

Secondary School Students' Misconceptions of Covalent Bonding

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ABSTRACT

Since chemical bonding subject generally covers abstract concepts, it is one of the difficult subjects for students to understand. Therefore, most students have misconceptions about chemical bonding and its types. The aim of this study is to investigate eleventh grade students' understanding about covalent bonding and to determine their related misconceptions. In the study, a test comprising four open-ended questions and semi-structured interviews were employed to collect data. The test used in the study was administered to 58 eleventh grade students in a public high school. 10 students selected randomly from the sample were also interviewed. *Sound understanding, partial understanding, partial understanding with a specific misconception, specific misconceptions and no response/no understanding* categories were used for analyzing students' responses for both test and interview questions. Results showed that students had many misconceptions especially on *the types or properties of atoms which form covalent bonding, how covalent bonding was formed, the types of covalent bonding, and the characteristics of giant covalent structures*. Study presents some suggestions for teachers, curriculum developers and textbook authors to make students understand the subjects easier and to remediate their misconceptions.

Key Words: Chemistry Education; Covalent Bonding; Students' Understanding; Misconceptions.

INTRODUCTION

Learning is the process of making connections between the new knowledge and the existing ones. In learning process, students construct the new knowledge through their cognitive frameworks, abilities, values and experiences (Nakhleh, 1992; Osborne & Freyberg, 1996). Since students themselves construct the meanings of new knowledge in their mind, they may sometimes differ from the scientifically accepted ones. Students bring their ideas not consistent with scientifically accepted ones into their science class (Osborne & Freyberg, 1996). Students' ideas which are not consistent with scientific conceptions are called with different terms such as misconceptions, preconceptions, alternative frameworks, children's science, spontaneous knowledge, preconceived notions, and factual misconceptions (Nakhleh,

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1992; Colletta & Chiapetta, 1989). Although students' conceptions are not consistent with scientifically accepted ones, they are deeply settled down in students' cognitive structure since they are reasonable for them (Gilbert et al., 1982). These non-scientific conceptions negatively affect students' further learning and hinder students from the new constructions which are consistent with scientifically accepted ideas (Gilbert and Watts, 1983; Griffiths & Preston, 1999). Therefore, the first step for performing an effective concept teaching is to elicit students' preconceptions, some of which may differ from the scientific ones.

As in the other sciences, it has been known that student misconceptions are also common in chemistry (Tan & Treagust, 1999; Nicoll, 2001). Chemistry courses commonly cover a great number of abstract concepts because chemistry generally deals with the inner structure of the matter. As a consequence, it is more complicated and difficult for students to construct the meanings of chemistry concepts than those of the concepts in other natural sciences (Johnstone, 1982). Chemical phenomena or chemistry concepts are explained at three levels which are named as macroscopic, sub-microscopic, and symbolic. Macroscopic level includes the observable properties or events that students may encounter in their daily life. Sub-microscopic level includes the particles and their interactions such as atom, molecule, electron, reactions and chemical bonding which cannot be seen directly. Symbolic level represents the chemical processes in terms of formulas, equations, numbers and signs. They are directly connected with each other, so that students' knowledge at each level has great importance to understand a chemical phenomenon clearly (Nakhleh, 1992; Raviolo, 2001). In the science education literature, not making the correct connections among three levels is referred as the most important reason of students' misconceptions about most chemistry subjects in the science education literature (Johnstone, 1982; Hewson & Hewson, 1984; Nakhleh, 1992; Ayas & Demirbaş, 1997).

In the last two decades, a great number of studies have been conducted on students' understanding about different chemistry subjects (Gorodetsky & Gussarsky, 1986; Mak & Young, 1987; Hand, 1989; Renström et al., 1990; Zoller, 1990; Bar & Travis, 1991; Haidar & Abraham, 1991; Garnett & Treagust, 1992; Griffiths & Preston, 1999; Hesse & Anderson, 1992; Quilez & Solaz, 1995; Staver & Lumpe, 1995; Tan & Treagust, 1999; Ebenezer & Fraser, 2001; Nicoll, 2001). They have elicited and reported various misconceptions of students at almost all grades ranging from primary school to universities. One of the most problematic subjects on which students generally have misconceptions is chemical bonding (Tan & Treagust, 1999). Understanding the subject of chemical bonding is crucial for students' further learning because it underlies most of the advancing subjects in chemistry lessons. It is necessary for students to construct the meanings of chemical bonding concepts properly to understand other chemistry subjects such as chemical reactions, chemical reactivity, structure of matter, change of state, physical and chemical change (Nicoll, 2001; Eshach & Garik, 2001). However, chemical bonding concepts are abstract and far from students' daily experiences (Birk & Kurtz, 1999; Tan & Treagust, 1999). Therefore, most students have difficulties in understanding chemical bonding and have various misconceptions about it (Nicoll, 2001; Griffiths & Preston, 1999; Tan & Treagust, 1999).

There have been many studies reporting students' various misconceptions about chemical bonding and its types in the international science education literature (Butts & Smith, 1987; Treagust, 1988; Peterson et al., 1989; Peterson & Treagust, 1989; De Posada, 1997; Boo, 1998; Robinson, 1998; Birk & Kurtz, 1999; Griffiths & Preston, 1999; Coll & Treagust, 2001a,b; Eshach & Garik, 2001). Peterson and Treagust (1989) developed a former diagnostic test to investigate students' misconceptions about covalent bonding. This instrument was administered to 84 grade 12 students from three different types of high school. It was ensued that students commonly had misconceptions about shapes of molecules, polarity of molecules, bond polarity, covalent lattices, intermolecular forces and octet rule.

Taber (1997a) investigated British students' understanding level about ionic bonding. The author aimed to determine how common the misconceptions which had been reported in the earlier studies were in a larger group of students. He collected data through a questionnaire which was administered to the sample consisting of 370 students. Results of the study showed that a high percentage of students had misconceptions about the lattice structure of sodium chloride and how ionic bonding was formed.

Tan and Treagust (1999) investigated 14- to 16-year-old Singaporean students' misconceptions on chemical bonding. Researchers developed and used a diagnostic instrument to collect data. The diagnostic test was administered to the sample consisting of 119 students. They found that students had some misconceptions about the formation of bonding between atoms, lattice structure of compounds, the electric conductivity of graphite, intramolecular and intermolecular forces.

Nicoll (2001) carried out a study to bring out college students' misconceptions about the characteristics of the atoms which form different types of chemical bonding. He conducted individual interviews with 56 students to collect data. Author found that students had misconceptions about atom, molecule, formation of chemical bonding, bond polarity, Lewis dot structures, polarity of molecules, and the types of chemical bonding. Moreover, it is found that the percentage of students who had misconceptions did not decrease considerably in spite of the increasing level of education.

There have been limited number of studies probing students' understanding and misconceptions on chemical bonding in Turkey (Yılmaz & Morgil, 2001; Atasoy et al., 2003; Ünal et al., 2002), although a great number of studies, some of which are summarized above, have been conducted in many countries (Butts & Smith, 1987; Treagust, 1988; Peterson et al., 1989; Peterson & Treagust, 1989; De Posada, 1997; Boo, 1998; Robinson, 1998; Birk & Kurtz, 1999; Griffiths & Preston, 1999; Coll & Treagust, 2001a,b; Eshach & Garik, 2001). Besides, all studies in Turkish science education literature have focused on students' understanding of all types of chemical bonding, namely on the whole concepts in the subject of chemical bonding, rather than focusing on that of a specific type of chemical bonding such as either ionic or covalent bonding. Moreover, all studies, in both Turkish and international science education literature, have rarely focused on the possible sources or reasons of these misconceptions. The aim of chemistry education is not only to provide students all knowledge related to chemistry, but also to help them clearly understand the basic concepts and the connections among them. Therefore, teaching strategies which allow students to make correct scientific connections among concepts should be employed in chemistry education. The first step in this process is to elicit students' preconceptions and the connections which they established among the concepts (Ebenezer & Erickson, 1996). Revealing students' misconceptions and their erroneous connections among the concepts makes major contributions to both chemistry teachers and curriculum developers. By this means, teachers could plan their teaching activities in such a manner that students could remedy their misconceptions and have scientific ideas about the phenomena. Moreover, curriculum developers could use students' misconceptions revealed from such studies in order to design learning environments in which effective concept teaching is performed, or to decide the instructional activities which should be taken place in these learning environments.

Considering the abovementioned rationales, it was aimed to investigate eleventh grade students' understanding about covalent bonding and to determine their related misconceptions. It is believed that forthcoming studies on students' conceptual change about covalent bonding will provide important benefits for chemistry teachers, curriculum developers and textbook writers.

