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Evaluating students' understanding of chemical bonding

Kim-Chwee Daniel Tan and David F. Treagust

A two-tier multiple-choice diagnostic instrument provides an easy-to-use means of assessing 14–16 year-old students' alternative conceptions of chemical bonding

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In Singapore, chemical bonding is usually taught in the early part of the third year of secondary school, when 14–15 year-old students study chemistry as a subject for the first time. Chemical bonding is an abstract topic, something far removed from the daily experiences of secondary school students; one cannot see an atom, its structure and how it reacts with other atoms. Thus many students have difficulty in understanding the concepts in chemical bonding, and there is great potential for the formation of alternative conceptions.

Student difficulties with chemical bonding

Previous research, usually interviews or diagnostic tests, with students in Australian grades 11 and 12 (aged 16–18 years), has identified a range of difficulties with understanding chemical bonding. A review of related research on particles with students aged 8–18 years (Driver *et al*., 1994) identified several problems in learning this topic. Using interviews, Butts and Smith (1987) found that most grade 12 chemistry students associated sodium chloride with ionic bonding and the transfer of electrons from sodium to chloride, but many did not understand the three-dimensional nature of ionic bonding in solid sodium chloride. A few students thought sodium chloride exists as molecules, and these molecules were held together in the solid by covalent bonds. Others thought that sodium and chlorine atoms were bonded covalently but that ionic bonds between these molecules produced the crystal lattice. A three-dimensional ball-and-stick model of sodium chloride also caused confusion among the students as many interpreted the six wires attached to each ball (ion) as each representing a bond of some sort.

In interviews with grade 12 students, Griffiths and Preston (1992) identified 52 misconceptions, grouped into 11 categories, relating to the fundamental characteristics of atoms and molecules. They found that many students regard matter as continuous, and some believe that water molecules are held together by something external to the molecules and that heat causes water molecules to expand leading to their separation in melting. Using similar research techniques, Harrison and Treagust (1996) probed 48 grade 8–10 students' mental models of atoms and molecules, and found that many students prefer models of atoms and molecules that depict these entities as discrete, concrete structures. Several students concluded that atoms can reproduce and grow and that atomic nuclei divide. Electron shells were visualised by the students as shells that enclose and protect atoms, while electron clouds were structures in which

ABSTRACT
Problems students encounter with understanding the abstract concept of chemical bonding, as revealed in previous research, are outlined. The development of a two-tier multiple-choice diagnostic instrument for assessing alternative conceptions about chemical bonding held by 14–16 year-olds is described. The instrument was administered to 119 chemistry students and the results analysed. The common alternative conceptions they were found to hold are listed and discussed. It was found that this instrument provided an easy-to-administer tool, providing results in a readily accessible form.

electrons were embedded. Harrison and Treagust propose that student understanding breaks down when students mistake the analogical models, used by teachers or given in textbooks, for reality.

In an effort to make better sense of these and related aspects of students' understanding of bonding, Taber (1994) describes the tendency of students to think of an 'ion-pair molecule' as a 'molecular framework' and suggests that many students adopt the alternative molecular framework because they believe:

- that the atomic electronic configuration determines the number of ionic bonds formed;
- that bonds are only formed between atoms that donate/accept electrons;
- that ions interact with the counter-ions around them, but for those not ionically bonded these interactions are just forces.

Results from the administration of a diagnostic instrument on ionic bonding (Taber, 1997) support the above conjectures. Taber and Watts (1996) focus on students' use of anthropomorphic language in science and argue that anthropomorphic language is common amongst scientists as well as science students. However, caution is required in the use of anthropomorphic language; although it can aid communication and understanding, it can be an impediment to further learning. Taber and Watts give the example of the 'full outer shell' heuristic approach of most students, which is of little help in discussing bond polarity, hydrogen bonding, van der Waals' forces and many other important bonding phenomena (p. 565). Taber (1998) argues that students' use of the octet rule, to explain chemical reactions and chemical bonding, forms the basis of an alternative conceptual framework for understanding chemistry. This octet rule framework can be used to explain why students see bond types as a dichotomy, believe in ionic molecules and consider 'proper bonds' and 'just forces' to be ontologically distinct rather than just different in magnitude (p. 606).

