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## **An analysis of two textbooks on the topic of intermolecular forces**

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### **Abstract**

This paper describes the analysis of two commonly used high school (Grades 11 and 12) chemistry textbooks in Singapore to determine if the content presented in the topic of intermolecular forces is consistent with the concepts and propositional knowledge identified by the authors as essential for the learning and understanding of the topic



according to the Singapore high school chemistry syllabus. The authors found that the two textbooks did not adequately discuss the electrostatic nature of intermolecular forces, and the factors influencing the polarity of bonds/molecules, hydrogen bonding and instantaneous dipole-induced dipole interactions. The insufficient coverage of the above areas may lead to students having alternative conceptions of intermolecular forces as they may have incomplete or little understanding of the concepts involved and relationships between these concepts. Thus, teachers need to analyse textbooks carefully before using the textbooks so that they can be more aware of the difficulties that students may face when reading the textbooks, and attend to these areas by careful elaboration and integration of concepts in their lessons.

## Introduction

Textbooks in science education not only act as a general source of information on the subject for both teachers and students, they are also deemed as influential to the curriculum, coverage of content and teaching approaches (Chiang-Soong & Yager, 1993; de Jong, Acampo, & Verdonk, 1995; Eltinge & Roberts, 1993; Kirk, Matthews, & Kurtt, 2001; Sanger & Greenbowe, 1997, 1999). A study by Chiang-Soong and Yager (1993) found that teachers in United States used textbooks in excess of 90% of the time. The American students not only expected science lessons to be centered around textbooks but their parents also expressed grave concerns if textbooks were not issued and used for assignments. According to Eltinge and Roberts (1993), textbooks need to be carefully evaluated as they play a dominant role in school science. To make the learning from textbooks "meaningful, conceptually integrated, and active" (de Posada, 1999, p. 427), textbooks should not only be free from ambiguities and alternative conceptions, they should also present and explain information such that students can relate new material to that already learnt, and integrate both new and existing knowledge in a coherent way. Analysis of textbooks can indicate the procedures, content, sequences and activities that are used in the class, trends in science education, and the "pedagogical, psychological, and epistemological positions of textbook authors" (de Posada, 1999, p. 425). Numerous studies have been done on the analysis of textbooks as the sources of alternative conceptions (Cho, Kahle, & Nordland, 1985; Sanger & Greenbowe, 1999) and for use of analogy (Curtis & Reigeluth, 1984; Thiele, Venville, & Treagust, 1995). Textbooks also have been analysed to determine the treatment of topics and concepts (Dall'Alba et al., 1993; de Berg & Treagust, 1993; de Berg & Greive, 1999; de Posada, 1999; Palmer & Treagust,



1996; Shiland, 1997), the treatment of various issues of science literacy and goals of science education (Chiang-Soong & Yager, 1993; Wilkinson, 1999), and how science and scientists are portrayed (Eltinge & Roberts, 1993; Williams, 2002).

In a study by Sanger and Greenbowe (1999), ten college-level chemistry texts were analysed for examples of statements or drawings that could lead to alternative conceptions in electrochemistry. The authors found that many of the illustrations and statements used in the textbooks could be misconstrued by students, for example, the use of vague or misleading terms such as 'ionic charge carriers' and the constant drawing of the anode as the left-hand half-cell. A basis for textbook selection would be the extent to which textbooks contain vague, misleading or incorrect material (Sanger & Greenbowe, 1999); indeed, Cox (1996) reported the replacement of a series of science books in a school because of "excessive number of needless errors" (p. 23).

## Research Focus

This paper focusses on whether the concepts and propositional knowledge present in two chemistry textbooks commonly used by high school students in Singapore are consistent with the concepts and propositional knowledge required for the understanding of the topic of intermolecular forces as required by the Singapore high school chemistry syllabus. The textbooks were also analysed for ambiguous or problematic language and illustrations, and alternative conceptions. It needs to be noted that the two textbooks were not specifically written for the Singapore high school chemistry syllabus, so areas of inconsistency will be present. Teachers, however, need to know these areas of inconsistency to be able to address them in the classroom.

