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Students' Mental Model Profiles on Chemical Bonding Concept Using a Two-Tier Mental Model Diagnostic Test (TDM-Two-Tier)

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Abstract: This study aims to analyze students' mental models on the concept of chemical bonds using a two-tier mental model diagnostic test. A test with the first tier asking the content and the second tier asking the reasons for the answers at the first tier. The test used has been developed and declared valid with a degree of reliability 0.751. This research is qualitative research with a case study design. Students' mental models are categorized into complete mental models, partial mental models, mental models with misconceptions, and mental models with inconsistencies. In the concept of chemical bonds found 17, 9, 15, and 59% of students with complete, partial, misconceptions, and inconsistencies in mental models respectively. Most students have misconceptions by stating that ionic bonds are formed through atomization and the formation of bonding electrons by reason of the sharing of electrons in ionic crystals. In addition, students understand that the process of forming covalent bonds in oxygen and fluorine occurs because of the attraction between atoms which is greater than the repulsion between bonded atoms. Among the inconsistent concepts found are students explaining the phenomenon of solubility, boiling point, and melting point based on the concept of the electron cloud.

Keywords: chemical bonding concept; mental model profiles; two-tier diagnostic test

Introduction

The process of learning chemistry encourages students to form mental models. The mental model that is formed is based on students' understanding of the concepts that build a concept (Pagán, 2006; Yildirir & Demirkol, 2018). The mental model formed can be a complete mental model or an incomplete mental model (Kurnaz & Emen, 2014). Chemical phenomena are generally described using all three levels of chemical representation, so according to Johnstone (2000) the main difficulty of students in learning chemical concepts is their inability to understand concepts by involving the interrelation of three levels of representation to explain intrinsic properties. of an object or phenomenon (Johnstone, 2000). Students with wrong conceptions (misconceptions) or with unknown conceptions of the basis for taking them cause students to have incomplete mental models related to a concept.

Chemical bonding is a concept that is still considered difficult for students so students find many misconceptions about the concept of chemical bonds. The concept of chemical bonding is considered difficult by students because it requires students to understand concepts that involve proper submicroscopic explanations (Barke et al., 2008; Pérez et al., 2017; Sen & Yilmaz, 2017; Vrabec & Prokša, 2016; Wang, 2007). In addition, the concept of chemical bonds is a threshold concept for other chemical concepts (Park, 2015; Ulfa et al., 2020).

Profile analysis of students' mental models related to the concept of chemical bonds needs to be done to help teachers consider the design of learning that will be carried out in class. The description of the student's mental model profile can also be used as a teacher's consideration to direct learning that is more easily understood by students to avoid the formation of a mental model profile with inconsistent or unknown misconceptions or conceptions. The result of this

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research reveals students' mental models to help teachers to design and evaluate their learning. This result also helps teachers to understand how to diagnose or analyze students' mental models related to the concept of chemical bonding.

Diagnostic tests are tests used to identify and analyze students' conceptions. The diagnostic test used must consider the characteristics and potential of students, be time efficient, collect the understanding of each student, and can be easily mapped. Diagnostic tests can be performed by several methods (Coll & Taylor, 2002; Mulyani et al., 2016; Talanquer, 2015; Yildirir & Demirkol, 2018). Each method has advantages and disadvantages. Interview diagnostic tests, such as mental diagnostic tests, and interviews about event models, are often done. The interview test is preferred because it will get more complete data but the time required is very much, both for the interview process and for making transcripts and the assessment process is often subjective. A descriptive form test has also been carried out but this test will make it difficult for students with limited interests or abilities to write ideas while interviews are only suitable for students who can speak or convey good ideas. The essay form test is also difficult in terms of processing or assessment which takes longer. Single-level multiple choice form tests are considered to have a large luck guess factor. By using a two-tier diagnostic test, answers and reasons will form a pattern that provides information related to students' conceptions through the relationship between the two (Damanhuri et al., 2016; Mutlu & Şeşen, 2016).