An alternative approach to identifying students' understandings with diagnostic tests found that students had difficulties with bond polarity, shape of molecules, polarity of molecules, intermolecular forces and the octet rule (Peterson, 1986; Peterson and Treagust, 1989; Peterson, Treagust and Garnett, 1989; and Goh, Khoo and Chia, 1993). For example, Peterson and Treagust (1989) highlighted that intermolecular forces were incorrectly identified, by 23 per cent of the students in their study, as the forces within a molecule, and by 33 per cent of the students as the forces present within a continuous covalent solid. The students were equating intermolecular forces with covalent bonds and were not aware of the variations in strength of covalent bonds compared with intermolecular forces.

Diagnosing student understanding

Methods used to determine students' understanding of concepts include concept mapping (Novak, 1996), interviews (Carr, 1996) and multiple-choice diagnostic instruments (Treagust, 1988, 1995). However, multiple-choice diagnostic instruments are more readily administered and scored than the other methods, and thus are particularly useful for classroom teachers.

The two-tier multiple-choice diagnostic instrument on covalent bonding and structure developed by Peterson (1986) to determine 16–18 year-old Australian students' alternative conceptions of covalent bonding could not be used to determine the alternative conceptions of chemical bonding held by Secondary Three and Four students (14–16 year-olds) in Singapore, because much of its content is not taught at this level. Consequently, a two-tier multiple-choice diagnostic instrument to identify Secondary Three and Four students' alternative conceptions in basic chemical bonding was developed by Tan (1994).

The diagnostic instrument

The content of the instrument was based on a list of propositional knowledge and a concept map (Figure 1) which were validated by a tertiary academic and three experienced chemistry teachers. The instrument was developed and refined, in 1994, through two pilot studies, and the final version of the instrument was validated by two senior chemistry teachers and a tertiary science educator. Three items in the diagnostic instrument were modified from three items in the diagnostic instrument developed by Peterson (1986). The remaining items were developed from interviews with students, the study of student-drawn concept maps, past examination questions and personal teaching experiences. The areas of alternative conception highlighted by each question are given in Table 1.

