

CONTENT FRAMEWORK FOR INTER-MOLECULAR FORCES

Kim Chwee Daniel, Tan

*National Institute of Education
Nanyang Technological University, Singapore
and*

Kim Seng, Chan

Raffles Junior College, Singapore

High school students have difficulty in understanding the concepts involved in intermolecular forces. A sound starting point for the teaching and learning of a difficult chemistry topic would be the clarification of the content framework that is required for the topic. Lists of propositional knowledge statements and concept maps should be drawn up to define the content framework for the topic to make explicit the essential concepts of the topic and how these concepts are linked to each other. In this paper, the authors described how the content framework for high school intermolecular forces was developed to facilitate the teaching and learning of intermolecular forces.

INTRODUCTION

The topic 'intermolecular forces' is usually taught in the early part of high school chemistry (Grades 11 and 12), subsumed under the main topic of chemical bonding. In Singapore, ideas about hydrogen bonding and other types of dipole-dipole interactions including those frequently termed 'van der Waals' forces' are taught mainly in the General Certificate of Education Advanced Level (A-Level) and tertiary chemistry courses. Most of the physical properties of

simple molecular gases, liquids and solids are determined by the strengths of intermolecular attractions, the electrostatic forces of attraction between neighbouring particles. In liquids and solids, these forces are much more dominant than in gases because of the lower energy and closer proximity of the particles; the electrostatic force falls off rapidly with distance. It is important to realise that attraction between molecules (intermolecular) are always much weaker than attraction within molecules (intramolecular). To understand and explain the physical properties of simple molecular solids, liquids and gases, students need to learn about the types of intermolecular forces and their relative strengths. Although they are all electrostatic in nature, it is useful to distinguish between them because different intermolecular forces may be involved in a chemical reaction. More importantly, it is necessary to link the concepts involved in intermolecular forces with the more fundamental concepts such as electronegativity differences between atoms which actually give rise to the intermolecular forces.

The topic of intermolecular forces has received relatively little attention from chemical education researchers unlike ionic and covalent bonding (Peterson & Treagust, 1989; Goh, Khoo, & Chia, 1993; Tan & Treagust, 1999; Barker & Millar, 2000; Harrison & Treagust, 2000; Schmidt, 2000; Taber 2001). Studies on bonding showed that students have great difficulty in understanding the concepts involved in bonding; intermolecular forces would be no different. Indeed, Chan (2003) studied Grade 11 and 12 students' understanding of intermolecular forces and found that the students had difficulty in comprehending the nature of hydrogen bonding and dipole-dipole interactions. He also found that many students could not determine the polarity of the molecules by analyzing the polarity of the bonds within the molecules, and hence, could not describe the intermolecular forces involved.

A sound starting point for the teaching and learning of a difficult chemistry topic would be the clarification of the content framework that is required for the topic (Tan, 2002). Lists of propositional knowledge statements and concept maps should be drawn up to define the content framework for the topic to make explicit the essential concepts of the topic and how these concepts are linked to each other. In this paper, the authors described how the content framework for high school intermolecular forces was developed (Chan, 2003) to facilitate the teaching and learning of A-level intermolecular forces.

DEVELOPING THE CONTENT FRAMEWORK

Four procedures (Tan, 2002) were used to limit and specify the subject content related to the topic, intermolecular forces. The steps were:

1. extract the relevant assessment objectives from the A-level Chemistry 9258 syllabus (2003 GCE A-Level Examination Syllabuses, n.d.) pertaining to intermolecular forces
2. develop a concept map,
3. identify the propositional knowledge, and
4. relate the propositional knowledge to the concept map.

The above procedures also form part of the procedures used to develop two-tier multiple choice diagnostic instruments (Tan & Treagust, 1999; Treagust, 1995)

A-level syllabus

There is no specific section in the A-level Chemistry 9258 syllabus (2003 GCE A-Level Examination Syllabuses, n.d.) on intermolecular forces. The main assessment objectives for intermolecular are found in the section on Chemical Bonding. Additional assessment objectives were extracted from other sections such as States of Matter

and Chemical Periodicity. It has to be noted that although nothing explicit is stated in the section on Organic Chemistry, it is very important to be able to apply the concept of intermolecular forces in the discussion of physical properties (melting point, boiling point, enthalpies of vapourisation and fusion, vapour pressure) of homologous series and compounds from different homologous series. All relevant assessment objectives on intermolecular forces are described in Appendix 1.

Concept map

The concept map (Figure 1) was prepared following the procedure described by Novak and Gowin (1984). The arrangement of the concepts is hierarchical with the more general, more-inclusive concepts at the top of the map, and the progressively more specific and less inclusive concepts arranged below. Related concepts are then linked by words describing their relationships. Figure 1 succinctly shows how concepts from different topics are related to those on intermolecular forces – the cross-links provide indicate the inter-relatedness of concepts. Hopefully, this will encourage them to seek such linkages rather than treat concepts in different topics as unrelated discrete units.

