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Student's Mental Model using Four-Tier Diagnostic Test on Acid-Base

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Abstract

The purpose of this study was to describe the mental model of students on the acid-base material class XI phase F. The type of research used is descriptive research with a quantitative approach. The research population consisted of students in class XI Phase F, and the research sample comprised 31 students from XI F9 at SMAN 2 Payakumbuh, using a purposive sampling technique. The data collection technique was conducted in two stages: the test stage and the interview stage. This test stage utilises a four-tier diagnostic test instrument, employing three levels of chemical representation. Then, the interview stage is conducted to gather data and confirm the results of the diagnostic tests that have been performed. The findings of this study detected that students have varied mental models. There are 41.1% have a mental model of synthesis-partial understanding B; 19.6% synthesis-partial understanding A; 15% initial model; 12.5% scientific model, and 11.8% synthesis-misconception. This is supported by the presentation agreement of the interview result with the diagnostic test.

Keywords: acid-base; four-tier diagnostic test; mental model; three levels of representation

Abstrak

Tujuan penelitian ini adalah mendeskripsikan model mental peserta didik pada materi asam basa kelas XI fase F. Jenis penelitian yang digunakan adalah penelitian deskriptif dengan pendekatan kuantitatif. Populasi penelitian adalah peserta didik kelas XI fase F, dan untuk sampel penelitian yang diambil yakni 31 orang peserta didik XI F9 di SMAN 2 Payakumbuh dengan teknik pengambilan sampel menggunakan teknik purposive sampling. Teknik pengumpulan data dilakukan dengan dua tahap yaitu tahap tes dan tahap wawancara. Tahap tes ini menggunakan instrumen tes diagnostik four-tier dengan penerapan tiga level representasi kimia. Kemudian untuk tahap wawancara dilakukan untuk mendapatka data dan mengkonfirmasi kembali hasil tes diagnostik yang telah dilakukan. Adapun temuan penelitian ini terdeteksi peserta didik memiliki model mental yang bervariasi. Terdapat 41.1% memiliki model mental synthesis-partial understanding B; 19.6% synthesis-partial understanding A; 15% initial model; 12.5% scientific model dan 11.8% synthesis- misconception. Hal ini didukung dengan persentase kesesuaian hasil wawancara dengan tes diagnostik.

Keywords: asam basa; model mental; tes diagnostic four-tier; tiga level representasi

Introduction

Chemistry is a science that includes complex and abstract concepts (Gabel, 1999). Abstract chemistry requires the application of three levels of chemical representation in the learning process. The three levels of representation are the macroscopic level, the submicroscopic level, and the symbolic level (Johnstone, 1991). Three levels of representation are significant in explaining a chemical phenomenon (Jansoon et al., 2009). However, in reality, the application of the three levels of representation in the school learning process is not yet complete. This can be seen from learning that focuses on the macroscopic and symbolic levels, while the submicroscopic level is often neglected. Whereas the explanation of chemical phenomena depends on the submicroscopic level because this level explains something that is not visible to the naked eye, and can be described at the level of molecules, atoms, and particles (Johnstone, 1982).

The incomplete application of the three levels of representation in the learning process will impact chemical understanding, resulting in the development of an incomplete mental model (Suja et al., 2021). A mental model is a representation of ideas or thoughts by students to describe, explain, and predict a phenomenon (Wang, 2007). A mental model is the ability to connect three levels of representation: macroscopic level, submicroscopic level, and symbolic level (Chittleborough, 2004). Mental models are very important because they encourage the development of a good understanding of a learner. This understanding will affect good critical thinking and higher-order thinking skills (Hillen, 2013).

According to Lin & Chiu (2010), learners' mental models are influenced by several factors, namely a) teaching methods in the school environment; b) teaching outside school; c) experiences experienced in daily life; d) social environment and e) cause-and-effect relationships and intuition. Mental models serve to support the creation of a good understanding. Learners with a good understanding can be reflected in the ability to think critically and think at a higher level. Therefore, this mental model needs to be studied to assess the extent of students' understanding and their thinking process (Wu et al., 2003).

