
Intra- and Intermolecular Forces			
12. NaCl is a molecular substance.	4	16.0	0.0
13. Hydrogen bonds are formed in compounds having H atoms plus atoms of F, N or O.	7	19.0	16.0
14. H-bonds are stronger in compounds containing nitrogen because its electronegativity is higher than the oxygen one.	8	15.0	0.0
15. H-bonds are stronger in compounds containing more hydrogen atoms.	8	13.0	0.0
16. Iodine is a molecular substance with covalent bonds between iodine atoms that are broken at the boiling point.	9	34.2	19.2
17. HF is a covalent substance since consists of two non-metallic elements bonded by sharing electrons.	10	27.8	8.0
18. HF is an ionic substance since the difference in electronegativity of H and F atoms allows establishing and ionic bond between them.	10	15.2	9.0
19. SiO_2 is a molecular substance since consists of two non-metallic elements linked by covalent bonds.	11	29.0	17.2
Geometry and Polarity of molecules			
20. Identify the arrangement of electron pairs around the central atom with the geometry of the molecule.	12	19.0	0.0
21. Attribute the shape of the molecule to the electron pairs, both lone and bonded.	12	50.6	83.8
22. Bond polarity determines the shape of a molecule.	12	15.2	0.0
23. Assume that tetrahedral geometry is a necessary and sufficient condition to cancel the bond dipole moments regardless of the atoms bonded to the central atom.	13	21.5	15.2
24. Identify the Lewis structure with the shape of the molecule and make wrong predictions of the geometry and polarity of molecules.	14	15.0	0.0
25. H_2S molecule is linear because the two lone electron pairs are balanced and the resultant dipole moment is zero.	14	10.0	0.0
26. All molecules having lone electron pairs are polar.	15	25.3	12.0

4. CONCLUSIONS AND IMPLICATIONS FOR TEACHING

Firstly, throughout the entire questionnaire, underlies a widespread misconception: the fact that students confuse or attribute the macroscopic properties of substances with the properties of the particles, atoms and/or molecules. We believe that this fact is a consequence of mixing the three levels of approximation or explanation of chemical bond: macroscopic, sub-microscopic and symbolic, with which teachers work in everyday lectures. Therefore, teachers should emphasize the relationship between them and the transition between them in order to avoid misconceptions.

Secondly, it would be important to clarify the language used in classrooms to define very precisely the concepts of element, simple substances and compounds. Although these concepts are taught to students in the early years of secondary education, are confused because very often neither the programs nor the textbooks tend to repeat contents that were already explained in lower courses. For instance, the term "element" can refer to an atomic specie characterized by its atomic number. However, some authors (Furió and Dominguez, 2007) are inclined to differentiate "element" as defined above from "simple substance" to refer to substances formed by a unique element, such as oxygen (O2) or ozone (O3). And refer to a "compound" when is formed by two or more different elements, such as carbon dioxide (CO2).

Thirdly, in order to students understand that different substances have different melting and boiling points they need to considered the interatomic and the intermolecular forces that account in the substance as well as the intensity of both. These conceptions also require that students are able to correctly classify the substances according to their types of bonds (ionic, covalent, molecular or metallic), and in the particular case of molecular substances, students must also take into account the possible existence of hydrogen bonds.

Apart from the general classification of substances in metallic, ionic, molecular or covalent networks, teachers should take into account some considerations. For example, when explaining ionic compounds, they must insist and draw the formation of a network and not a single pair of ions, as well as use models of networks that considerably help students to visualize real molecules and substances. Also, it should be necessary to establish a relationship between the formation of ionic bonds and ionic lattices. This would prevent the misconception that ionic compounds are formed by molecules. In the same way, it would also be strongly recommended to show models of covalent networks in classroom and compare them with molecular substances insisting in all types of bonds given in both, which can help to clearly distinguish one from another.

In conclusion, teachers should design new strategies to introduce molecular substances and covalent networks and make clear what kind of forces (intra and inter) lie behind each type of compound.

Moreover, the models used in classrooms to build different molecules, can help to visualize their geometry and to differentiate the distribution of electron pairs from the shape of the molecule. Also is very necessary to insist in the fact that although the geometry of a molecule is determined by the arrangement of the lone and bonded electron pairs around the central atom, the shape is the relative spatial arrangement of atomic nuclei around the central atom. The proper methodology of teaching this topic must be: first, set the structure of Lewis; second, set the distribution of bonded and lone electron pairs and predict the bond angles; and finally, set the geometry as the arrangement of the atomic nuclei around the central atom.