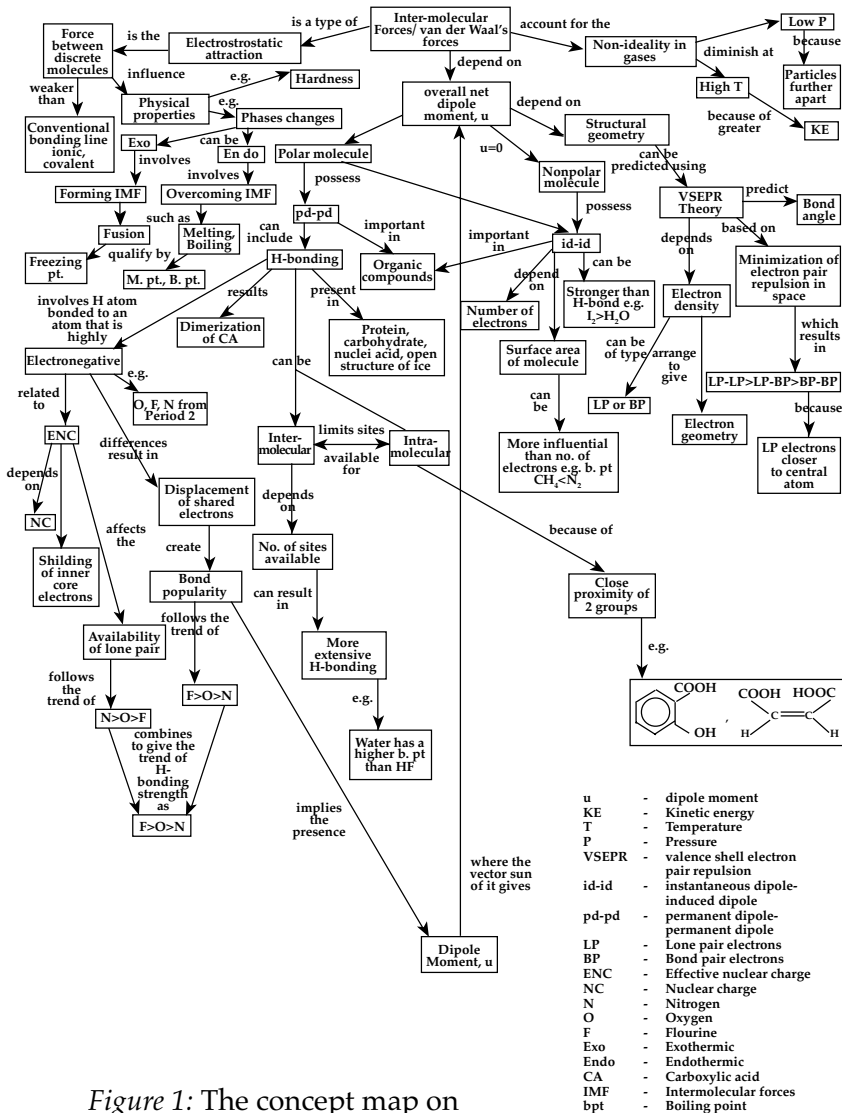


Figure 1: The concept map on intermolecular forces

Propositional knowledge statements

Propositional knowledge statements (Figure 2) were written for content and concepts relevant to the topic of intermolecular forces. The propositional knowledge statements were identified from the relevant assessment objectives (Appendix 1) on intermolecular forces and a recommended textbook. Content validity of the propositional knowledge statements and the concept map was established by subjecting all statements and the concept map to a review by a tertiary science education professor and two experienced chemistry teachers. The reviewers agreed that the concept map and propositional knowledge statements, in terms of accuracy and relevance, met the compiled assessment objectives of the A-Level Chemistry 9258 syllabus on intermolecular forces (Appendix 1).

1. Intermolecular force or van der Waals' forces is a type of electrostatic attraction.
2. The electrostatic attraction is between simple discrete molecules.
3. Intermolecular forces is very much weaker than conventional bonds like ionic, covalent and metallic because the particles are further apart and the electrical dipoles are usually weaker.
4. Intermolecular forces influence physical properties of simple covalent compounds such as hardness and phase changes.
5. Phase changes can be exothermic or endothermic.
6. Exothermic phase changes involve formation of intermolecular forces, for examples, condensation and solidification.
7. Endothermic phase changes involve overcoming of intermolecular forces, for examples, melting and boiling