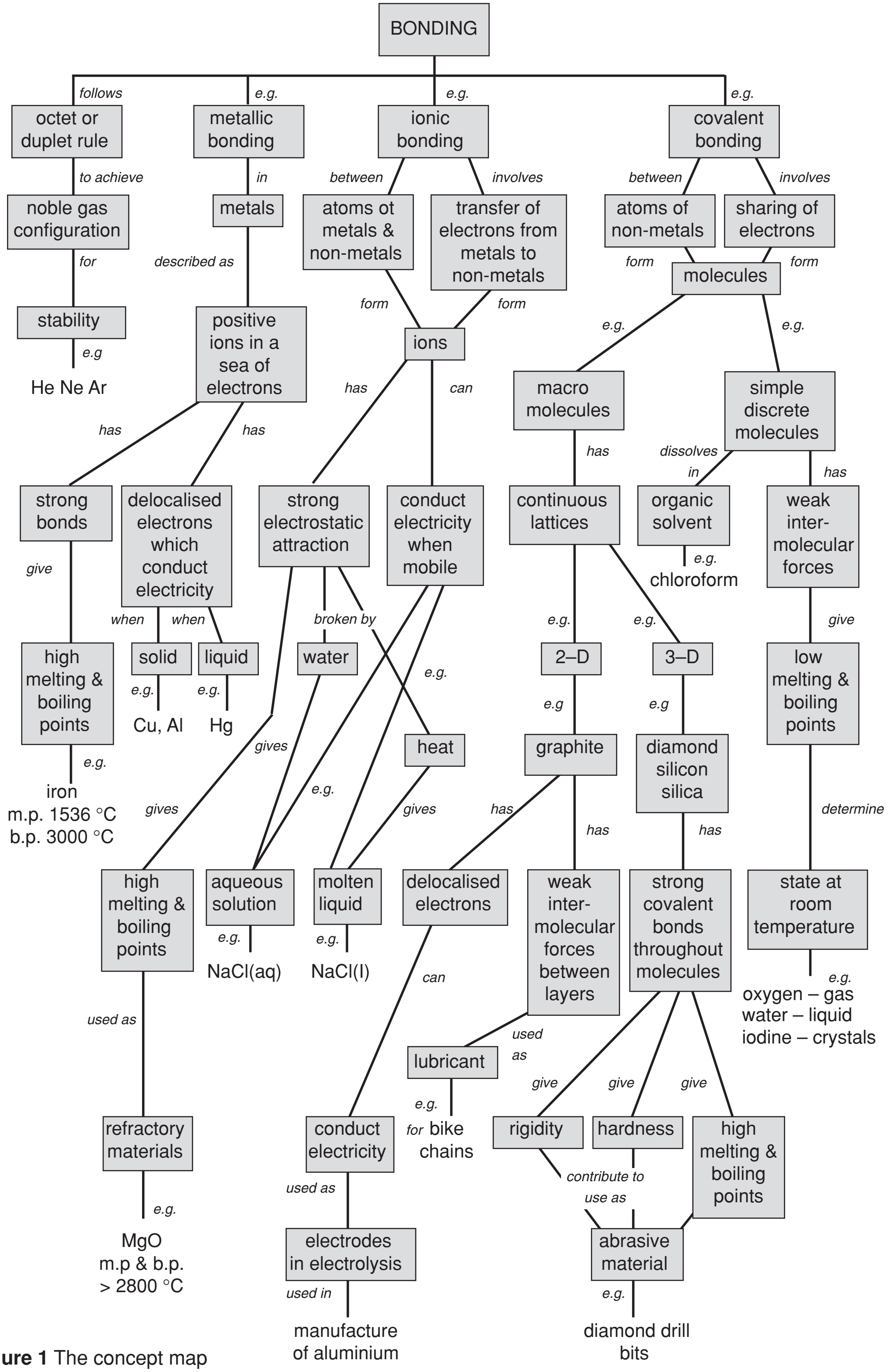

Figure 1 The concept map on chemical bonding.

Table 1 Areas of alternative conception highlighted by each item of the test instrument.

Item no.	*Areas of alternative conception*
1	bonding, lattice
2	lattice, intermolecular forces
3	bonding
4	bonding, intermolecular forces
5	electrical conductivity of graphite
6	bonding
7	lattice
8	intermolecular forces
9	lattice, intermolecular forces

The instrument was reviewed in early 1998 and minor changes were made to it. The revised instrument (see Appendix) was then administered, in April 1998, to 119 Secondary Four (15–16 year-old) chemistry students from the same secondary school. Students' responses to each item of the test were collated according to their selection of particular response combinations. If a student did not select a response to both parts of an item, then it was not included in the analysis. The results of this scoring process are given in Table 2.

Results and discussion

Evidence of a student holding an alternative conception was established by the student choosing an incorrect answer and/or choosing an incorrect reason (Peterson *et al.*, 1989). Alternative conceptions are listed, in Table 3, only if they existed in at least 10 per cent of the student sample; a higher minimum value would possibly eliminate some valid alternative conceptions from the results (Peterson, 1986). They are grouped and discussed under the categories of bonding, lattices, intermolecular and intramolecular forces and electrical conductivity of graphite.