## Methodology

The content of a complex chemistry topic needs to be analysed and described in order to determine the relationship between the relevant concepts and the logical order in which the concepts should be presented (Taber, 2003). Content analysis helps teachers not to underestimate the complexity of a topic to a learner, which may lead to "assuming too much prior learning, or not allowing enough time to process the complexity of the new information" (Taber, 2003, p. 153). A concept map and a list of



proposition knowledge statements were drawn up by the authors to describe and relate the concepts in the topic of ionisation energy (see Tan & Chan, 2003) following the procedures suggested by Treagust (1995) to define the content framework of a topic.

Two commonly used approved high school chemistry textbooks in Singapore were analysed on the topic of intermolecular forces. The textbooks were:

HH: Hill, G. & Holman, J. (1989). Chemistry in Context 3rd Edition. Hong Kong: Thomas Nelson and Sons Ltd.

R: Ramsden, E. N. (1994). A-Level Chemistry 3rd Edition. London: Stanley Thornes (Publishers) Ltd.

In the textbook by Hill and Holman (1989), the topic of intermolecular forces was described in 19 pages and presented as a separate chapter from the chapter on chemical bonds which consisted of 14 pages. In Ramsden (1994), the topic of intermolecular forces was integrated within the topic of chemical bonds, and eight pages out of the total of 33 pages for the topic on chemical bonds were allocated to it. Text, illustrations (drawings and tables), and activities proposed were examined to determine if the concepts and propositions identified by Tan and Chan (2003) on the topic of intermolecular forces were mentioned and discussed in the two textbooks.

## Results and Discussion

The results of analysis of the two textbooks based on the propositional knowledge identified by Tan and Chan (2003) are given in Table 1 and discussed in the following sections below.

Table 1. Analysis of two textbooks based on the propositional knowledge statements identified by Tan and Chan (2003) on the topic of ionisation energy

	Propositional knowledge statements	HH	R
Nature of intermolecular forces			
1.	Intermolecular forces or van der Waals' forces are electrostatic attractions.	N	Y
2.	The electrostatic attraction is between simple discrete molecules.	Y	Y
3.	Intermolecular forces are very much weaker compared to conventional bonds (e.g., ionic, covalent and metallic) because the molecules involved are further apart and have weaker electrical dipoles.	N	Y <sup>1</sup>



4.	Intermolecular forces influence the physical properties (e.g., hardness and phase changes) of simple covalent compounds.	Y	Y
5.	Exothermic phase changes (e.g., condensation and solidification) involve the formation of intermolecular forces.	N	Y <sup>2</sup>
6.	Endothermic phase changes (e.g., melting and boiling) involve the overcoming of intermolecular forces.	Y	Y <sup>2</sup>
7.	Intermolecular forces account for the non-ideality in gases because they account for a greater decrease in volume with a pressure increment, i.e., the ideal gas equation, $pV = nRT$ , is not obeyed.	Y <sup>3</sup>	Y <sup>4</sup>
8.	At high temperatures, the particles of a gas have greater kinetic energy and move faster and more randomly, thus minimizing the effect of intermolecular forces.	Y <sup>5</sup>	N
9.	At low pressures, the particles of a gas are further apart, thus minimizing the effect of intermolecular forces.	Y <sup>5</sup>	N
Polarity of a bond/molecule			
10.	The type of van der Waals' forces present between molecules depend on whether the molecules involved have net dipole moments, $m$ .	N	N
11.	Differences in electronegativity between two atoms cause the displacement of the shared electrons between them.	Y	Y <sup>6</sup>
12.	Displacement of the shared electrons between two atoms results in the formation of a polar bond.	Y	Y <sup>6</sup>
13.	A polar bond has a dipole moment, $m$ .	N	N
14.	The vector sum of dipole moments gives the resultant net dipole moment of a molecule.	N	N
15.	The net dipole moment of a molecule depends on its structural geometry.	N	N
16.	The structural geometry of a molecule can be determined using the VSEPR theory.	N	Y <sup>7</sup>
17.	The electronegativity of an atom is related to its effective nuclear charge.	N	N
18.	The effective nuclear charge of an atom is dependent on its nuclear charge and the shielding of its nucleus by the inner core electrons.	N	Y <sup>8</sup>
19.	The effective nuclear charge of an atom affects the availability of any lone pair of electrons for hydrogen bonding.	N	N
Permanent dipole-permanent dipole interaction			
20.	If the net dipole moment of a molecule is not zero, it is known as a polar molecule.	N <sup>9</sup>	N
21.	Permanent dipole-permanent dipole interactions are present between polar molecules.	Y	Y
22.	Permanent dipole-permanent dipole interactions are important in aldehyde, ketone, ether, acyl chloride, ester and alkyl halide.	Y	Y <sup>10</sup>
Hydrogen bonds			