8. Intermolecular forces account for the non-ideality in gases because it would result in a greater decrease in volume with a pressure increment, that is, it would not obey the ideal gas equation, that is, $pV = nRT$.
9. Non-ideality will diminish at high temperature and low pressure.
10. At high temperature, the particles have greater kinetic energy and move faster and more randomly, thus the intermolecular forces are weaker.
11. Low pressure will result in the particles further apart and thus weaker intermolecular forces between the particles.
12. The types of van der Waals' forces depend on whether molecule has a net dipole moment, m .
13. Electronegativity differences caused the displacement of shared electrons between two atoms.
14. Displacement of shared electrons between two atoms result in the formation of a polar bond.
15. A polar bond has a dipole moment, m .
16. Vector sum of dipole moments give the resultant net dipole moment of a molecule.
17. Electronegativity is related to the effective nuclear charge of the atom.
18. Effective nuclear charge is dependent on the nuclear charge and the shielding provided by the inner core electrons.
19. Effective nuclear charge affects the availability of the lone pair of electrons for hydrogen bonding.
20. If net dipole moment of a molecule is not zero, it is known as a polar molecule.

21. Polar molecules possess permanent dipole-permanent dipole interaction between the molecules.
22. Permanent dipole-permanent dipole interaction is important in organic compounds such as aldehyde, ketone, ether, acyl chloride, ester and alkyl halide.
23. Hydrogen bonding is a type of permanent dipole-permanent dipole interaction.
24. Hydrogen bonding is defined as the electron deficient hydrogen atom bonded to oxygen, fluorine or nitrogen, attracted to the lone pair of electrons on another oxygen, fluorine or nitrogen atom of a corresponding molecule.
25. Oxygen, fluorine and nitrogen atoms are highly electronegative atoms from Period 2.
26. The availability of the lone pair of electrons for hydrogen bonding results in the trend: $\text{H-N—H-N} > \text{H-O—H-O} > \text{H-F—H-F}$ (in decreasing order from left to right).
27. The bond polarity between a hydrogen atom covalently bonded to oxygen, fluorine or nitrogen follows the trend: $\text{H-F—H-F} > \text{H-O—H-O} > \text{H-N—H-N}$ (in decreasing order from left to right).
28. The strength of hydrogen bonding has the following trend: $\text{H-F—H-F} > \text{H-O—H-O} > \text{H-N—H-N}$ (in decreasing order from left to right), since bond polarity plays a greater part compared with the availability of lone pair.
29. The extensivity of hydrogen bonding depends on the number of sites available.
30. More extensive hydrogen bonding results in water having a higher boiling point than hydrogen fluoride.
31. Hydrogen bonding can be intermolecular or intramolecular in nature.

32. Intramolecular hydrogen bonding exists between close proximity of the groups, for example, 2-hydroxybenzoic acid and butenedioic acid.
33. Presence of intramolecular hydrogen bonding limits number of sites available for intermolecular hydrogen bonding formation, which may result in lower boiling point or melting point, for example, 2-nitrophenol has a lower boiling point than 4-nitrophenol.
34. Hydrogen bonding results in dimerisation of simple carboxylic acid molecules.
35. Hydrogen bonding is present in structure of proteins, carbohydrates and nuclei acid.
36. Hydrogen bonding results in open structure of ice.
37. If net dipole moment is zero, it is a non-polar molecule.
38. Non-polar molecule possesses instantaneous dipole-induced dipole interaction.
39. Polar molecule also possesses instantaneous dipole-induced dipole interaction.
40. Strength of instantaneous dipole-induced dipole depends on the surface area of the molecule.
41. The greater the surface area of contact between the molecules, the more extensive would be the instantaneous dipole-induced dipole interaction.
42. Strength of instantaneous dipole-induced dipole depends on the number of electrons in the molecule.
43. The greater the number of electrons, the greater the polarisability of the electron cloud and hence greater electrical dipoles would be created.

44. Surface area of the molecule can be a more influential factor than the number of electrons, for example, methane has a higher boiling point than nitrogen.
45. Instantaneous dipole-induced dipole interaction can be a stronger type of interaction compared to hydrogen-bonding, for example, iodine has a higher melting point than water.
46. The overall net dipole moment depends on the structural geometry of the molecule.
47. The structural geometry can be determined by the valence shell electron pair repulsion theory (VSEPR theory).
48. VSEPR theory is based on the minimisation of electron pairs repulsion in space.
49. VSEPR theory can be used to predict the bond angle of a molecule.
50. VSEPR theory depends on the number of electron densities around a central atom.
51. Electron densities can include a lone electron, lone pair of electrons, a dative covalent bond, a single covalent bond, a double bond and a triple bond.
52. The bonding electron pair and lone pair electrons arranged to give the electron geometry.