Bonding

The alternative conceptions relating to bonding show that some students in the sample were confused about the differences between covalent and ionic bonding. In item 1, only 16.7% of Secondary Four students pointed out that sodium chloride forms an ionic lattice. A high percentage of the students (80.4%) believed that sodium chloride exists as molecules, and 46.1% thought that one sodium ion and one chloride ion form an 'ion-pair molecule' (Taber, 1994).

Table 2 The percentage of Secondary Four (15–16 year-old) students (*n* = 119) selecting each response combination.

Item	*Answer chosen*	*Reason chosen*			
		A	*B*	*C*	*D*
1	I	22.5	46.1	7.8	3.9
	II	1.0	1.0	16.7*	1.0
2	I	0	2.9	0	0
	II	0	21.6*	13.7	61.8
3	I	20.0	2.0	46.0*	10.0
	II	3.0	9.0	4.0	6.0
4	I	5.1	14.3	3.1	50.0*
	II	1.0	2.0	24.5	0
5	I	29.4*	9.8	13.7	29.4
	II	5.9	2.0	7.8	2.0
6	I	18.0	2.0	3.0	10.0
	II	2.0	4.0	58.0*	3.0
7	I	8.2	7.2	21.6	9.3
	II	3.1	41.2*	6.2	3.1
8	I	21.4	21.4	5.8	33.0*
	II	4.9	7.8	0	5.8
9	I	17.8	24.8	27.7*	5.0
	II	6.9	5.0	10.9	2.0

Note: *This indicates the correct answer for the item.

Taber (1994) and Tan (1994) believe that a factor which encourages students to adopt the molecular framework could be the way ionic bonding is presented. Teachers illustrate ionic bonding by drawing the transfer of an electron from a sodium atom to a chlorine atom to form a positive sodium ion and a negative chloride ion. They then point to the pair of ions and say that the sodium and chloride ions are attracted by strong electrostatic forces. Thus the picture of a discrete unit of sodium chloride can be implanted in the minds of the students. Ionic lattices are typically only introduced a few lessons later when the students learn about the structure of solids; many of them would not make the link between the formation of ionic bonds and ionic lattices.

Some students have the idea that when atoms of metals and non-metals combine, they form covalent bonds. They see that by sharing electrons, the non-metals complete their octet of outermost shell electrons, but they neglect the outermost shell of metal atoms. They need to draw out the 'molecules' of ionic compound and have their attention focused on the fact that the metal atom cannot achieve a stable octet if it forms covalent bonds. Taber (1997) suggests that the

Table 3 Common alternative conceptions of chemical bonding held by Secondary Four (15–16 years old) students (n = 119).

Alternative conception	*Choice combination*	*Percentage of students holding the alternative conception*
Bonding		
Metals and non-metals form molecules	Item 1 [I]	80.4
Metals and non-metals combine to form molecules consisting of oppositely charged ions	Item 1 [IB]	46.1
Atoms of a metal and a non-metal share electrons to form molecules	Item 1 [IA]	22.5
A metal is covalently bonded to a non-metal to form a molecule	Item 6 [IA] Item 6 [IB]	18.0 10.0
Metals and non-metals form strong covalent bonds	Item 4 [IB]	14.3
Ionic compounds exist as molecules formed by covalent bonding	Item 3 [IA]	20.0
In ionic bonding, the number of electrons transferred depends only on the number of electrons that the atoms of the non-metal need to achieve a stable octet	Item 3 [ID]	10.0
Lattice		
A macromolecule is composed of covalently bonded molecules	Item 2 [IIC] Item 7 [C]	13.7 27.8
When atoms of an element are covalently bonded, they will form macromolecules	Item 7 [D]	12.4
The high viscosity of a molecular solid is due to the presence of layers of covalently bonded atoms	Item 9 [IA]	17.8
Simple molecular solids consist only of small molecules made up of two to four atoms	Item 7 [A]	11.3
Intermolecular and intramolecular forces		
Metals and non-metals form molecules with weak intermolecular forces	Item 4 [IIC]	24.5
There are strong intermolecular forces in a macromolecule	Item 2 [IID]	61.8
A macromolecule consists of molecules with weak intermolecular forces	Item 9 [IIC]	10.9
The strength of intermolecular forces is determined by the strength of the covalent bonds present in the molecules	Item 8 [IA]	21.4
Covalent bonds are broken when a substance changes state	Item 8 [IB]	21.4
Molecular solids consist of molecules with weak covalent bonding between the molecules	Item 9 [IB]	24.8
Electrical conductivity of graphite		
Graphite conducts electricity because it has layers of carbon atoms which can slip over each other	Item 5 [C]	21.5
Graphite conducts electricity because in graphite some carbon atoms are delocalised and they conduct electricity	Item 5 [D]	31.4