Intimately connected with geometry, are the misconceptions that students present in relation with the polarity of molecules. This topic has been revealed enough difficult for both secondary school and first year undergraduate students. In this regard, two main alternative conceptions were observed: the belief that the mere presence of lone electron pairs in a molecule makes it polar; and the belief that a tetrahedral geometry is a sufficient condition to predict the polarity of a molecule regardless of the chemical nature of the atoms around the central atom. A good way to improve the results related with geometry and polarity could be that geometrical figures or models were, systematically and repeatedly, handled by teachers in everyday classrooms.

Finally, we would like to stress that there are many strategies to improve student understanding about chemical bond. To do that, teachers have to be aware of the more usual misconceptions and at what level, in order to handle and implement new approaches to our teaching.

5. ACKNOWLEDGEMENT

We are deeply grateful to all those who participated in this work: high school and college students, and specially to the teachers of chemistry at the six secondary schools in Valencia (Spain) and university professors of chemistry and pharmacy degrees who administered the questionnaire in their respective classrooms.

6. REFERENCES

[1] Barker, V. and Millar, R. (2000). "Students´ reasoning about basic chemical thermodynamics and chemical bonding: what changes occur during a context-based post-16 chemistry course", *International Journal of Science Education*, 22(11), pp. 1171-1200.
[2] Birk, J.P. and Kurtz, M.J. (1999). "Effect of experience on retention and elimination of misconceptions about molecular structure and bonding", *Journal of Chemical Education*, 76(1), pp. 124-128.
[3] Boo, H.K. (1998). "Students´ understandings of chemical bonds and the energetics of chemical reactions", *Journal of Research in Science Teaching*, 35(5), pp. 569-581.
[4] Butts, B. and Smith, R. (1987). "HSC chemistry students´ understanding of the structure and properties of molecular and ionic compounds". *Research in Science Education*, 17, pp. 192-201.
[5] Coll, R.K. and Treagust, D.F. (2003). "Investigation of secondary school, undergraduate and graduate learners´ mental models of ionic bonding", *Journal of Research in Science Teaching*, 40(5), pp. 464-486.
[6] Cooper, M.M., Corley, M.L. and Underwood, S.M. (2013). "An investigation of college chemistry students´ understanding of structure-property relationships", *Journal of Research in Science Teaching*, 50(6), pp. 699-721.
[7] Furió, C. and Calatayud, M.L. (1996). "Difficulties with geometry and polarity of molecules: beyond misconceptions", *Journal of Chemical Education*, 73(1), 36-41.
[8] Furió-Más, C., Calatayud, M.L. and Bárcenas, S.L. (2007). "Surveying students´ conceptual and procedural knowledge of acid-base behavior of substances", *Journal of Chemical Education*, 84(10), pp. 1717-1724.
[9] Furió, C. and Dominguez, M.C. (2007). "Deficiencias en la enseñanza habitual de los conceptos macroscópicos de sustancia y de cambio químico". *Revista de Educación en Ciencias*, 8(2), pp. 84-91.
[10] Johnson, P. (2000). "Children's understanding of substances, part 1: recognizing chemical change", *International Journal of Science Education*, 22(7), pp. 719-737.
[11] Johnson, P. (2002). "Children's understanding of substances, part 2: explaining chemical change", *International Journal of Science Education*, 24(10), pp. 1037-1054.
[12] Johnstone, A.H. (1982). Macro- and micro-chemistry. *School Science Review*, 64, 377-379.
[13] Johnstone, A.H. (1993). "The development of chemistry teaching: a changing response to changing demand", *Journal of Chemical Education*, 70(9), pp. 701-705.
[14] Johnstone, A.H. (2000). "Teaching of chemistry- logical or psychological?", *Chemistry Education Research & Practice*, 1(1), pp. 9-15.
[15] Kind, V. (2004). Beyond appearances: students´misconceptions about basic chemical ideas, (2nd edition), School of Education, Durhan University.
[16] Luxford, C.J. and Bretz, S.L. (2013). "Moving beyond definitions: what student-generated models reveal about their understanding of covalent bonding and ionic bonding", *Chemistry Education Research & Practice*, 14(2), pp. 214-222.
[17] Nahum, T.L., Mamlok-Naaman, R., Hofstein, A. and Krajcik, J. (2007). "Developing a new teaching approach for the chemical bonding concept aligned with current scientific and pedagogical knowledge", *Science Education*, 91(4), pp. 579-603.
[18] Nahum, T.L., Mamlok-Naaman, R., Hofstein, A. and Taber, K.S. (2010). "Teaching and learning the concept of chemical bonding", *Studies in Science Education*, 46(2), pp. 179-207.
[19] Nakhleh, M.B. (1992). "Why some students don´t learn chemistry: chemical misconceptions", *Journal of Chemical Education*, 69(3), pp. 191-196.
[20] Nakhleh, M.B. (1994). "Students´ models of matter in the context of acid-base chemistry", *Journal of Chemical Education*, 71(6), pp. 495-499.
[21] Nicoll, G. (2001). "A report of undergraduates´ bonding misconceptions", *International Journal of Science Education*, 23(7), pp. 707-730.
[22] Nicoll, G. (2003). "A qualitative investigation of undergraduate chemistry students' macroscopic interpretations of the submicroscopic structures of molecules", *Journal of Chemical Education*, 80(2), pp. 205-213.
[23] Nyachwaya, J.M. Mohamed, A.R., Roehrig, G.H., Wood, N.B., Kern, A.L. and Schneider, J.L. (2011). "The development of an open-ended drawing tool: an alternative diagnostic tool for assessing students' understanding of the particulate nature of matter", *Chemistry Education Research & Practice*, 12(2), pp. 121-132.
[24] Othman, J., Treagust, D.F. and Chandrasegaran, A.L. (2008). "An investigation into the relationship between students' conceptions of the particulate nature of matter and their understanding of chemical bonding", *International Journal of Science Education*, 30(11), pp. 1531-1550.
[25] Özmen, H. (2004). "Some student misconceptions in Chemistry: a literature review of chemical bonding", *Journal of Science Education and Technology*, 13(2), pp. 147-159.
[26] Peterson, R.F. and Treagust, D.F. (1989). "Grade-12 students' misconceptions of covalent bonding and structure", *Journal of Chemical Education*, 66(6), pp. 459-460.
[27] Peterson, R.F., Treagust, D.F. and Garnett, P. (1989). "Development and application of a diagnostic instrument to evaluate grade-11 and -12 students´ concepts of covalent bonding and structure following a course of instruction", *Journal of Research in Science Teaching*, 26(4), pp. 301-314.