METHODOLOGY

This study was conducted with the case study research design because it allows researchers to collect detailed qualitative data about a case under investigation in a short time.

a) Sample

The sample of the study comprises 58 eleventh grade students from two different classes in a public high school located in the city centre of Trabzon.

b) Data Collection Tools

In this study, a test comprising open-ended questions and semi-structured interviews were used to collect data. The contents of both test items and interview questions were determined by considering the current chemistry curriculum and textbooks for eleventh grade. Moreover, the questions in both data collection tools were developed by considering the misconceptions related to covalent bonding which had been reported in the earlier studies. Both data collection tools were also reviewed by a researcher studying on inorganic chemistry, so that the validity and the reliability of them were increased.

The test used in this study is comprised of four open-ended questions which are assigned to investigate students' understanding and to determine their misconceptions about covalent bonding. All students in the sample answered the test. Interviews were conducted with 10 students who were chosen randomly from the sample. Three main questions were asked students during the interview protocols. Students' understanding was also investigated by means of follow-up questions according to their responses. The questions in both data collection tools and the conceptions to be investigated by them are summarized in Table 1 and Table 2.

Table 1. *The test items and the conceptions to be investigated by them*

Items	Conceptions
1	Students could predict what type of atoms form covalent bonding and explain their reason
2	Students could determine the positions of bonding electrons in polar and nonpolar covalent bonding and explain their reasons
3	Students could explain how covalent bonding is formed between oxygen and hydrogen atom in a water molecule.
4	Students could explain why graphite conducts electricity, but diamond does not.

Table 2. *The interview questions and the conceptions to be investigated by them*

Questions	Conceptions
1	Students could explain what type of atoms form covalent bonding and explain their reason.
2	Students could present different examples of compounds and explain how covalent bonding is formed between the atoms within the molecules of these compounds.
3	Students could explain the types of covalent bonding presenting examples of compounds for each type.

c) Process

The research was conducted in the spring term of 2006-2007. After the instruction of the subject of chemical bonds, the test was administered to the sample. Afterwards, semi-structured interviews were conducted with 10 students who were chosen randomly from the sample. Student responses to both test items and interview questions were analyzed in detail to elicit students' understanding and misconceptions about covalent bonding. In analyzing open-ended test items and the interview questions, firstly student responses were examined thematically and the following criteria were developed for classification: *sound*

understanding, partial understanding, partial understanding with specific misconception, specific misconception, and no response/no understanding. These criteria are similar to those used by Abraham et al. (1992), Çalık (2005) and Ünal et al. (2002). Descriptions of these criteria are as follows:

Sound Understanding: Responses that include all components of the validated response

Partial Understanding: Responses that include at least one of the components of the validated response, but not all.

Partial Understanding with Specific Misconception: Responses that show partial understanding of the concepts by students but that also contain misconception.

Specific Misconception: Responses that include incorrect or illogical information.

No Response/No Understanding: Responses that include repetitions of a part or full of the question, irrelevant ideas, and no answer.

FINDINGS

a) Findings from the Open-Ended Test Items

Student responses in the specified categories to each open-ended test item are elaborated rigorously and presented in this section. The percentages of student responses in each category for all open-ended test items are shown in Table 3.

Table 3. The percentages of student responses in each category for the test items

Test Items	SU (%)	PU (%)	PUSM (%)	SM (%)	NR/NU (%)
1	22	31	16	19	12
2	29	21	17	24	9
3	24	29	21	19	7
4	21	26	-	43	10

Item 1. What type of bonding is formed in the given compounds below? Please explain your reasons (H: 1, Cl: 17, C: 6, O: 8, Mg: 12, N: 7)

a) HCl b) CO₂ c) MgCl₂ d) NH₃

Item 1 investigates whether or not students could predict what type of atoms form covalent bonding. It also investigates whether or not students could determine the type of chemical bonding which is formed between the atoms in the given compounds. The percentages of student responses in each category for item 1 are shown in Table 3. As seen in Table 3, %22 of students responded in the category of *sound understanding*, %31 of them responded in that of *partial understanding*, %16 of them responded in that of *partial understanding with specific misconception*, %19 of them responded in that of *specific misconception*, and %12 of them responded in that of *no response/no understanding* for item 1.

Students whose answers were classified in the category of *sound understanding* determined the type of chemical bonding which was formed between the atoms in the given compounds and explained their reasons correctly. In other words, they stated that covalent bonding was formed in HCl, CO₂ and NH₃ molecules through the sharing of electrons. Moreover, they affirmed that ionic bonding was formed between the magnesium and chloride ions in MgCl₂ by means of the attraction due to opposite electric charge. One of the student responses in this category is as follows:

"HCl : It is covalent bond, because it is formed between two nonmetal atoms. They share their electrons."

CO₂ : It is covalent bond, because it is formed between two nonmetal atoms. Carbon and oxygen atoms bond with each other by sharing of their single electrons."

MgCl₂ : It is ionic bond, because it is formed between a metal and a nonmetal atom. Bonding is formed by means of the attraction between oppositely charged ions."

NH₃ : It is covalent bond, because it is formed between two nonmetal atoms. Bonding is formed by sharing of a pair of electrons."

Students who determined the type of chemical bonding which is formed between the atoms in only some of the given compounds or who explained their reasons for only some of them were classified in the category of *partial understanding*. One of the student responses in this category is as follows:

"HCl : It is covalent bonding."

CO₂ :

MgCl₂ : Mg: 12, Cl: 17, Mg⁺² Cl⁻¹. It is ionic bonding. Magnesium and chloride ions bond with each other by means of their opposite electric charges."

NH₃ : N: 7, N: 1s² 2s² 2p³ Nitrogen share their single electrons with three hydrogen atoms, so that they have full outer shell. Therefore, covalent bonding is formed between nitrogen and hydrogen atoms."

Students whose answers were classified in the category of *partial understanding with specific misconception* determined the type of chemical bonding which is formed between the atoms in only some of the given compounds and explained their reasons for only some of them by using scientifically accepted ideas. However, students whose responses were classified in this category also incorrectly determined the type of chemical bonding in some of the given compounds and presented non-scientific ideas when explaining their reasons for them. One of the student responses in this category is as follows:

"HCl : It is ionic bonding. While the chlorine atom wants to take an electron to have full outer shell, the hydrogen atom wants to give. So, one electron is transferred from the hydrogen to the chlorine atom."

CO₂ : It is covalent bonding. Both oxygen and carbon atoms need to take electrons. So, they share their electrons with each other."

MgCl₂ : It is ionic bonding. While magnesium atom is metal, chlorine atom is nonmetal. So, magnesium atom transfers one electron to each chlorine atom."

NH₃ : It is ionic bonding. Nitrogen is nonmetal. Hydrogen is nonmetal. One electron is transferred from each hydrogen atom to the nitrogen atom."

Students whose answers were classified in the category of *specific misconception* incorrectly determined the type of chemical bonding in some or all of the given compounds. Students who presented nonscientific ideas when explaining their reasons were also classified in this category. One of the student responses in this category is as follows:

"HCl: It is ionic bonding, because both atoms are nonmetal."

CO₂: It is ionic bonding, because both atoms are nonmetal."

MgCl₂ : It is covalent bonding, because magnesium is metal, chlorine is nonmetal."

NH₃ : It is ionic bonding, because both atoms are nonmetal."

Item 2. *Could you determine the positions of bonding electrons between the atoms in the given compounds? Please explain your answers by drawings? (Please consider the distances of bonding electrons to the bonded atoms in your drawings) (H: 1, S: 16, F: 9, C: 6).*

a) HF b) H_2 b) H_2S d) CH_4

Item 2 investigates students' ideas about the position of bonding electrons between covalently bonded atoms. In other words, this item aims to determine to what extent students could predict the position of bonding electrons between two nonmetal atoms whose electronegativities are different from each other. The percentages of student responses in each category for item 2 are shown in Table 3. As seen in Table 3, %29 of students responded in the category of *sound understanding*, %21 of them responded in that of *partial understanding*, %17 of them responded in that of *partial understanding with specific misconception*, %24 of them responded in that of *specific misconception*, and %9 of them responded in that of *no response/no understanding* for item 2.