teaching of covalent bonding before ionic bonding could result in the learner tending to perceive ion-pairs as molecules and interpreting electrovalency as a determinant of the number of bonds a species forms (p. 94). This, together with the octet rule framework (Taber, 1998), could explain why in item 6, 18% chose IA and 10% selected IB to represent the species formed when A and B react.

In item 3, 10.0% (ID) did not have a thorough understanding of the octet rule in ionic bonding. They were able to apply it to ensure that both the metal and the non-metal ions had stable octets of electrons, but did not consider the ratio of the metal and non-metal ions required.

Lattices

The alternative conceptions relating to lattices indicated that students in the sample were confused with regard to the nature of continuous covalent and molecular lattices. As in Peterson *et al*. (1989), continuous covalent lattices and ionic lattices were often described as having molecular properties, and molecular lattices were often described as having properties of continuous covalent lattices. In items 2 and 7, many students believed that macromolecules are composed of covalently bonded molecules.

In item 9, 17.8% (IA) liken XYZ, a product with a smooth, thick, cream-like texture, to graphite; they tend to picture graphite as something viscous because of its lubricating property and not as a solid which can be deformed easily. In item 7, it would seem that some students take the term 'simple' to mean 'uncomplicated or small' and thus hold the alternative conception that the molecules in simple molecular lattices are made up of two to four atoms. Some students believed that macromolecules were big molecules formed when smaller molecules were bonded together; they did not understand that macromolecules are formed by covalently bonded atoms. The third alternative conception in item 7 might have arisen because some students overgeneralised what they had learnt about diamond, silicon and graphite, thinking that all covalently bonded atoms form macromolecules.

Intermolecular and intramolecular forces

The alternative conceptions relating to intermolecular forces illustrate that the students in the sample were confused about the nature of, and the difference between, intermolecular and intramolecular forces. In item 2, 61.8% (IID) indicated that strong intermolecular forces exist in a continuous covalent lattice. Peterson *et al.* (1989) reported similar findings, with 48% of grade 11 and 33% of grade 12 students having the same alternative conception. The Secondary Four students did not understand the nature of continuous covalent lattices and the forces in such lattices. An alternative explanation would be that they did not realise that silicon carbide is a macromolecule; they thought that silicon carbide forms simple molecules with one atom of silicon sharing four electrons with one atom of carbon. This might give rise to the belief that there are strong intermolecular forces in silicon carbide to explain its high melting and boiling points.

In item 8, 21.4% (IA) indicated that the strength of intermolecular forces is determined by the strength of the covalent bonds present in molecules. Peterson (1986) reported that 49% of grade 11 and 17% of grade 12 students in his study believed that covalent bonds are broken when a substance changes state; 21.4% (IB) of the students in this study have the same belief. The above showed that the students have not understood the nature of intermolecular forces in a molecular solid and the strength of intermolecular forces compared with that of the covalent bonds within a molecule, or what happens when a substance changes state and when it decomposes. More evidence of students' confusion about intermolecular and intramolecular forces can be seen in item 9, where 10.9% (IIC) stated that weak intermolecular forces exist in continuous covalent lattices and 24.8% (IB) indicated that molecular solids consist of molecules with weak covalent bonding between molecules.