[28] Schmidt, H.J., Kaufmann, B. and Treagust, D. F. (2009). “Students' understanding of boiling points and intermolecular forces”, *Chemistry Education Research & Practice*, 10(4), pp. 265-272.
[29] Smith, K.C. and Nakhleh, M.B. (2011). “University students' conceptions of bonding in melting and dissolving phenomena”, *Chemistry Education Research & Practice*, 12(4), pp. 398-408.
[30] Taber, K. S. (1994). “Misunderstanding the ionic bond”, *Education in Chemistry-London*, 31(4), pp. 100−103.
[31] Taber, K. S. (1997). “Student understanding of ionic bonding: molecular versus electrostatic framework?”, *School Science Review*, 78(285), pp. 85–95.
[32] Taber, K.S. (2002). “Chemical misconceptions: prevention, diagnosis and cure. Volume 1: Theoretical background”. London: Royal Society of Chemistry, chapter 8, pp.125-139.
[33] Taber, K.S. (2003). “Mediating mental models of metals: acknowledging the priority of the learner's prior learning”, *Science Education*, 87(5), pp. 732-758.
[34] Taber, K. S., Tsaparlis, G. and Nakiboglu, C. (2012). “Student conceptions of ionic bonding: patterns of thinking across three European contexts”, *International Journal of Science Education*, 34(18), pp. 2843–2873.
[35] Tan, K.C.D. and Treagust, D.F. (1999). “Evaluating students´ understanding of chemical bonding”, *School Science Review*, 81(294), pp. 75-83.
[36] Tarhan, L., Ayar-Kayali, H., Urek, R.O. and Acar, B. (2008). “Problem–based learning in 9th grade chemistry class: Intermolecular Forces”, *Research in Science Education*, 38(3), pp. 285-300.
[37] Treagust, D. F. and Chandrasegaran, A. L. (2009). “The efficacy of an alternative instructional programme designed to enhance secondary students’ competence in the triplet relationship”. In J.K. Gilbert & D.F. Treagust (Eds.), *Multiple representations in chemical education*. Springer Netherlands. (pp. 151-168).
[38] Treagust, D.F., Chittleborough, G. and Mamiala, T. (2003). “The role of submicroscopic and symbolic representations in chemical explanations”, *International Journal of Science Education*, 25(11), pp. 1353-1368.
[39] Ünal, S., Costu, B. and Ayas, A. (2010). “Secondary school students´ Misconceptions of covalent bonding”, *Journal of Turkish Science Education*, 7(2), pp. 4-29.
[40] Uyulgan, M.A., Akkuzu, N. and Alpat, S. (2014). “Assessing the students' understanding related to molecular geometry using a two-tier diagnostic test”, *Journal of Baltic Science Education*, 13(6), pp. 839-855.
[41] Vladusic, R., Bucat, R.B. and Ozic, M. (2016). “Understanding ionic bonding- a scan across the Croatian education system”, *Chemistry Education Research & Practice*, 17(4), pp. 685-699.