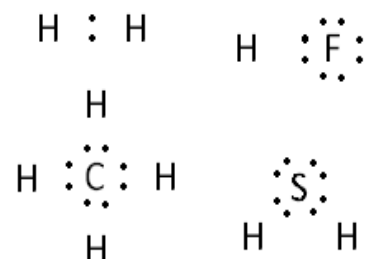
Students whose answers were classified in the category of *sound understanding* determined the position of bonding electrons between the bonded atoms in the given compounds, expressed that the position of bonding electrons between two atoms depended on the electronegativities of them, and also correctly placed the bonding electrons between two atoms in their drawings. In other words, they stated that bonding electrons were shared equally in only H_2 among the given molecules, because there were two hydrogen atoms in it and their electronegativities were the same. Moreover, they stated that bonding electrons were not shared equally in the other molecules, because bonded atoms in these molecules had different electronegativities. One of the student responses in this category is as follows:

"Bonding electrons are attracted equally to the nuclei of both atoms in H_2 molecule, because hydrogen atoms have the same electronegativity.

Bonding electrons are closer to sulphur atom in H_2S , because sulphur is more electronegative than hydrogen atom.

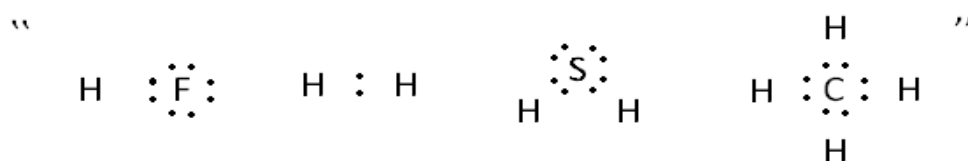
Bonding electrons are closer to fluorine atom in HF, because fluorine is more electronegative than hydrogen atom.

Bonding electrons are closer to carbon atoms in CH_4 , because carbon atoms are more electronegative than hydrogen atom."



Students whose answers were classified in the category of *partial understanding* determined the positions of bonding electrons between the atoms in the given compounds, but did not explain their reasons for them or did not make any drawings to demonstrate the positions of bonding electrons in the given compounds. Students who correctly placed the bonding electrons between covalently bonded atoms in their drawings for all compounds but not presented any explanations for their drawings were also classified in this category. Moreover, students who determined the positions of bonding electrons between the atoms in only some of the given compounds and explained their reasons for only some of them were also classified in this category. Two of the student responses in this category are as follows:

"It is different in H_2 molecule, because hydrogen bond with different atoms in the other molecules. However, hydrogen bond with the same atom (hydrogen) in H_2 molecule."

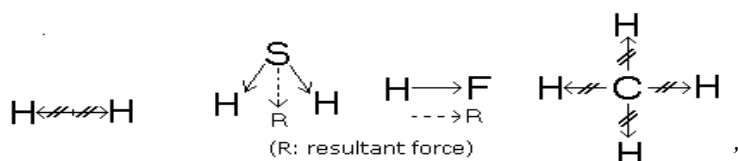


Students whose answers were classified in the category of *partial understanding with specific misconception* determined the positions of bonding electrons between the atoms in some of the given compounds and explained their reasons for them. However, they also incorrectly determined the positions of bonding electrons between the atoms in some of the given compounds or presented non-scientific ideas when explaining their reasons for them. Although students stated that the position of bonding electrons in H_2 compound were different from those in the other molecules because of the nonpolar covalent bonding formed between two hydrogen atoms, they who incorrectly placed bonding electrons equidistantly to the bonded atoms in all compounds in their drawings were also classified in this category. Moreover, students who incorrectly determined the shapes of molecules were classified in this category, although they presented some correct ideas in their explanation. One of the student responses in this category is as follows:

“ H_2 : non-polar $\text{H} : \text{H}$
 H_2S : polar $\text{H} : \text{S} : \text{H}$
 HF : polar $\text{H} : \text{F}$
 CH_4 : polar $\text{H} : \text{C}$ ”

Students who stated that bonding electrons were shared equally in all covalent molecules and placed the bonding electrons equidistantly to the bonded atoms in their drawings for all of the given molecules were classified in the category of *specific misconception*. Students who confused “*polar and nonpolar molecule*” with “*polar and nonpolar covalent bonding*” when explaining the positions of the bonding electrons between the bonded atoms and confused polar and nonpolar covalent bonding with each other were also classified in this category. One of the student responses in this category is as follows:

“ H_2 and CH_4 are nonpolar, while H_2S and HF are polar. Bonding electrons are attracted equally by two atoms in H_2 and CH_4 molecules. Although resultant forces in these molecules are zero, those in H_2S and HF are not.



Item 3. What type of chemical bonding is formed between the atoms within water molecules (H_2O)? Please explain how this chemical bonding is formed between hydrogen and oxygen atom?

Item 3 investigates students' ideas about how covalent bonding is formed. Moreover, this item aims to determine whether or not students could predict the type of chemical bonding within a water molecule. The percentages of student responses in each category for item 3 are shown in Table 3. As seen in Table 3, %24 of students responded in the category of

sound understanding, %29 of them responded in that of *partial understanding*, %21 of them responded in that of *partial understanding with specific misconception*, %19 of them responded in that of *specific misconception*, and %7 of them responded in that of *no response/no understanding* for item 3.

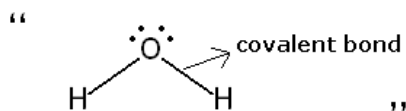
Students whose answers were classified in the category of *sound understanding* clearly explained that covalent bonding was formed by the sharing of a pair of electrons between hydrogen and oxygen atom. Some students also described the type of covalent bonding within water molecules. Moreover, some students gave additional information about the position of the bonding electrons, or the attraction of them by the nuclei of hydrogen and oxygen atom. One of the student responses in this category is as follows:

“Covalent bonding is formed within a H_2O molecule. $H: 1s^1$ $\begin{array}{c} H \cdot \\ \cdot \ddot{O} \cdot \end{array}$ $\begin{array}{c} \cdot \ddot{O} \cdot \\ \cdot \cdot \end{array}$ $\begin{array}{c} \cdot \cdot \\ H \cdot \end{array}$ $\begin{array}{c} \cdot \cdot \\ H \cdot \end{array}$ $O: 1s^2 2s^2 2p^4$

Hydrogen and oxygen atoms covalently bond with each other by sharing of their single electrons. A covalent bond is the attraction of the bonding electrons by the nuclei of both hydrogen and oxygen atom.”

Students whose answers were classified in the category of *partial understanding* stated that covalent bonding is formed between hydrogen and oxygen atoms within a water molecule, but did not explain explicitly how it is formed. Two of the student responses in this category are as follows:

“Covalent bond is formed between oxygen and hydrogen atoms in a water molecule.”



Students whose answers were classified in the category of *partial understanding with specific misconception* stated that covalent bonding was formed between oxygen and hydrogen atoms within water molecules, but presented non-scientific ideas when explaining how it was formed. Students who incorrectly determined the type of chemical bonding within water molecules, but presented correct explanations about how oxygen and hydrogen atoms bonded with each other were also classified in this category. Two of the student responses in this category are as follows:

“Hydrogen and oxygen atoms form covalent bond. This bond is formed by the transfer of one electron from the hydrogen to the oxygen.”

“Hydrogen bonding is formed between oxygen and hydrogen atoms in a water molecule. They bond with each other by sharing of their single electrons.”

Students who only stated that oxygen and hydrogen atoms formed ionic bonding and those who only claimed that the chemical bonding within water molecules is formed by the electron transfer were classified in the category of *specific misconception*. Students who stated that hydrogen bonding was formed between oxygen and hydrogen atoms within water molecules were also classified in this category, although they did not present any explanation about how oxygen and hydrogen atoms bonded with each other. Two of the student responses in this category are as follows:

“Ionic bonding is formed between oxygen and hydrogen atom within a water molecule, because hydrogen is a metal and oxygen is a nonmetal atom. They bond with each other by the electron transfer.”

“Hydrogen bonding is formed between hydrogen and oxygen atom within water molecules.”

Item 4. *Why does diamond not conduct electricity but graphite does? Please explain what characteristics of them do cause this diversity?*

Item 4 investigates students' ideas about the characteristics of giant covalent structures such as diamond and graphite. The percentages of student responses in each category for item 4 are shown in Table 3. As seen in Table 3, %21 of students responded in the category of *sound understanding*, %26 of them responded in that of *partial understanding*, %43 of them responded in that of *specific misconception*, and %10 of them responded in that of *no response/no understanding* for item 4. No students responded in the category of *partial understanding with specific misconception* for this test item.