The two-tiered multiple choice diagnostic test was first developed by (Treagust, 1988). This test was developed to facilitate the process of conceptual understanding or student conception. The two-tier type is a two-level test with the second level in the form of explanations or reasons related to the questions at the first level (Treagust, 1988; Tsui & Treagust, 2010). The relationship between answers and students at both levels will describe students' understanding so that more data is obtained than the one-level choice form and reduces the existence of elements of reason. This two-tier diagnostic test also facilitates the scoring process so that a large number of participants can be involved in one test (Adodo, 2013; Mulyani et al., 2016; Mutlu & Şeşen, 2016; Rahmawati et al., 2019; Tuysuz, 2009). Students who find it difficult to convey their understanding both orally and in writing will be helped when a diagnostic test is carried out using this test. Students will not find it difficult to explain orally or write long explanations because the second level is designed to be able to summarize all understandings that students may have.

Based on these considerations, in this study, a two-tier mental model diagnostic test was used to analyze the profile of students' mental models. The two-tier mental model diagnostic test was developed through several studies, namely curriculum analysis, multi-representation studies of chemistry, and literature on the conception of chemistry. Diagnostic tests are different from other tests in that each option in the item is different because it is based on variations in understanding that students may have.

The use of a two-tier mental model diagnostic test that integrates three levels of chemical representation to identify the mental profile of students' mental models on the colloid concept has been carried out. The two-tier mental model diagnostic test was proven to be able to identify the mental profile of students' models related to colloidal material and group them into three levels, namely intact, partial, and empty (Mulyani et al., 2016).

The results of previous studies revealed that students' misconceptions regarding chemical bonding material were caused by the inability of students to understand substances at the sub-microscopic level (Barke et al., 2008; Pérez et al., 2017; Sen & Yilmaz, 2017; Vrabec & Prokša, 2016; Wang, 2007). This two-tier mental model diagnostic test was also developed by linking the three levels of chemical representation to obtain an overall picture of students' understanding of chemical bonds. Each pattern of student answers will describe the consistency and relevance of student answers. The results of the analysis can distinguish students who only guess and have a correct and intact conception. Mental models and conceptions that have been identified using mental model diagnostic tests will help in the analysis of troublesome knowledge and threshold concepts of chemistry (Andriani et al., 2021; Delisma et al., 2020; Ulfa et al., 2020; Wiji et al., 2021) namely the further analysis of important or basic concepts and concepts that cause difficulties for students in learning chemical concepts. So that the two-tier mental model diagnostic test was used in this study to analyze the profile of students' mental models on the concept of chemical bonds.

Method

This research is a case study research that aims to analyze the profile of students' mental models on the chemical bonding concept. The analysis was carried out using a diagnostic test instrument, namely a mental model diagnostic test in the form of two-tier or two-tier multiple choice (TDM-Two-tier).

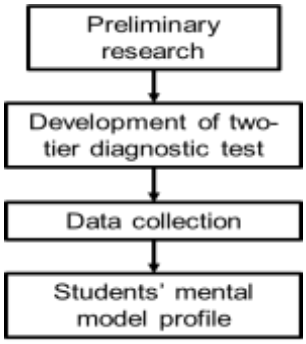


Figure 1. Research Flow Chart

The following is an explanation related to the stages of analysis in this research.

The first stage is a preliminary study; defining the concept, namely the analysis of basic competencies for the chemical bonding concept in the revised 2013 curriculum and multi-representation analysis of the chemical bonding concept in textbooks; studies related to mental model profiles, misconceptions, troublesome knowledge, and threshold concepts; development of a two-tier mental model diagnostic test. The test was developed by adapting and modifying the development stages proposed by Treagust, (1988).

The second stage is the development of a test that begins with developing a two-tier mental model diagnostic test item consisting of six two-tier multiple-choice questions to analyze the profile of students' mental models on chemical bonding concept. The first tier is a multiple-choice question which was developed based on the literature review and the second tier is a question related to the reasons for the first-tier answer which was developed based on the results of the student's misconception study on chemical bonding concept. Next, compose a key of determination containing the pattern of answers, descriptions, and types of mental models. The test was validated by five expert lecturers and revised based on the suggestions of the validators. Furthermore, a trial test was carried out in two schools, one of which was a private school in the city of Jakarta and one public school in the city of Bandung with a total of 38 students. The results of the reliability test using the Cronbach alpha test have a degree of reliability of 0.751 which can be categorized as high or already reliable.