23.	Hydrogen bonding is a type of permanent dipole-permanent dipole interaction.	Y	N
24.	Hydrogen bonding is defined as the attraction of an electron deficient hydrogen atom, bonded to oxygen, fluorine or nitrogen atom of a molecule, for a lone pair of electrons on another oxygen, fluorine or nitrogen atom.	Y	Y <sup>11</sup>
25.	The availability of the lone pair(s) of electrons for hydrogen bonding follows the trend: H-N---H-N > H-O---H-O > H-F---H-F (in decreasing order from left to right).	N	N
26.	The bond polarity between a hydrogen atom covalently bonded to oxygen, fluorine or nitrogen follows the trend: H-F---H-F > H-O---H-O > H-N---H-N (in decreasing order from left to right).	N	N
27.	The strength of hydrogen bonding follows the trend: H-F---H-F > H-O---H-O > H-N---H-N (in decreasing order from left to right), since bond polarity plays a greater part in hydrogen bonding compared to the availability of lone pair(s) of electrons.	N	Y <sup>12</sup>
28.	The extensivity of hydrogen bonding depends on the number of sites available on the molecules involved.	Y	Y <sup>13</sup>
29.	More extensive hydrogen bonding in water results in it having a higher boiling point than hydrogen fluoride.	Y	N
30.	Hydrogen bonding can be intermolecular or intramolecular in nature.	N	Y
31.	Intramolecular hydrogen bonding can exist when functional groups capable of hydrogen bonding are in close proximity.	Y <sup>14</sup>	N
32.	Presence of intramolecular hydrogen bonding limit number of sites available for intermolecular hydrogen bonding, and this may result in lower boiling point or melting point.	N	N
33.	Hydrogen bonding results in dimerisation of simple carboxylic acid molecules.	Y	Y
34.	Hydrogen bonding is present in structures of proteins, carbohydrates and nucleic acid.	Y	Y
35.	Hydrogen bonding results in ice having an open structure.	Y	Y
<b>Instantaneous dipole-induced dipole interaction</b>			
36.	If the net dipole moment of a molecule is zero, it is known as a non-polar molecule.	N	N
37.	Non-polar molecules possess instantaneous dipole-induced dipole interactions.	Y	Y
38.	Polar molecules also possess instantaneous dipole-induced dipole interactions.	Y <sup>15</sup>	N
39.	The strength of instantaneous dipole-induced dipole interactions depends on the surface area of molecules involved.	Y <sup>16</sup>	Y <sup>17</sup>
40.	The greater the surface area of contact between molecules, the more extensive would be the instantaneous dipole-induced dipole interactions between the molecules involved.	Y	Y <sup>17</sup>
41.	The strength of instantaneous dipole-induced dipole interactions depends on the number of electrons in the molecules involved.	Y	Y
42.	The greater the number of electrons a molecule has, the greater the polarisability of its electron cloud, and hence the greater its electrical dipoles.	N	Y