Students whose answers were classified in the category of *sound understanding* explained that each carbon atom in diamond had four nearest neighbors to which it was bonded by sigma bonds while that in graphite was only bonded to three neighbor carbon atoms by strong sigma bonds. Students also explained that there were distributed pi bonds in which paired electrons were not held as tightly as the sigma bonds in graphite. They claimed that graphite conducted electricity due to these delocalized pi bonds. One of the student responses in this category is as follows:

“Each carbon atom in diamond is covalently bonded to four carbon atoms, although that in graphite is bonded to three. There are three sigma bonds and one pi bond in graphite. Electrons in pi bonds are much more reactive than those in sigma bonds, because they are not held tightly as the electrons in sigma bonds. These electrons are free to move through the planes of carbon atoms in graphite, so that it conducts electricity.”

Students whose answers were classified in the category of *partial understanding* stated that each carbon atom in diamond was covalently bonded to four carbon atoms while that in graphite was only bonded to three by sigma bonds. However, students in this category did not explain exactly how graphite conducted electricity whereas diamond did not. Moreover, students who mentioned the pi bonds in graphite but did not explain what properties of pi electrons enabled graphite conduct electricity were also classified in this category. Two of the student responses in this category are as follows:

“There are pi bonds in graphite, but not in diamond. So, diamond does not conduct electricity.”

“Each carbon atom in diamond is covalently bonded to four carbon atoms. However, in graphite, each carbon atom is bonded to three carbon atoms by sigma bonds and bonded to one carbon atom by pi bond. Therefore, graphite conducts electricity.”

No students responded in the category of *partial understanding with specific misconception*. Students who claimed that graphite conducted electricity due to the layers of carbon atoms which were able to slide over each other were classified in the category of *specific misconception*. Students who claimed that graphite conducted electricity through the nonbonding carbon atoms which were free to move in graphite were also classified in the

category of *specific misconception*. Two of the student responses in this category are as follows:

“Each carbon atom in diamond is bonded to four carbon atoms while that in graphite is only bonded to three carbon atoms. So, there is a free carbon atom which was not bonded to any carbon atom. These free carbon atoms move through the structure of graphite. Graphite conducts electricity due to these free carbon atoms. Diamond does not conduct electricity, because there is no free carbon atom which was not bonded to other carbon atoms.”

“Diamond has a unitary structure. It has no layers. However, in graphite, there are the layers of carbon atoms which slide over each other. Therefore, graphite conducts electricity due to the ability of layers of carbon atoms to move over each other, whereas diamond does not.”

b) Findings from the Interview Questions

Three main questions related to covalent bonding were asked in the interviews. Detailed information about students' understanding of covalent bonding and related concepts were also gathered through follow-up questions based on their answers to main questions. Students were asked to explain what type of atoms formed covalent bonding in the first interview question. In the second question, students were asked to give an example of covalent compounds and to explain how covalent bonding is formed between the atoms within its molecules. In the third question, students were asked to describe the types of covalent bonding and to give an example compound for each type of covalent bonding. After the interviews, student responses to each question were examined in detail and classified in the specified categories. Student responses in the specified categories to each interview question are elaborated rigorously, and some of them presented in this section. The percentages of student responses in each category for all interview questions are shown in Table 4. When presenting the interview findings, some abbreviations such as *R* to imply *researcher* and *S* to imply *student* are used.

Table 4. The frequency distributions of student responses in each category for the interview questions

Test Items	SU	PU	PUSM	SM	NR/NU
1	4	2	2	2	-
2	4	1	3	2	-
3	3	2	2	3	-

First Interview Question: *What type of atoms forms covalent bonding? Please explain why covalent bonding is formed between these types of atoms.*

The first interview question investigates students' ideas about the type of atoms which form covalent bonding. The frequency distributions of student responses in each category for the first interview question are shown in Table 4. As seen in Table 4, four students responded in the category of *sound understanding*, two of them responded in that of *partial understanding*, two of them responded in that of *partial understanding with specific misconception*, and two of them responded in that of *specific misconception* for the first interview question. There were no students who did not respond to this interview question.

Students whose answers were classified in the category of *sound understanding* explained that covalent bonding is formed between nonmetal atoms because their electron affinities were greater than the other groups of atoms. They also explained that because

nonmetals lacked only one or two electrons in their outer shells and their ionization potentials were usually high, they had a tendency to gain electrons instead of losing electrons to have more stable configuration. A sample quotation of the student responses in this category is as follows:

R: *What type of atoms forms covalent bonding?*

S3: *Nonmetal atoms.*

R: *Why do they form covalent bonding? What properties of them do you think make them form covalent bonding?*

S3: *Nonmetal atoms usually have high electron affinities. They generally tend to gain electrons when forming molecules. In other words, nonmetal gains electrons, so that they have more stable configuration as noble gases. When two nonmetal atoms react with each other, they form molecules by sharing of their single electrons.*

Students whose answers were classified in the category of *partial understanding* stated that covalent bonding was formed between nonmetals, although they could not explain what properties of nonmetals enable them to form covalent bonding. A sample quotation of the student responses in this category is as follows:

R: *What type of atoms forms covalent bonding?*

S8: *Nonmetals.*

R: *Why do they form covalent bonding? What properties of nonmetals do you think enable them to form covalent bonding?*

S8: *I don't know. I remember that teacher told us that covalent bond was formed between two nonmetal atoms while ionic bond was formed between metal and nonmetal atoms.*

R: *Do you know why? I mean, I ask you to explain why two nonmetal atoms form covalent bonding while metal and nonmetal atoms form ionic bonding? What properties of nonmetals do make them form covalent bonding?*

S8: *I don't know the reason. If the atoms were nonmetal, they would form covalent bonding. However, if one of them was a nonmetal and the other was a metal, they would form ionic bonding. I remember teacher said like that...*

Students whose answers were classified in the category of *partial understanding with specific misconception* determined the type of atoms which form covalent bonding, but presented non-scientific ideas in their explanation about what properties of nonmetals enable them to form covalent bonding. A sample quotation of the student responses in this category is as follows:

R: *What type of atoms forms covalent bonding?*

S1: *Covalent bonding is formed between two nonmetal atoms.*

R: *Why do they form covalent bonding? What properties of nonmetals do you think enable them to form covalent bonding?*

S1: *They form covalent bonding, because they want to gain electrons to resemble stable noble gases configuration. They want to have a full outer shell.*

R: *You used the word "want". What do you mean?*

S1: *I mean, nonmetals want to gain electrons because they want to have full outer shells.*

R: *Do atoms have wants or wishes?*

S1: *I remember it was like that. Metals want to lose electrons, while nonmetals want to gain. If two nonmetals will form a molecule, they share their single electrons. However, if a metal and a nonmetal atom will form a molecule, the metal atom gives its electron to the nonmetal atom. They form ionic bonding.*

R: *You think that atoms have some wants or wishes like humans, don't you?*

S1: It must be like that. We learned that metals want to lose electrons, but nonmetals want to gain. If so, they are able to think and want.

Students whose answers were classified in the category of *specific misconception* claimed that covalent bonding was formed between metal and nonmetal atoms. Moreover, students who presented non-scientific ideas when explaining what properties of nonmetals enable them to form covalent bonding were also classified in this category. A sample quotation of the student responses in this category is as follows:

R: *What type of atoms forms covalent bonding?*

S5: *Covalent bonding... it is formed between metals and nonmetals.*

R: *Why do they form covalent bonding? What properties of metals and nonmetals do make them form covalent bonding?*

S5: *They form covalent bonding because metals want to give electron while nonmetals want to take. Metal atoms transfer some electrons to the nonmetal atoms. So, they bond to each other.*

R: *If both of them were nonmetal atoms, what type of chemical bonding would be formed? Or, would they bond with each other?*

S5: *Yes, they form ionic bonding.*

R: *I ask you to explain what properties the atoms should have if they form covalent bonding?*

S5: *One of them should want to give electron and the other should want to take. One of them should have one or two electrons in its outer shell. The other should lack of one or two electrons in its outer shell.*

R: *You used the word "want". What do you mean?*

S5: *I mean, want... We learned that metals wanted to lose electrons, while nonmetals wanted to gain.*

R: *You think that atoms have some wants like humans, don't you?*

S5: *Yes. It must be like that...*

Second Interview Question: *Could you give an example of covalent compounds and explain how chemical bonding is formed between the atoms in its molecules?*

Second interview question investigates whether or not students could give an example of covalent compounds and explain how covalent bonding is formed between the atoms in its molecules. The frequency distributions of student responses in each category for the second interview question are shown in Table 4. As seen in Table 4, four students responded in the category of *sound understanding*, one of them responded in that of *partial understanding*, three of them responded in that of *partial understanding with specific misconception*, and two of them responded in that of *specific misconception* for the second interview question. There were no students who did not respond to this interview question.