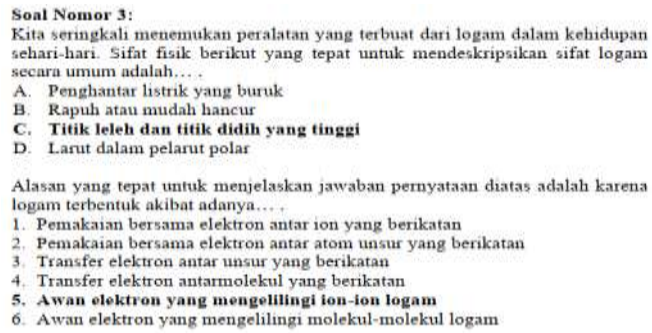
The two-tier mental model diagnostic test that had been developed in the previous stage was used in the next stage, namely the data collection stage. A total of 37 high school students from a public school in Bandung were given a two-tier TDM test. Students who are participants in this study are high school students majoring in natural sciences. Students have studied chemical bonding material in the previous semester. This research was conducted at the end of the semester, namely June-July 2022 in a public school in Bandung.

Student responses to the test were further analyzed to obtain an overview of the profile of the student's mental model. The student's mental model profiles were grouped and analyzed based on the type of mental model proposed by Wiji et al. (2021). The technique used was further adapted so that it can be used on TDM-Two-tier questions, more details can be seen in Table 1 below.

Table 1. Mental Model Types

Type	Student answer criteria on the two-tier diagnostic test
Complete Mental Model (CMM)	Students can answer both tiers correctly (students understand all three levels of representation).
Partial Mental Model (PMM)	Students can answer the first tier correctly but choose the wrong answer in the second tier. Students can answer the second tier correctly but choose the wrong answer in the first tier. *The answer options selected are related but inconsistent
Mental Model with Misconception (MM-MC)	Students choose the wrong answer on both tiers but the two answers are related (student answers are consistent and repeated).
Inconsistent Mental Model (IMM)	Students give answers that are irrelevant and inconsistent so that the rationale and decision are not known.

The following is an example of a two-tier question used to analyze the profile of students' mental models on the concept of metallic bonding.


Soal Nomor 3:
Kita seringkali menemukan peralatan yang terbuat dari logam dalam kehidupan sehari-hari. Sifat fisik berikut yang tepat untuk mendeskripsikan sifat logam secara umum adalah....
A. Penghantar listrik yang buruk
B. Rapuh atau mudah hancur
C. Titik leleh dan titik didih yang tinggi
D. Larut dalam pelarut polar

Alasan yang tepat untuk menjelaskan jawaban pernyataan diatas adalah karena logam terbentuk akibat adanya....
1. Pemakaian bersama elektron antar ion yang berikatan
2. Pemakaian bersama elektron antar atom unsur yang berikatan
3. Transfer elektron antar unsur yang berikatan
4. Transfer elektron antarmolekul yang berikatan
5. Awan elektron yang mengelilingi ion-ion logam
6. Awan elektron yang mengelilingi molekul-molekul logam

Figure 2. Example of a Two-tier Question used

Result and Discussion

The pattern of student answers will describe how students understand the concepts in the chemical bonding concept being tested. The test questions consist of 6 questions with 7 concepts that can be identified by the profile of the student's mental model, namely; the

concept of the formation of ionic bonds, the formation of covalent bonds, metallic bonds, solubility, and boiling points and melting points of substances based on the type of bond, hardness of substances based on the type of bond, and electrical conductivity of substances based on the type of chemical bond.

The pattern of student answers is then grouped based on the type of mental model so that it is known the profile of the student's mental model on the seven concepts or six questions. Students' mental models are grouped into CMM (Complete mental model), PMM (Partial mental model), IMM (Inconsistency mental model), and MM-MC (Mental model with misconceptions). The pattern of answers was analyzed based on the key of determination that had previously been developed. More details can be seen in the previous Table 1. The profile of students' mental models on each item tested is as follows.