Electrical conductivity of graphite

In item 5, the alternative conceptions relating to the electrical conductivity of graphite illustrate that the students in the sample did not understand the concept of delocalisation of electrons in graphite. Only 27.7% understood that only three of the four valence electrons in an atom of carbon in graphite are involved in bonding, the fourth electron being delocalised within the layers of atoms, giving rise to the electrical conductivity of graphite. A number of students (13.7%) believed that the movement of the layers of atoms in graphite gives rise to its electrical conductivity. This might be because they were taught that mobile electrons and ions conduct electricity and therefore the layers of atoms could also conduct electricity because they could move. More than a quarter of the students thought that 'delocalised atoms' were responsible for conducting electricity in graphite. In graphite, one carbon atom is bonded to three other carbon atoms, but in diamond one carbon atom is bonded to four other atoms. Thus students may believe that there are 'free' carbon atoms in graphite which move about and are responsible for conducting electricity.

Conclusions

The results from the administration of the chemical bonding diagnostic instrument agree with many of the findings from research on bonding conducted by, for example, Butts and Smith (1987), Peterson (1986), Peterson *et al*. (1989) and Taber (1994, 1997 and 1998). The study also highlighted another area of student difficulty in relation to understanding bonding, that is, the concept of delocalisation of electrons and the electrical conductivity of graphite. An important outcome of this study is the development of a diagnostic instrument that can be used by teachers of 14–16 year-old students studying chemistry.

To date, although considerable research has highlighted problems in students' learning about chemical bonding, there have been few avenues for classroom teachers to easily utilise this information. This pencil-and-paper, two-tier diagnostic instrument addresses this need. It is easy to administer and the results obtained can be analysed in a shorter time than student concept maps and interviews. The 'Chemical Bonding Diagnostic Instrument' allows teachers to assess their students' understanding of the concepts and propositional statements relating to chemical bonding, and to identify alternative conceptions during the course of instruction or immediately after the completion of the topic.

Duit, Treagust, and Mansfield (1996) state that investigating students' conceptions not only reveals important insights into students' ways of thinking and understanding, but can also help teachers to see their own views in totally new ways. This can result in major reconstruction of their science knowledge or their conviction of how this knowledge should be presented in class. Teachers will be more receptive and willing to try or develop alternative teaching strategies if they find that their present methods are inadequate in addressing students' difficulties. Thus the quality of teaching and learning would be raised as teachers would be teaching for understanding of concepts, and not merely for the acquisition of facts (Peterson *et al.*, 1989).

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Appendix: Chemical Bonding Diagnostic Instrument

1 Sodium chloride, NaCl, exists as a molecule.

I True **II** False

Reason

A The sodium atom shares a pair of electrons with the chlorine atom to form a simple molecule.

B After donating its valence electron to the chlorine atom, the sodium ion forms a molecule with the chloride ion.

C Sodium chloride exists as a lattice consisting of sodium ions and chloride ions.

D Sodium chloride exists as a lattice consisting of covalently bonded sodium and chlorine atoms.

2 Silicon carbide has a high melting point and high boiling point. This information suggests that the bonds in silicon carbide are:

I weak **II** strong

Reason

A Silicon carbide is a simple molecular solid.

B Silicon carbide is a macromolecule composed of covalently bonded atoms.

C Silicon carbide is a macromolecule composed of covalently bonded molecules.

D A large amount of energy is required to break the intermolecular forces in silicon carbide.

3 Element C (electronic configuration 2,8,18,8,2) and element E (electronic configuration 2,7) react to form an ionic compound, CE_2.

I True **II** False

Reason

A An atom of C will share one pair of electrons with each atom of E to form a covalent molecule, CE_2.

B A macromolecule consists of covalently bonded atoms of C and E.