Students whose answers were classified in the category of *sound understanding* presented correct examples of covalent compounds and explained that covalent bonding is formed by sharing of pairs of electrons between the atoms within these examples. Moreover, they affirmed that covalent bonding is the attraction of bonding electrons by the nuclei of both nonmetal atoms. A sample quotation of the student responses in this category is as follows:

R: *Could you give an example of covalent compounds?*

S10: *Water... Covalent bonding is formed between the atoms in water molecules.*

R: *Could you explain how covalent bonding is formed between the atoms in a water molecule?*

S10: *Hydrogen and oxygen atoms form covalent bonding in a water molecule. Both are nonmetal atoms, they tend to gain electrons to have stable configurations. They share their single electrons, so they have full outer shell. Thus, they form covalent bond.*

R: *You said they formed bond. What do you mean? What is bond?*

S10: Force of attraction.

R: How does this force of attraction exist between atoms? How do they bond to each other?

S10: They bond to each other because they share their single electrons. Hydrogen has one electron in its outer shell. Oxygen has two single electrons in its outer shell. Oxygen shares its single electrons with two hydrogen atoms. Two covalent bonds are formed...

R: I mean, why do they bond to each other? You said they shared their single electrons and bonded to each other. How they bonded to each other? What forces do hold them together and how do these forces exist?

S10: They share their single electrons. These electrons belong to both hydrogen and oxygen atoms anymore. These bonding electrons are attracted by the nuclei of both hydrogen and oxygen atom, because they share their electrons. Thus, they are hold together.

Student whose answer was classified in the category of *partial understanding* presented correct examples of covalent compounds and stated that covalent bonding is formed between nonmetal atoms, although he did not explain exactly how it is formed between the atoms within these examples. He couldn't explain that covalent bonding is the force of attraction of bonding electrons by the nuclei of covalently bonded atoms. His responses to the second interview question are as follows:

R: Could you give an example of covalent compounds?

S7: I think it is water. Yes, water.

R: What is the formula of water?

S7: H₂O.

R: Could you explain how covalent bonding is formed between the atoms in water molecules?

S7: Oxygen atom tends to take two electrons to have full outer shell, while hydrogen atom tends to take one. They share their electrons and form water molecules.

R: What happened when they shared their electrons? You said they formed water molecule. How they formed water molecule? How bonding was formed?

S7: They shared their electrons, so they bonded together?

R: What do you mean? What is bond?

S7: Combining of two atoms.

R: You said bond was combining of two atoms. You said they shared their electrons. Could you explain how they combine? I mean, how bonding is formed? What holds atoms together and how bond or bonding is formed?

S7: This is... because of sharing of electrons...

R: What happened when they shared their electrons? How they formed bonding? I mean what forces make atoms be together, so that they could form a molecule?

S7: I don't know...

Students whose answers were classified in the category of *partial understanding with specific misconception* presented correct examples of covalent compounds although they presented non-scientific ideas in their explanations about how covalent bonding is formed between the atoms within these molecules. While one of the students described the bond as *shared electrons between the bonded atoms*, the others claimed that *atoms were held together due to their wishes to gain electrons or their needs to each other*. A sample quotation of the student responses in this category is as follows:

R: Could you give an example of covalent compounds?

S2: Water. That is, H₂O.

R: Could you explain how covalent bonding is formed between the atoms in a water molecule?

S2: Hydrogen needs an electron to have two electrons in its outer shell. Oxygen needs two electrons to have eight electrons in its outer shell. Each hydrogen atom shares one electron with oxygen. So, all atoms have full outer shell and they bond to each other.

R: How bonding is formed between atoms? How they bonded to each other by sharing of electrons? Could you explain your answers by thinking the interactions which is taken place in sub-microscopic level?

S2: I don't know how I can explain the bonding in the sub-microscopic level. I just know that they bond to each other, because they share their single electrons.

R: You said they shared their single electrons. However, the question that I want to ask is how they bond to each other and form a molecule. That is, what is bond?

S2: I don't know exactly. Bond is... it must be shared electrons. They are also called bonding electrons. Thus, shared electrons must be bond. They hold the atoms together.

Students whose answers were classified in the category of *specific misconception* presented incorrect examples of covalent compounds and presented non-scientific ideas in their explanations about how covalent bonding is formed between the atoms in the molecules. A sample quotation of the student responses in this category is as follows:

R: Could you give an example of covalent compounds?

S4: Sodium chloride.

R: Could you explain how covalent bonding is formed between the atoms in sodium chloride?

S4: Sodium atom gives an electron and chlorine atom takes this electron, because they want to have noble gas configuration. Each of them has full outer shell. Therefore, they form covalent bonding.

R: What happens when each one of them have full outer shell?

S4: Both of them are full. They, now, have noble gas configuration.

R: You said they had noble gas configuration. How bonding was formed between them?

S4: That is... sodium gave one electron to the chlorine atom, and the chlorine atom took the electron. Both of them meet the needs of each other, so that they bonded to each other.

R: What is bond or what is bonding?

S4: It must be electron... the electron which transferred from the sodium to the chlorine atom.

R: Do you say that the transferred electron hold atoms together?

S4: Yes. They bonded to each other by means of the electron that sodium gave and chlorine took.

R: If I use your words, why they bond to each other when one of them gives and the other takes an electron? What holds them together? You said atoms wanted to have noble gas configuration. According to your answers, they had noble gas configuration after the transferring of the electron. So, how they bond to each other?

S4: I don't know exactly. One electron is transferred between two atoms... An electron is transferred from sodium atom to chlorine atom. They are hold together by this means. Electron transfer must be performed between to atoms, so that covalent bonding is formed.

Third Interview Question: Are there types of covalent bonding? If there are types of covalent bonding, can you explain how they are formed? Could you give an example compound for each type of covalent bonding?

Third interview question investigates students' ideas about the types of covalent bonding. Students were asked to explain the types of covalent bonding by exemplifying. The frequency distributions of student responses in each category for the third interview question are shown in Table 4. As seen in Table 4, three students responded in the category of *sound understanding*, two of them responded in that of *partial understanding*, two of them responded in that of *partial understanding with specific misconception*, and three of them responded in that of *specific misconception* for the third interview question. There were no students who did not respond to this interview question.

Students whose answers were classified in the category of *sound understanding* distinguished the types of covalent bonding as polar and nonpolar covalent bonding, explained that the diversity between two types of covalent bonding were resulted from the electronegativity difference between the bonded atoms, and presented correct examples of compounds for each type of covalent bonding. A sample quotation of the student responses in this category is as follows:

R: *Are there types of covalent bonding?*

S3: *Yes, polar and nonpolar covalent bonding.*

R: *Could you explain them? Could you explain how they are formed?*

S3: *If two atoms of the same element bond to each other, nonpolar covalent bonding is formed. If different atoms bond to each other, it is polar covalent bonding. Of course, these atoms must be nonmetal atoms.*

R: *Can you explain your answer by exemplifying?*

S3: *For example hydrogen gas. Two hydrogen atoms are bonded to each other, so that they form hydrogen gas. Because two identical hydrogen atoms bond to each other, nonpolar covalent bonding is formed between them. If it is water, polar covalent bonding is formed between oxygen and hydrogen atoms because two different atoms are bonded to each other.*

R: *What do polar and nonpolar covalent bonding mean?*

S3: *Polar means the bonding electrons are closer to one of the bonded atoms than the other. On the contrary, nonpolar means the bonding electrons are attracted equally between the identical bonded atoms.*

R: *Why are the bonding electrons attracted equally to the nuclei of bonded atoms in nonpolar covalent bonding, and why not in polar covalent bonding?*

S3: *If the bonded atoms are identical, the attraction forces of the bonding electrons by the nuclei of two identical atoms will be the same. Because two hydrogen atoms have the same electronegativity, the bonding electrons are attracted equally to the nuclei of both hydrogen atoms in hydrogen molecules. However, one of the bonded atoms which has greater electronegativity than the other will attract the bonding electrons more powerfully than the other atom, if bonded atoms are different from each other.*

Students whose answers were classified in the category of *partial understanding* distinguished the types of covalent bonding as polar and nonpolar covalent bonding, although they did not explain the reason why two types of covalent bonding differed from each other. Moreover, students classified in this category presented correct examples of compounds for each type of covalent bonding. A sample quotation of the student responses in this category is as follows:

R: *Are there types of covalent bonding?*

S8: *Yes, there are two types of covalent bonding. These are polar and nonpolar covalent bonding.*

R: *Could you explain them? Could you explain how they are formed?*

S8: *If different nonmetal atoms bond to each other, they form polar covalent bonding. If the identical nonmetal atoms bond to each other, they form nonpolar covalent bonding.*

R: *Could you explain your answers in detail by exemplifying?*

S8: *For example hydrogen. Nonpolar covalent bonding is formed in hydrogen molecules, because the bonded atoms are identical. Two hydrogen atoms react with each other in hydrogen molecules. Covalent bonding in hydrogen chloride is formed between two different nonmetal atoms. When two different nonmetal atoms react with each other, it is called as nonpolar covalent bonding.*

R: *What do polar and nonpolar covalent bonding mean?*

S8: *Polar covalent bonding means that the covalently bonded atoms are different from each other. Nonpolar covalent bonding means that the covalently bonded atoms are identical.*

R: Is there anything that you want to say about polar and nonpolar covalent bonding? Do you know how they are formed between the atoms? Could you explain why two types of covalent bonding differ from each other by thinking the properties of bonded atoms and the interactions taken place in sub-microscopic level?