Student mental model profile on the concept of ionic bond formation

The profiles of students' mental models on the formation of ionic bonds were analyzed using questions that in the first tier asked students to determine the process or stages of the formation of ionic crystals by providing the Born-Haber cycle as a symbol-macroscopic representation of the formation of ionic bonds. While in the second tier, students are asked to choose the right reasons to explain their answers in the first tier. The distribution of students' answers and the percentage of mental model types can be seen in Table 2.

Table 2. Distribution of Student Answers for the Concept of Ionic Bond Formation

Tier 1	*Tier* 2	Answer patterns	Mental model type	Percentage
True	True	A3	CMM	24.30
True	False	A4, A5, A6	PMM	10.80
		A1, A2, A7	IMM	10.80
False	True	B3, C3, D3	IMM	2.70
False	False	B4, B5, C7, D1	MM-MC	21.60
False	False	B1, B2, B6, B7, C1, C2, C4, C5, C6, D2, D4, D5, D6 dan D7	IMM	29.80

Students who choose the answer pattern A3 are students with the CMM mental model type. The student understands the process of forming ionic bonds in ionic crystals and can give reasons that are related, consistent, and following scientific concepts. Students with pattern answers A4, A5, and A6 are students with PMM generally students understand that there is an ionization process and attraction between ions in ionic crystals or understand that there is an electrostatic force on ionic crystals but students use other terms to define it such as using the term electron transfer or electron transfer. students do not understand that in ionic crystals there are only ions, not atoms of the elements that are bonded.

Students who choose the pattern of answers B4, B5, C7, and D1 are students with mental models formed from misconceptions or wrong concepts. These students understand that the process of forming an ion crystal occurs through atomization and electron sharing or ionization and the formation of an electron cloud and the reasons associated with these two concepts (Underwood et al., 2021). Students consistently define covalently bonded or metallic bonded ionic crystals. While students who have the IMM mental model choose a variety of answer patterns, students with this type of mental model do not understand the concept so they choose an answer pattern with inconsistent and unrelated understanding. Students understand that electrostatic forces on ionic bonds occur between atoms not between ions (B4) or students understand ionic bonds as a result of electron transfer between elements (B5). These findings are in line with the explanation of Barke et al. (2008) which states that one of the misunderstandings related to chemical bonds is the understanding that sodium chloride consists of sodium and chlorine atoms. Vrabec & Prokša (2016) also found that some students understand that sodium atoms and chlorine atoms attract each other and form NaCl.

Students who choose the answer pattern C1 and D1 are also students with the MM-MC mental model type. Students who choose the D1 pattern understand that ionic crystals are formed through the process of ion formation and consistently understand that the formation of ionic crystals is caused by the sharing of electrons between atoms of bonded elements. These findings are in line with the findings of Vrabec & Prokša (2016) which found that some students stated that there was the formation of a shared electron pair in ionic compounds.

Student mental model profile on the concept of covalent bond formation

Profiles of students' mental models on the concept of covalent bond formation were identified by using questions that in the first tier asked students to choose the most appropriate curve to describe the process of forming covalent bonds at O_2 and F_2. Students who understand the concept of covalent bond formation will be able to choose the right curve because they can understand the meaning of potential energy for bond formation and its relationship to atomic distance or bond length.

The distribution of students' answers on the concept of covalent bond formation can be seen in Table 3.

Table 3. Distribution of Student Answers for the Concept of Covalent Bonds

Tier 1	*Tier* 2	Answer patterns	Mental model type	Percentage
True	True	B1	CMM	2.70
True	False	B2, B3	IMM	29.70
False	True	A1	PMM	5.40
		C1, D1	IMM	8.10
False	False	C2, D2	MM-MC	21.60
False	False	A2, A3, C1, C3	IMM	32.50

Students with the type of mental model CMM are students who choose the answer pattern B1. Students with this type of mental model are students with an understanding that is following scientific concepts with a complete understanding. Students understand that the formation of covalent bonds requires a balance between the attractive and repulsive forces between the bonding atoms (Hunter et al., 2022; Nordholm & Bacskay, 2020; Zohar & Levy, 2019; Zwyssig, 2023). In addition, covalent bonds will form at a certain optimum distance until the most stable condition with the lowest potential energy is reached. Students with this mental model will be able to choose the right curve to describe the formation of covalent bonds in O_2 and F_2.