43.	The surface area of a molecule can be a more influential factor than the number of electrons it has.	N	N
44.	Instantaneous dipole-induced dipole interactions can be stronger than hydrogen-bonding.	N	N

Note:

- 1 During the discussion of H-bonding.
- 2 In a diagram.
- 3 The non-ideality of real gases was ascribed to "existence of cohesive forces between non-polar molecules". (p. 116)
- 4 In the chapter on "Gases"
- 5 It was presented as a question "Why does this real gas equation reduce to  $pV=nRT$  at low pressure and high temperature?" (p.116)
- 6 In the discussion of intermediate bond types.
- 7 In the chapter on "The Shapes of Molecules".
- 8 In the section on "Ionic Bond".
- 9 Polar was defined as "positive charge center and negative charge center do not coincide".
- 10 In Organic Chemistry.
- 11 The "attraction to the lone pair" part was not mentioned.
- 12 In a question to compare the boiling point of  $\text{CH}_3\text{CH}_2\text{NH}_2$  and  $\text{CH}_3\text{CH}_2\text{OH}$ .
- 13 In a question at the end of the chapter.
- 14 In a diagram on hydrogen bonding in the coiled helical structure of proteins
- 15 In the example on estimating the strength of hydrogen bonds in water, "Remember, however, that molecules which are hydrogen bonded will also be attracted by van der Waals' forces." (p. 121)
- 16 The term "contact" was used.
- 17 The term "shape" was used.

### **Electrostatic nature of intermolecular forces**

Hill and Holman presented intermolecular forces as a topic separate from chemical bonds. This separation might prevent students from seeing the links between intermolecular forces and the other types of chemical bonds. Although Ramsden integrated intermolecular forces as a section of the topic of chemical bonds, there was no explicit discussion on the similarities and differences between intermolecular forces and other conventional chemical bonds. In addition, there were several statements in the textbooks which could cause difficulties for students. For example,



*These weak, short-range forces of attraction between molecules are known as Van der Waals' forces. Van der Waals' bonds are, of course, much weaker than covalent and ionic bonds.*

*(Hill & Holman, 1989, p. 116)*

The above statement might lead to students, who were novices in chemistry, to be confused with the terms "force" and "bond". From the electrostatic perspective (Taber, 1997), intermolecular forces were just another type of chemical bond which differed from other chemical bonds because the types of particles involved were different. Thus, emphasis should be placed on the electrostatic nature of chemical bonds irrespective of the types of bonds. If such a perspective was not emphasised, students would see intermolecular forces as very much different from other chemical bonds, and this might hinder the formation of a more coherent and meaningful conceptual framework (Taber, 1997).

Another problematic statement which required more elaboration was

*When molecules pack together in the liquid or solid state, there must be forces of attraction between them. J D van der Waals postulated the existence of forces of attraction and repulsion that are neither ionic or covalent. Such forces arise in a number of ways and are collectively called van der Waals' forces.*

*(Ramsden, 1994, p. 117)*

There was no mention of any force of attraction between gases in the section on van der Waals forces in Ramsden (1994), only between solids and liquids. This could be problematic as students might think that there were no van der Waals forces between gases, and these forces account for the non-ideal behaviour of real gases. In addition, the statements,

*"In the liquid state, the molecules of alcohols are associated by hydrogen bonding. Energy must be supplied to break these bonds when the liquid is vaporized..."*

*(Ramsden, 1994, p. 120)*

could give students the impression that when a liquid was boiled, intermolecular forces would be broken resulting in no intermolecular forces between the particles in a gas.