S8: I don't know... the diversity between two types of covalent bonding is whether or not the bonded atoms are identical.

R: What happens when covalent bonding is formed between identical nonmetal atoms or different nonmetal atoms? Could you explain the differences between polar and nonpolar covalent bonding by thinking the properties of the bonded atoms and the interactions taken place in sub-microscopic level?

S8: I don't know how I can explain. Scientists have differentiated covalent bonding according to being formed between different nonmetal atoms or the identical ones. I think this is the only difference.

Students whose answers were classified in the category of *partial understanding with specific misconception* incorrectly described two types of covalent bonding or presented incorrect examples of compounds for each type of covalent bonding although they correctly distinguished the types of covalent bonding as polar and nonpolar covalent bonding. A sample quotation of the student responses in this category is as follows:

R: Are there types of covalent bonding?

S7: Yes, there are two types. These are polar and nonpolar covalent bonding.

R: Could you explain them? Could you explain how they are formed?

S7: Nonpolar covalent bonding is formed between different nonmetal atoms, while polar covalent bonding is formed between identical nonmetal atoms.

R: Could you explain your answer in detail? Can you describe the types of covalent bonding by exemplifying?

S7: I can give hydrogen gas as an example for polar covalent bonding. Oxygen gas is also given as an example. As concern with nonpolar covalent bonding, water could be given as an example.

R: What do polar and nonpolar covalent bonding mean?

S7: If covalent bonding is formed between different nonmetal atoms, it will be nonpolar covalent bonding. On the contrary, it is polar covalent bonding when identical nonmetal atoms bond to each other.

R: Does the difference between polar and nonpolar covalent bonding only stem from being formed between different nonmetal atoms or the same nonmetal atoms?

S7: I think so. Yes, the only difference is whether it is formed between different nonmetal atoms or the same nonmetal atoms. I don't know more about this.

R: Is there any different reason for this diversion? Could you explain the differences between polar and nonpolar covalent bonding by thinking properties of atoms and the interactions taken place in sub-microscopic level?

S7: I don't know. There is no more difference between polar and nonpolar covalent bonding. They are covalent bonding in anyway. They differ from each other only according to being formed between different nonmetal atoms or the same nonmetal atoms.

While two of the students whose answers were classified in the category of *specific misconception* stated that there was no type of covalent bonding, the other student whose answer was classified in this category claimed that hydrogen bonding, Van der Waals forces and dipole-dipole attractions were the types of covalent bonding. A sample quotation of the student responses in this category is as follows:

R: Are there types of covalent bonding?

S9: What did you mean?

R: How covalent bonding is formed between atoms?

S9: *By sharing of their single electrons.*

R: *Are there types of covalent bonding which is formed by sharing of single electrons? I want to ask you whether covalent bonding diverse according to any factor such as the types of atoms or their properties.*

S9: *No, all covalent bonds are the same. Covalent bonding is formed between atoms by sharing of single electrons.*

R: *Could you give examples for covalent compounds or molecules?*

S9: *For example hydrogen chloride. Carbon dioxide, oxygen and hydrogen gases are also other examples of covalent compounds.*

R: *I think I should ask the question in a different way. Is there any difference between the chemical bond formed within HCl molecules and that in O₂ molecules?*

S9: *There is a difference between them. Yes, I remember. Hydrogen bond is formed within HCl molecules.*

R: *You have given this molecule as an example of covalent bonding, haven't you?*

S9: *Yes. But, it is both covalent bond and hydrogen bond. .*

R: *Could you explain your answer? Could you explain how it is both covalent and hydrogen bond?*

S9: *They must share their single electrons, because both of them need one electron to have full outer shell. So, they form covalent bonding.*

R: *Why did you say that they formed hydrogen bonding?*

S9: *Because chlorine atom bond to hydrogen atom, we could say that they form hydrogen bonding as well.*

R: *Could you explain clearly how hydrogen bonding is formed between hydrogen and chlorine atoms?*

S9: *It is the same with covalent bonding. It is formed between hydrogen and chlorine atom by sharing of their single electrons.*

R: *If so, what is difference between them?*

S9: *There is no difference.*

R: *Do you mean that hydrogen bonding is a kind of covalent bonding?*

S9: *Yes, sure. It is covalent bonding. But, it is also hydrogen bonding because it is formed between an atom "chlorine" and hydrogen atom.*

R: *Based on your answers, what type of atoms form hydrogen bonding? Or, is hydrogen bonding formed between different atoms or molecules?*

S9: *Hydrogen bonding is formed within molecules comprising of one hydrogen atom with other atoms.*

R: *Is there any other types of covalent bonding?*

S9: *I remember Van der Waals.*

R: *Could you explain how it is formed?*

S9: *I think it is formed within O₂ molecules. If the atoms in a molecule are the same, the bond between these atoms will be Van der Waals.*

R: *You have given carbon dioxide molecule as an example of covalent bonding? What is the type of covalent bonding within a carbon dioxide molecule?*

S9: *It must be dipole-dipole. I think that the bond between them will be dipole-dipole, if the bonded atoms are different from each other.*

DISCUSSION

The results of the study showed that students had various misconceptions about four important areas related to covalent bonding. These are; *the types or properties of atoms which form covalent bonding, how covalent bonding was formed, the types of covalent bonding, and the characteristics of giant covalent structures.*

The first area related to covalent bonding in which students had various misconceptions was *the types or properties of atoms which form covalent bonding.* It was found that a great

deal of students had misconception that covalent bonding is formed between a metal and a nonmetal atom. It was clearly seen that this misconception was held by students who stated that “*ionic bonding is formed in HCl and NH₃ molecules*” in their explanations for the first test item, “*ionic bonding is formed in water molecules*” in those for the third test item, “*covalent bonding is formed between a metal and a nonmetal atom*” in those for the first interview question, and “*covalent bonding is formed in sodium chloride*” in those for the second interview question. These non-scientific ideas also showed that students confused ionic and covalent bonding with each other. Previous studies also reported that students confused the types of chemical bonding and thought as if covalent bonding was formed between a metal and a nonmetal atom (Nicoll, 2001; Tan & Treagust, 1999; Boo, 1998; Taber, 1997). This special result for students’ confusion of ionic and covalent bonding with each other is parallel with the idea which was discussed in the study of Sökmen et al. (2000) who claimed that students generally confused the concepts with each other after they had learned in the school courses. The most possible reason for students’ misconception that covalent bonding is formed between a metal and a nonmetal atom is that students could not understand exactly what properties of nonmetals enable them to form covalent bonding or what properties of metals and nonmetals enable them to form ionic bonding. Similarly, it can be concluded they also could not understand how ionic and covalent bonding is formed between atoms. Another possible reason for this misconception is that students only confuse the names of ionic and covalent bonding because students generally tend to memorize facts or concepts. This could be a foregone result of traditional methods which are generally used by science teacher in order to teach all subjects involving in the overloaded curriculum in Turkey. Teacher might not emphasize the facts or concepts sufficiently to teach all subjects till the end of the school term. This can be also considered as another source or reason for students’ confusion of ionic and covalent bonding with each other.