Figure 2: List of propositional knowledge statements for intermolecular forces

Relating propositional knowledge to the concept map

To ensure the list of propositional statements and the concept map were internally consistent, a matching of the propositional knowledge statements to the concept map was carried out. An example of the matching is shown in Figure 3.

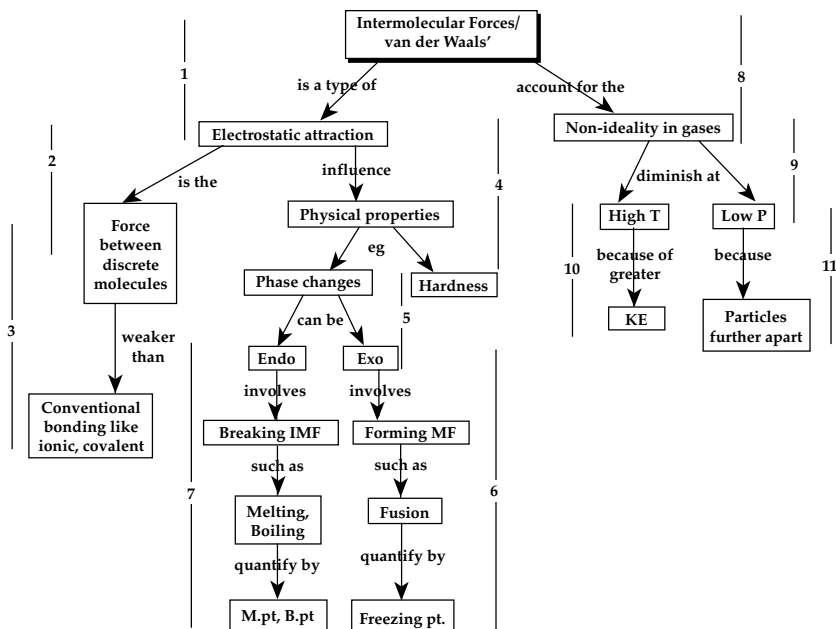


Figure 3: An example of relating propositional knowledge statements to the concept map

CONCLUSION

It can be seen from this paper that the content framework of A-level intermolecular forces is rather extensive. By making the content framework explicit, teachers can ensure that they have included all relevant concepts in the preparation of lessons, discuss the concepts during lessons, as well as show their students how the concepts are linked together. Students can also refer to the framework, especially the concept map, to get an overall picture of the topic of intermolecular forces to guide them in their learning of the topic. The content framework can also be used to develop diagnostic instruments, such as interview protocols, free-response questions and two-tier multiple choice tests, to determine students' understanding of intermolecular forces.

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Appendix 1

Extract of assessment objectives from the A-level Chemistry 9258 syllabus pertaining to intermolecular forces

Candidates should be able to:

Chemical Bonding

- (a) Predict the shape of, and bond angles in, molecules analogous to BF_3 (trigonal); CO_2 (linear); CH_4 (tetrahedral); NH_3 (pyramidal); H_2O (non-linear); SF_6 (octahedral); ethane; ethane; benzene.

- (b) Describe hydrogen bonding, using ammonia and water as simple examples of molecules containing -NH (including amines and amide) and -OH (including alcohol, carboxylic acid, phenol) groups.
- (c) Describe intermolecular forces (van der Waals' forces), based on permanent and induced dipoles, as in $\text{CHCl}_3(\text{l})$; $\text{Br}_2(\text{l})$ and the liquid noble gases.
- (d) Describe, interpret and /or predict the effect of different types of bonding (ionic bonding; covalent bonding; hydrogen bonding; other intermolecular interactions; metallic bonding) on the physical properties of substances.
- (e) Deduce the type of bonding present from given information.
- (f) Show understanding of chemical reactions in terms of energy transfers associated with the breaking and making of chemical bonds.

States of Matter

- (a) Explain qualitatively in terms of intermolecular forces and molecular size:
 - (i) the conditions necessary for a gas to approach ideal behaviour
 - (ii) the limitations of ideality at very high pressures and very low temperatures
- (b) Describe, in simple terms, the lattice structure of a crystalline solid which is:
 - (i) simple molecular, as in iodine
 - (ii) hydrogen-bonded, as in ice
- (c) Outline the importance of hydrogen bonding to the physical properties of substances, including ice and water.

- (d) Suggest from quoted physical data the type of structure and bonding present in a substance.

The Periodic Table: Chemical Periodicity

- (a) Interpret the variation in melting point and in electrical conductivity in terms of the presence of simple molecular, giant molecular or metallic bonding in the elements.
- (b) Suggest the types of chemical bonding present in chlorides and oxides from observations of their chemical and physical properties.

Group VII

- (a) Describe the trend in volatility and colour of chlorine, bromine and iodine.
- (b) Analyse the volatility of the elements in terms of van der Waals' forces.