## **Polarity of a bond/molecule and permanent dipole-permanent dipole interactions**

There seemed to be a lack of integration between the concepts presented in the topic of intermolecular forces and those in topic such as atomic structure and valence bond theory. For example, both Ramsden and Hill and Holman did not attempt to discuss the polarity of a molecule from a net dipole moment perspective using the valence shell electron pair repulsion (VSEPR) theory. Students needed to use the VSEPR theory to deduce the shape, and from there, consider the vector sum of each of the individual dipole moments (qualitatively only, no calculation required) to determine whether the molecule was polar. If the dipole moments in a molecule did not cancel each other out, there would be a separation of both the positive and negative centers, and the molecule would be considered to be polar. If a molecule had a net dipole moment, there would be permanent dipole-permanent dipole interactions in addition to the instantaneous dipole-induced dipole interactions. If the molecule was non-polar, then there would only be instantaneous dipole-induced dipole interactions present. This would enable students to appreciate one rationale of learning the VSEPR theory. It would also be meaningful if the concept of dipole moment with the concept of electronegativity (which could also be related to the concepts of nuclear charge, shielding by inner shell electrons and distance from the nucleus). This would integrate the concepts from both the topics of atomic structure and intermolecular forces.

## **Hydrogen bonding**

Problematic statements on the nature of hydrogen bonding in Hill and Holman (1989) are highlighted in the following discussion.

*“Now, if we assume that  $H_2S$ ,  $H_2Se$  and  $H_2Te$  have intermolecular forces due only to Van der Waals' bonds (negligible H-bonding) we can estimate a value for the strength of Van der Waals' forces in water.”*

*(Hill & Holman, 1989, p. 120)*

Hill and Holman (1989) defined “H-bonding” as “extra strong intermolecular, permanent dipole-permanent dipole attractions” (p. 119) involving hydrogen atoms attached to N, O or F, so the statement that “negligible H-bonding” existed in  $H_2S$ ,  $H_2Se$  and  $H_2Te$  was misleading. Thus, permanent dipole-permanent dipole interaction should be used instead of the term “H-bonding”. Hydrogen bonding was also



described as “extra strong intermolecular, permanent dipole-permanent dipole attractions”. This statement might easily mislead students into thinking that hydrogen bonding was the strongest intermolecular force, and hence whenever there was hydrogen bonding between molecules, the physical properties (e.g., melting and boiling points) of the substances involved would be the highest; indeed Chan (2003) found such results when he interviewed students and administered a free-response test on intermolecular forces. Examples such as the states of iodine and water at room temperature should be given to illustrate that other factors need also be considered.

It was noticed that the trend of the strength of the hydrogen bonding of  $\text{HF} > \text{H}_2\text{O} > \text{NH}_3$  and the observed trend in boiling point were not explicitly explained. The bond polarity followed the trend,  $\text{H-F} > \text{H-O} > \text{H-N}$ , but the availability of the lone pair followed the trend,  $\text{H-N} > \text{H-O} > \text{H-F}$ . These two antagonistic trends combined to give the trend of the strength of hydrogen bonding as follows:  $\text{H-F} > \text{H-O} > \text{H-N}$ . This showed that bond polarity was a more important factor than the availability of lone pair(s) of electrons in this situation. However, the observed trend in boiling point was  $\text{H}_2\text{O} > \text{HF} > \text{NH}_3$ . This was due to more extensive hydrogen bonding between the water molecules because each water molecule could form two hydrogen bonds compared to hydrogen fluoride and ammonia which could form only one hydrogen bond per molecule. Again, students needed to consider additional factors, and could be at a loss to explain why water had the highest boiling point of the three substances based only on the strength of hydrogen bonding.

It was also noted that there was little discussion in both textbooks on the nature of intramolecular hydrogen bonding which could exist when functional groups capable of hydrogen bonding were in close proximity, and the effect of intramolecular hydrogen bonding in limiting the sites available for intermolecular hydrogen bonding.

### **Instantaneous dipole-induced dipole interactions**

Hill and Holman (1989) had not attempted to indicate that instantaneous dipole-induced dipole interactions did exist in polar molecules as given below.