The second area related to covalent bonding in which students had various misconceptions was *how covalent bonding is formed*. It was clearly seen that this misconception was held by students who stated that “*covalent bonding is formed by the electron transfer within hydrogen chloride and ammonia*” in their explanations for the first test item, “*covalent bonding is formed by the electron transfer within a water molecule*” in those for the third test item, “*covalent bonding is formed by the electron transfer between metal and nonmetal atoms*” in those for the first interview question, “*covalent bonding is formed by the electron transfer in sodium chloride*” in those for the second interview question. Moreover, it could be deduced that students who had misconception that *covalent bonding is formed between a metal and a nonmetal atom* also had misconception about *how covalent bonding is formed*. As the student misconceptions about *the types or properties of atoms which form covalent bonding*, those about *how covalent bonding is formed* also showed that students confused ionic and covalent bonding with each other. Previous studies also reported that students thought as if covalent bonding was formed through electron transfer, because they confused the types of chemical bonding (Nicoll, 2001; Tan & Treagust, 1999; Boo, 1998; Taber, 1997). The discussion held in the preceding paragraph also goes for the possible reasons of misconceptions about how covalent bonding is formed. In addition, one possible reason for this misconception is that students have poor understanding about the sub-microscopic level. If they were able to envisage the atoms and their interactions when forming molecules, they could predict correctly what characteristics the atoms forming covalent bonding must have had and how chemical bonding was formed between atoms.

The third area related to covalent bonding in which students had various misconceptions was *the types of covalent bonding*. It was clearly seen that students who stated that “*polar covalent bonding is formed within H₂ molecules*” and “*nonpolar covalent bonding is formed*

within H_2S , HF and CH_4 molecules” in their explanations for the second test item confused polar and nonpolar covalent bonding with each other. This confusion could be also seen from the students who stated that “*nonpolar covalent bonding is formed within water molecules*” in their explanations for the third test item. Moreover, students’ confusion between polar and nonpolar covalent bonding with each other was clearly seen from the answers such as “*polar covalent bonding is formed within H_2 molecules*”, “*polar covalent bonding is formed within O_2 molecules*”, “*polar covalent bonding is formed between identical nonmetal atoms*”, “*nonpolar covalent bonding is formed between different nonmetal atoms*”, “*nonpolar covalent bonding is formed within water molecules*” for the third interview question. Besides the students who confused the types of covalent bonding, there were students who thought that *the bonding electrons place equidistantly to the bonded atoms because they are shared equally in all covalent molecules* without regarding the types of covalent bonding (see student answers to the second test item and third interview question). Nicoll (2001) also reported that students confused polar and nonpolar covalent bonding with each other. Moreover, the misconception that *bonding electrons place equidistantly to the atoms which form covalent bonding whether or not it is formed between the same atoms* also reported in previous studies (Peterson et al. 1989; Birk & Kurtz, 1999; Atasoy et al., 2003). The most possible reason for these misconceptions about the types of covalent bonding is students’ lack or ignorance of the electronegativity. Another possible reason for these misconceptions is that students’ confusion of the terms “polar” and “nonpolar”, because these terms are used as “*polar*” and “*apolar*” in Turkish. Because these terms were originated from English, students could not understand their meaning and, thus, they could not make connections between these terms and the types of covalent bonding. Moreover, Sökmen et al. (2000)’s claim about students’ confusion of the concepts which are taught in school courses may be another reason or source of these misconceptions about the types of covalent bonding.

The last area related to covalent bonding in which students had various misconceptions was *the characteristics of giant covalent structures*. It was clearly seen that misconceptions related to the characteristics of giant covalent structures were held by students who stated that “*because each carbon atom in graphite is only bonded to three carbon atoms. So, there is a free carbon atom which was not bonded to any carbon atom. These free carbon atoms move through the structure of graphite. Graphite conducts electricity due to these free carbon atoms*” and “*graphite conducts electricity due to the ability of layers of carbon atoms to move over each other*” in their explanations for the fourth test item. Misconceptions related to electric conductivity of graphite was revealed in the study by Tan & Treagust (1999). Moreover, Peterson et al. (1989) found out that students had various misconceptions about the covalent lattice structure. The most possible reason for these misconceptions related to the characteristics of giant covalent structures is that the lattice structure of diamond and graphite are taught superficially in school chemistry courses. Both teachers and students generally ignore the lattice structures because there is no question related to the characteristics of giant covalent lattice structures in University Entrance Exam in Turkey. Chemistry teachers might have not emphasized the covalent lattices, because they thought that only students who would study on chemistry and related fields in their university education would need to understand them. Another possible reason for these misconceptions related to the characteristics of giant covalent lattice structures is that students think that all matters have molecular structure. Thus, students couldn’t understand and envisage the giant covalent lattices in which all atoms are covalently bonded to each other. Students might have thought that a molecule must have been formed with the combining of two or several atoms, because the compounds they had been encountered were generally comprised of two (H_2 , O_2 , HCl , HF) or three (H_2O , CO_2 , H_2S) atoms.

Besides student misconceptions pointed out in the previous paragraphs related to four area in covalent bonding, it was found out that students hold more and various misconceptions related to covalent bonding. When all misconceptions revealed in this study were examined, it was noticed that some possible reasons of these misconceptions were common in fact. Students' misconceptions revealed from this study, their percentages, and the possible reasons for them are presented in Appendix-1 and Appendix-2. As seen in Appendix-1 and Appendix-2, possible reasons for students' misconceptions related to covalent bonding are as follows: (1) confusing ionic and covalent bonding with each other, (2) thinking as if hydrogen atom was a metal atom because it takes place on the left side of the periodic table, (3) thinking as if hydrogen bonding was a chemical bonding and as if it was formed within all molecules including a hydrogen atom, (4) confusing polar and nonpolar covalent bonding with each other, (5) confusing the concepts; "polar and nonpolar covalent bonding" and "polar and nonpolar molecule" with each other, (6) lacking in or ignoring the electronegativity concept and the electronegativities of the atoms (ignoring the types of covalent bonding), (7) thinking as if "the number of atoms which bond to the central atom within a molecule" or "the number of bonds which central atom forms with its neighbor atoms" is the only factor which determines the shape of a molecule, instead of thinking all factors affecting the shape of a molecule, (8) confusing chemical bonds and intermolecular forces, thinking as if intermolecular forces were chemical bonds or as if they were the types of covalent bonding, (9) having poor understanding about covalent lattice structures, and not envisaging them, (10) animising the sub-microscopic particles such as atoms and molecules, (11) not being able to envisage how bonding is formed at sub-microscopic level.

CONCLUSIONS AND IMPLICATIONS

It was found out that students have misconceptions about four areas related to covalent bonding after the analyses of students' responses to both test items and interview questions. As pointed out in the discussion section, these are; *the types or properties of atoms which form covalent bonding, how covalent bonding was formed, the types of covalent bonding, and the characteristics of giant covalent structures*. Besides the misconceptions about four areas related to covalent bonding, it was found out that students hold more and various misconceptions related to covalent bonding. Some of these misconceptions were held by only few students, while some of them were held by a larger group of students. Students' misconceptions revealed from this study, their percentages and the possible reasons for them are presented in Table 5 and Table 6.

It is found that students have difficulties in understanding the subject of covalent bonding consisting abstract concepts and facts, and they have many and various misconceptions. Teachers should use models such as concrete models, analogical models, theoretical models and simulations to make more concrete the abstract concepts or facts for their students. Moreover, teachers should emphasize the transitions from the macroscopic properties of a matter or event to the sub-microscopic properties of those. These are the ways to improve students' understanding about the covalent bonding at both macroscopic and sub-microscopic levels and to make students have fewer misconceptions. Moreover, learning environments based on teaching strategies or techniques for conceptual change such as concept mapping, conceptual change texts, and computer aided instruction should be designed to remediate students' misconceptions related to covalent bonding and its effectiveness should be investigated with extensive studies conducted by chemistry educators or researchers.