Students with the answer pattern A1 have an understanding that is by the scientific conception but their understanding is not complete or partial so their mental model belongs to the PMM type. Students understand that the potential energy on the curve shows that a covalent bond has been formed but students do not understand its relationship to the optimum distance or bond length. On the other hand, students understand well that in the formation of a covalent bond, there is a balance of repulsion and attraction between the bonding atoms.

Students with mental models built by misconceptions choose the answer pattern C2 or D2, students with this answer pattern choose to understand that the potential energy of the bond indicates the presence of an attractive force that is greater than the repulsive force and cannot choose the right scheme. Students consistently have a curve that describes that the optimum distance is reached when the attractive force between atoms is greater than the repulsion between covalently bonded atoms. Students who do not understand the concept of covalent bond formation and the meaning of potential energy and the relationship with bond distance will choose an unrelated and inconsistent answer pattern so that the basis for taking it is not known.

Student mental model profile on the concept of metallic bond

The students' mental model profile on the concept of metallic bonding was tested using the first tier questions that asked the physical properties of metals and the second tier asked the reason that there was a metallic bond, namely the existence of an electron cloud surrounding metal ions. The distribution of answers and types of students' mental models can be seen in Table 4.

Students with correct and intact conceptions will choose high boiling and melting points to define metallic properties because there is an electron cloud surrounding metal ions. While students with PMM choose the right properties but there are errors in the mention of metal constituent particles. Students with the MM-MC misconception assume that metals are covalently bonded and choose to state that metals do not conduct electricity. Furthermore, students with IMM will choose irrelevant answers such as choosing the wrong physical trait and giving unrelated reasons.

Table 4. Distribution of answers and types of mental models for the concept of metallic bonds

Tier 1	*Tier* 2	Answer patterns	Mental model type	Percentage (%)
True	True	C5	CMM	18.90
		C6	PMM	8.10
True	False	C1, C2, C3, C4	IMM	62.20
False	True	A5, B5, D5	IMM	0.00
False	False	A1, A2, B3, B4, D3, D4	MM-MC	5.40
False	False	A3, A4, A6, B1, B2, B6, D1, D2, D6	IMM	5.40

These findings are in line with the findings of previous researchers, namely metals have ionic bonds and covalent bonds formed due to electron transfer (Meltafina et al., 2019; Taber, 1998).

Profile of students' mental models on the concept of solubility, melting point, and boiling point of substances based on the type of chemical bond

The student's mental model profile was tested using questions that connected two concepts at once, namely solubility and melting and boiling points of substances based on the type of chemical bond. Students are asked to choose pairs of compounds with the same chemical bonds and to give reasons that define the

chemical bonds between them. The distribution of student answers can be seen in Table 5.

Table 5. Distribution of answers and types of mental models on the concept of solubility, melting point, and boiling point of substances based on the type of chemical bond

Tier 1	*Tier* 2	Answer patterns	Mental model type	Percentage (%)
True	True	C1	CMM	5.40
True	False	C2, C3, C4	IMM	2.70
False	True	A1, E1, B1, D1	PMM	16.20
False	False	A2, B3, D3, E2	MM-MC	18.90
False	False	A3, A4, B2, B4, D2, D4, E3, E4	IMM	56.80

Students who understand the concept will choose substances by considering the same tendency in both physical properties of substances while students with PMM will choose or consider only one physical property but the reason is still related to the first-tier answer. Students with misconceptions will choose related but incorrect patterns and students with IMM will choose a variety of answer patterns, some patterns indicate students only consider one trait in pairing these substances.

Profile of students' mental models on the concept of substance hardness based on the type of chemical bond

Profiles of students' mental models were analyzed using questions that asked students to choose the substance with the most brittleness of the several provided substances and the second tier asked students to choose reasons that were relevant to the chemical bonds in these substances. The distribution of student answers on the concept of substance hardness based on the type of chemical bond can be seen in Table 6.