*The existence of dipole-dipole attractions will explain the forces holding together polar molecules in liquids such as trichloromethane ( $\text{CHCl}_3$ ), propanone (acetone,  $\text{CH}_3\text{COCH}_3$ ) and nitrobenzene ( $\text{C}_6\text{H}_5\text{NO}_2$ ).*

*(Hill & Holman, 1989, p. 114)*



There are instances when instantaneous dipole-induced dipole interactions are the more prominent intermolecular force in play rather than permanent dipole-permanent dipole interactions. For example, the higher boiling point of hydrogen iodide as compared to hydrogen chloride could be explained by the stronger instantaneous dipole-induced dipole interactions between hydrogen iodide molecules.

There was also a lack of discussion on the factors that governed the strength of instantaneous dipole-induced dipole interaction, for example, the number of electrons a molecule had and its surface area. Iodine had a higher boiling point than nitrogen because it had more electrons than nitrogen, but methane also had a higher boiling point than nitrogen even though the number of electrons present in methane was less than nitrogen –in this situation, the surface area factor was more important. As mentioned in an earlier section, the states of iodine and water at room temperature should also be discussed to show that there were cases when instantaneous dipole-induced dipole interactions were stronger than hydrogen bonding. These examples, which showed the interplay of different factors in different situations, should be introduced to students to help them realise that they needed to carefully analyse the given physical data from various perspectives and consider all relevant factors. A summary of the major inconsistencies between the propositional knowledge identified by Tan and Chan (2003) and the content on the topic of ionisation energy in the two textbooks is given in Table 2.

Table 2. Summary of major inconsistencies between the propositional knowledge identified and the content of the two textbooks on the topic of intermolecular forces

	Major inconsistencies identified	Textbooks
1.	Intermolecular forces (IMF) were not discussed as electrostatic attractions which are very much weaker than conventional bonds.	HH, R
2.	Non-ideality of real gases was not related to IMF.	R
3.	Net dipole moment was not used to predict the molecular polarity.	HH, R
4.	Electronegativity was not related to nuclear charge, shielding by inner shell electrons and distance from the nucleus.	HH, R



5.	Hydrogen bonding was not mentioned as a type of permanent dipole-permanent dipole interaction.	R
6.	Trend of hydrogen bonding strength was not discussed.	HH, R
7.	The reason why water had a higher boiling point than hydrogen fluoride though its hydrogen bonding was weaker than that of hydrogen fluoride was not discussed.	R
8.	Intramolecular hydrogen bonding was not discussed in detail.	HH, R
9.	Presence of instantaneous dipole-induced dipole interactions for polar molecule was not emphasized.	R
10.	The number of electrons affecting the strength of instantaneous dipole-induced dipole interactions was not discussed.	HH
11.	The surface area of a molecule affecting the strength of instantaneous dipole-induced dipole interactions was not discussed.	HH, R
12.	Instantaneous dipole-induced dipole interactions could be stronger than hydrogen bonding was not discussed.	HH, R

## Conclusion

*“...the use of textbooks will only enhance learning if teachers use them with an awareness of the ideas that they are likely to promote. Textbooks should be used selectively to suit the approach and contexts that are of relevance to the course, as expressed in the course objectives. Accordingly, the objectives of a science course should not simply indicate what topics or concepts are dealt with but also the type of understanding to be developed.”*

*Dall’Alba et al. (1993, p. 634).*

It is important that the teacher uses textbooks appropriately to meet the learning objectives required by the local educational system. He/She must be aware that certain topics or concepts may not be adequately discussed in textbooks, especially if the textbooks were not specifically written for the local context, as in the case of this study. The teacher needs to identify the concepts which are not sufficiently elaborated



in the textbooks and discuss them with his/her students. He/She also needs to be aware of any problematic statements and illustrations. Thus, teachers need to analyse textbooks carefully before using the textbooks so that they can be more aware of the difficulties that students may face when reading the textbooks, and attend to these areas by careful elaboration and integration of concepts in their lessons.

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