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Appendix-1

Students' misconceptions determined from the test items, their percentages and possible reasons for them

Test Items	Students' Misconceptions	%
<i>First Test Item</i>	Ionic bonding is formed within HCl molecules ^(1, 2)	16
	Ionic bonding is formed within NH ₃ molecules ^(1, 2)	14
	Ionic bonding is formed within CO ₂ molecules ⁽¹⁾	14
	Covalent bonding is formed in MgCl ₂ ⁽¹⁾	10
	Ionic bonding is formed within HCl molecules, because it is formed between nonmetal atoms by the sharing of their single electrons ⁽¹⁾	10
	Covalent bonding is formed within HCl molecules, because it is formed between a metal and a nonmetal atom by the electron transfer ^(1, 2)	9
	Ionic bonding is formed within NH ₃ molecules, because it is formed between nonmetal atoms by the sharing of their single electrons ⁽¹⁾	12
	Covalent bonding is formed within NH ₃ molecules, because it is formed between a metal and a nonmetal atom by the electron transfer ^(1, 2)	7
	Ionic bonding is formed within CO ₂ molecules, because it is formed between nonmetal atoms by the sharing of their single electrons ⁽¹⁾	12
	Covalent bonding is formed in MgCl ₂ , because it is formed between a metal and a nonmetal atom by the electron transfer ⁽¹⁾	14
	Hydrogen bonding is formed within HCl molecules, because it is formed within all compounds including hydrogen atom ^(3, 7)	5
	Hydrogen bonding is formed within NH ₃ molecules, because it is formed within all compounds including hydrogen atom ^(3, 7)	7
<i>Second Test Item</i>	Polar covalent bonding is formed within H ₂ molecules ⁽⁴⁾	12
	Nonpolar covalent bonding is formed within H ₂ S molecules ⁽⁴⁾	14
	Nonpolar covalent bonding is formed within HF molecules ⁽⁴⁾	12
	Nonpolar covalent bonding is formed within CH ₄ molecules ⁽⁴⁾	16
	Polar covalent bonding is formed within H ₂ molecules, because it is formed between identical nonmetal atoms ⁽⁴⁾	9
	Nonpolar covalent bonding is formed within H ₂ S molecules, because it is formed between different nonmetal atoms ⁽⁴⁾	5
	Nonpolar covalent bonding is formed within HF molecules, because it is formed between different nonmetal atoms ⁽⁴⁾	7
	Nonpolar covalent bonding is formed within CH ₄ molecules, because it is formed between different nonmetal atoms ⁽⁴⁾	5
	Polar covalent bonding is formed within H ₂ S and HF molecules ⁽⁵⁾	5
	Nonpolar covalent bonding is formed within H ₂ and CH ₄ molecules ⁽⁵⁾	5
	Bonding electrons place equidistantly to the bonded atoms in all covalent molecules ⁽⁶⁾	7
	Hydrogen sulphide has a linear molecular shape ⁽⁷⁾	7
<i>Third Test Item</i>	Ionic bonding is formed within water molecules ^(1, 2)	9
	Ionic bonding is formed within water molecules. Because hydrogen is a metal atom and oxygen is a nonmetal atom, they bond to each other by the electron transfer ^(1, 2)	7
	Covalent bonding is formed within water molecules. Because hydrogen is a metal atom and oxygen is a nonmetal atom, they bond to each other through electron transfer ^(1, 2)	5
	Ionic bonding is formed within water molecules. Because both hydrogen and oxygen are nonmetal atoms, they bond to each other by the sharing of their single electrons ⁽¹⁾	2
	Hydrogen bonding is formed within water molecules, because it is formed within all compounds including a hydrogen atom with other atoms. They bond to each other by sharing of their single electrons ^(3, 8)	5
	Nonpolar covalent bonding is formed within water molecules ⁽⁴⁾	3
	Water has a linear molecular shape ⁽⁷⁾	9
<i>Fourth Test Item</i>	Because each carbon atom in graphite only bond to three carbon atoms, there is free carbon atoms which are not bonded to any carbon atom. Graphite conducts electricity due to these carbon atoms which are free to move ⁽⁹⁾	26
	Because graphite has the layers of carbon atoms which slide over each other, it conducts electricity due to these layers which could be able to move ⁽⁹⁾	17

- (1) Confusing ionic and covalent bonding with each other
- (2) Thinking as if hydrogen atom was a metal atom because it takes place on the left side of the periodic table
- (3) Thinking as if hydrogen bonding was a chemical bonding and as if it was formed within all molecules including a hydrogen atom
- (4) Confusing polar and nonpolar covalent bonding with each other
- (5) Confusing the concepts; “polar and nonpolar covalent bonding” and “polar and nonpolar molecule” with each other
- (6) Lacking or ignoring of the electronegativity concept and the electronegativities of the atoms (ignoring the types of covalent bonding)
- (7) Thinking as if “the number of atoms which bond to the central atom within a molecule” or “the number of bonds which central atom forms with its neighbour atoms” is the only factor which determine the shape of a molecule, instead of thinking all factors affecting the shape of a molecule
- (8) Confusing chemical bonds and intermolecular forces, thinking as if intermolecular forces were chemical bonds or as if they were the types of covalent bonding
- (9) Having poor understanding about covalent lattice structures, and not envisaging them

Appendix-2

Students' misconceptions determined from the interview questions, their percentages, and the possible reasons for them

Interview Questions	Students' Misconceptions	Students
First Interview Questions	Covalent bonding is formed between nonmetal atoms which want to resemble stable noble gases configuration. Because covalent bonding is formed by the sharing of single electrons, only the atoms which need electrons can form covalent bonding ⁽¹⁰⁾	S1, S9
	Covalent bonding is formed between metal and nonmetal atoms. One of the atoms which form covalent bonding must be a metal atom which loses electron to have stable configuration, and the other must be a nonmetal atom which gains electron when forming a chemical bonding or a molecule ⁽¹⁾	S4
	Covalent bonding is formed between metal and nonmetal atoms. One of the atoms which form covalent bonding must be a metal atom which wants to give electron, and the other must be a nonmetal atom which wants to take electron ^(1, 10)	S5
Second Interview Questions	Covalent bonding is formed within H ₂ O molecules. Because both oxygen and hydrogen atoms want to take electron to resemble noble gases, they need to each other. They bond to each other and they are held together due to this needs ^(10, 11)	S1
	Covalent bonding is formed within HCl molecules. Hydrogen bond to chlorine atoms and they are held together due to their needs to gain electron ^(10, 11)	S6
	Covalent bonding is formed within H ₂ O molecules. Hydrogen and oxygen are held together due to the shared (bonding) electrons. The chemical bond is the shared electrons between two atoms ⁽¹¹⁾	S2
	Covalent bonding is formed in NaCl. Sodium atom wants to give an electron, while chlorine atom wants to take. They bond to each other and they are held together due to these wishes ^(1, 10, 11)	S5
	Covalent bonding is formed in NaCl. Sodium gives an electron to the chlorine atom. They meet their needs. They bond to each other and they are held together due to the electron which is transferred from sodium to chlorine atom ^(1, 10, 11)	S4
Third Interview Questions	Polar covalent bonding is formed within H ₂ molecules ⁽⁴⁾	S1, S7
	Polar covalent bonding is formed within O ₂ molecules ⁽⁴⁾	S1, S7
	Polar covalent bonding is formed between identical nonmetal atoms ⁽⁴⁾	S1, S7
	Nonpolar covalent bonding is formed between different nonmetal atoms ⁽⁴⁾	S1, S7
	Nonpolar covalent bonding is formed within H ₂ O molecules ⁽⁴⁾	S1, S7
	Van der Waals, dipole-dipole and hydrogen bonding are the types of covalent bonding ⁽⁸⁾	S9
	Hydrogen bonding is formed within HCl molecules by the sharing of electrons ⁽⁸⁾	S9
	Van der Waals bonding is formed within O ₂ molecules by the sharing of electrons ⁽⁸⁾	S9
	Dipole-dipole bonding is formed within CO ₂ molecules by the sharing of electrons ⁽⁸⁾	S9
	If the same nonmetal atoms share their single electrons to form a molecule, Van der Waals bonding is formed between them ⁽⁸⁾	S9
	If a hydrogen atom shares its single electron with another nonmetal atom, hydrogen bonding is formed between them ⁽⁸⁾	S9
	If different nonmetal atoms share their single electrons to form a molecule, dipole-dipole bonding is formed between them ⁽⁸⁾	S9
	Covalent bonding in all molecules is the same in fact. There is no type of covalent bonding, because all of them is formed by the electron transfer and all of them is formed between metal and nonmetal atoms ^(1, 6)	S4, S5

⁽¹⁾ Confusing ionic and covalent bonding with each other

⁽⁴⁾ Confusing polar and nonpolar covalent bonding with each other

⁽⁶⁾ Lacking or ignoring of the *electronegativity* concept and the electronegativities of the atoms (ignoring the types of covalent bonding)

⁽⁸⁾ Confusing chemical bonds and intermolecular forces, thinking as if intermolecular forces were chemical bonds or as if they were the types of covalent bonding

⁽¹⁰⁾ Animising the sub-microscopic particles such as atoms and molecules

⁽¹¹⁾ Not being able to envisage how bonding is formed at sub-microscopic level