Students with the CMM mental model profile, have a correct understanding of the concept of hardness of substances so that they will be able to choose the most fragile substance and connect it with chemical bonds of the substance, namely ionic bonds. Meanwhile, students who have PMM will choose the correct answer in the first tier but the reasons chosen are not appropriate, especially related to the use of the term electron transfer. Students with MM-MC will assume that metal or dry ice (carbon dioxide) is the most brittle substance and relate it to the concept of metallic bonds or covalent bonds. Meanwhile, students with IMM will choose an unrelated and inconsistent answer pattern.

Table 6. Distribution of Student Answers for the Concept of Substance Hardness by Type of Bond

Tier 1	*Tier* 2	Answer patterns	Mental model type	Percentage (%)
True	True	A1	CMM	27.00
		A5	PMM	10.80
True	False	A2, A3, A4	IMM	18.90
False	True	B1, C1	IMM	5.40
False	False	B2, C3	MM-MC	10.80
False	False	B3, B4, B5, C2, C4, C5	IMM	27.00

Profile of students' mental models on the concept of electrical conductivity of substances based on the type of chemical bond

Profiles of students' mental models related to the concept of electrical conductivity of substances based on the type of bond were explored using questions that in the first tier required an understanding of the macroscopic level, namely testing the electrical conductivity of substances related to the concept of chemical bonds. Students are also required to understand what affects substances can conduct electricity based on the form of the substance and its relationship to the type of chemical bond. The second tier requires students to choose the most appropriate submicroscopic level explanation to explain the test results data in the first tier. The distribution of student answers on the concept of electrical conductivity of substances based on the type of chemical bond can be seen in Table 7.

Students with a complete mental model of CMM will be able to choose the test with the substance being tested and the results of the appropriate electrical conductivity test. students will choose that molten NaCl conducts electricity because of the presence of free-moving positive and negative ions. Students with PMM can choose the right test but the reason is not right even though it is still related to the concept of ionic bonding. Students with the MM-MC will choose the wrong substance test and give reasons relevant to the chemical bonding of the substance. Meanwhile, students with IMM will choose irrelevant and inconsistent tests and reasons.

Table 7. Distribution of Student Answers for the Concept of Electrical Conductivity of Substances Based on the Type of Bond

Tier 1	*Tier* 2	Answer patterns	Mental model type	Percentage (%)
True	True	D3	CMM	24.30
True	False	D4	PMM	2.70
		D1, D2, D5	IMM	13.50
False	True	E3	PMM	0.00
		A3, B3, C3	IMM	21.60
False	False	A1, B5, C1, E4	MM-MC	16.20
False	False	A2, A4, A5, B1, B2, B4, C2, C4, C5, E1, E2, E5	IMM	21.70

The percentage of students' mental model profiles on the chemical bond concept is generally obtained by averaging each mental model profile for each of the concepts tested. So that it is known that the percentage of students' mental model profiles, in general, are CMM (17%), PMM (9%), MM-MC (15%), and IMM (59%).

Conclusion

Based on the results of the analysis, it is known that the overall profile of students' mental models on chemical bonding concept with intact conceptions or CMM mental models is 17% of students, with PMM at 9%, with misconceptions or MM-MC by 15%, and with unknown basic conceptions. taking and inconsistent or IMM by 59%. Students' misconceptions were found in the seven concepts tested. Some misconceptions that build mental models with misconceptions that exist in students include; Ionic bonds are formed through the process of atomization and sharing of electrons, in the formation of covalent bonds the attraction between the bonding atoms is greater than the repulsion force, metals are covalently bonded (shared electrons) so they cannot conduct electricity, the type of chemical bond only affects solubility and does not affect the tendency the boiling and melting points of a substance, covalently bonded substances are very brittle, metallic bonded substances are very brittle, nonaqueous HCl can conduct electricity, and NaCl can conduct electricity.

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Conceptualization, Dian Hasanah. and Wiji, Wiji.; methodology and design, Dian Hasanah.; validation, Sri Mulyani, Wiji. and Tuszie Widhiyanti.; formal analysis, Dian Hasanah.; investigation, Dian Hasanah.; resources and data curation, Dian Hasanah.; writing—original draft preparation, Dian Hasanah.; writing—review and editing, Dian Hasanah and Wiji, Wiji.; supervision, Sri Mulyani. and Widhiyanti, Tuszie.

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The authors declare no conflict of interest

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