C Atoms of C will each lose two electrons and twice as many atoms of E will each gain one electron to form an ionic compound CE_2.

D An atom of C will lose one electron to an atom of E to form an ionic compound CE.

4 The compound formed between magnesium and oxygen can be used as a heat-resistant material to line the walls of furnaces.

I True **II** False

Reason

A The lattice of magnesium oxide resembles that of silicon dioxide.

B The covalent bonds between magnesium and oxygen atoms are strong.

C The intermolecular forces between the magnesium oxide molecules are weak.

D There are strong ionic forces between magnesium and oxide ions in the lattice.

5 Graphite can conduct electricity because it has delocalised electrons.

I True **II** False

Reason

A Only three of the four valence electrons of a carbon atom are involved in bonding and the fourth electron is delocalised.

B Electrons escape from the covalent bonds in graphite and are free to move within the molecule.

C Graphite can conduct electricity because it has layers of carbon atoms which can slip over each other.

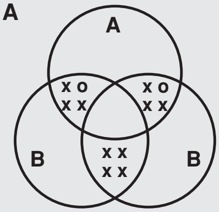
D Graphite can conduct electricity because in graphite, some carbon atoms are delocalised and they conduct electricity.

6 An atom of element A has two electrons in its outermost shell while an atom of element B has five electrons in its outermost shell. When A reacts with B, the compound will be:

I covalent **II** ionic

Reason

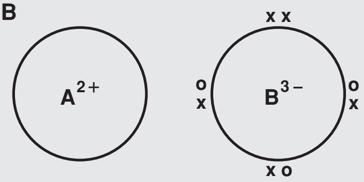
A



o represents an electron of A

x represents an electron of B

B



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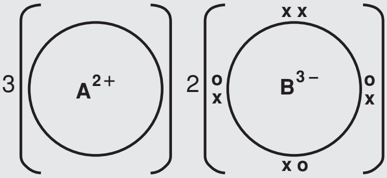

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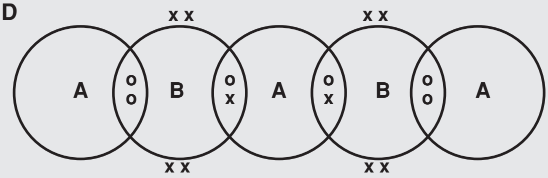

7 Sulphur atoms form rings consisting of eight atoms (S_8) covalently bonded together. From this information, it can be concluded that sulphur is a:

I macromolecule
II simple molecular compound

Reason

[See next column]

A Simple molecular solids consist only of small molecules made up of two to four atoms.

B Simple molecular solids consist of molecules with weak intermolecular forces between molecules.

C Macromolecules contain molecules which are covalently bonded together.

D When the atoms of an element are covalently bonded, they will form macromolecules.

8 Water (H_2O) and hydrogen sulphide (H_2S) have similar chemical formulae and structures. At room temperature, water is a liquid and hydrogen sulphide is a gas. This difference in state is due to:

I forces between molecules
II forces within molecules

Reason

A The difference in the forces attracting water molecules and those attracting hydrogen sulphide molecules is due to the difference in strength of the O–H and the S–H covalent bonds.

B The bonds in hydrogen sulphide are easily broken whereas those in water are not.

C The hydrogen sulphide molecules are closer to each other, leading to greater attraction between molecules.

D The forces between water molecules are stronger than those between hydrogen sulphide molecules.

9 A product XYZ has a smooth, thick, cream-like texture. Based on this, product XYZ would be classified as a:

I simple molecular substance
II macromolecule

Reason

A This cream-like substance is made up of layers of covalently bonded atoms.

B The thick, cream-like texture results from weak covalent bonding throughout the substance.

C The molecules in the substance experience weak forces between them and hence move to accommodate changes in the shape of the solid.

D The bonds within the molecules of the substance break easily to accommodate the changes in shape of the solid.

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