The follow-up to assess students' ability to connect the three levels of chemical representation involves identifying mental models. When students are unable to connect the three levels of representation, it will impact the development of an incomplete mental model, which in turn affects their ability to solve problems, answer questions, and make predictions about chemical phenomena (Chittleborough, 2004). Therefore, identifying students' mental models is important, but based on the results of the interviews, no school has yet identified these mental models.

Identification of mental models can be done by giving diagnostic tests to students (Wang, 2007). Diagnostic tests are tools used to detect problems or difficulties learners experience with a concept, and are useful for educators as a basis for providing follow-up (Rusilowati, 2015). One of them is a four-tier diagnostic test, which involves four distinct levels. The first level is a multiple-choice question with several answer options, and the third level provides several options for why students choose an answer. Meanwhile, the second and fourth levels are confidence levels, which reinforce learners' understanding.

The four-tier diagnostic test has several advantages is being able to detect students' understanding of a concept with the addition of a level of confidence in choosing answers or reasons, by knowing the level of understanding of students so that it can be used as a tool to determine material that requires deeper understanding, and used as a reference for designing better learning (Jubaedah et al., 2017).

One of the materials that needs to be identified is the acid-base mental model. Acid-base is a complex material; acid-base material is interrelated with other concepts. Acid-base material is related to chemical reactions, chemical equilibrium, electrolyte and non-electrolyte solutions, and stoichiometry. Therefore, it requires an understanding of the concept as a whole to comprehend acid-base chemistry. In addition, acid-base is a prerequisite material for learning further material such as salt hydrolysis, buffer solutions, and acid-base titration. Therefore, it is necessary to have a complete understanding of acid-base material so that students can understand subsequent materials. Students' incomprehension of acid-base material will result in their not understanding the following material. Research conducted by Redhana et al. (2020) shows that students are not yet fully grasping the concept of acid-base materials. This can be seen from the study's results, which show that students predominantly have a synthesis mental model of acid-base material.

Method

This research employs a descriptive, quantitative approach. The study was conducted from May to June 2024 at SMAN 2 Payakumbuh, one of the schools in West Sumatra. The samples used in this study consisted of 31 students from grade XI F9, selected using a purposive sampling technique.

The research data collection was conducted through tests and interviews with students. The test instrument used is a four-tier diagnostic test adopted from previous research (Devi & Azra, 2023). This four-tier diagnostic test is one of the multilevel diagnostic tests. With the confidence level component in tiers 2 and 4, it is an advantage of this test so that it can detect students' understanding specifically. Besides that, interviews are no less important in this study, as the purpose of the interview is to obtain information and reconfirmation of the tests that students have done.

Data processing using descriptive statistical analysis. Classification of mental models based on the level of understanding of students, namely, mental models that have been developed previously (Kania et al., 2020). Mental models are grouped into 5, namely the scientific model, synthesis-partial understanding A, synthesis-partial understanding B, synthesis-misconception, and initial model.

This research begins with primary data collection, which involves conducting diagnostic tests on students, followed by the analysis of mental models using a mental model coding rubric, as shown in Table 1. This study also conducted interviews with students, where each student was asked four questions, each representing the learning objectives of the related material.

Table 1

Rubric Four-Tier Diagnostic Test

Tier Soal	Kategori																
	SU		**PU**					**PU-AC**					**MC**		**NU**		**NC**
1	B	B	B	B	B	B	B	B	S	S	S	S	S	S	S	S	S
2	Y	T	Y	T	Y	T	Y	T	Y	T	Y	T	Y	Y	T	T	NR
3	B	B	B	B	S	S	S	S	B	B	B	B	S	S	S	S	S
4	Y	Y	T	T	Y	Y	T	T	Y	Y	Y	T	Y	T	Y	T	NR

Source : Kania et al., (2020)

Description:

C : Correct

S : Sure

NS : Not Sure

I : Incorrect

NR : Not Respon

After the analysis is carried out based on the coding above, it will then be converted to a percentage using the formula below.

$$P = \frac{f}{N} \times 100\%$$

P : percentage number (%) per mental model category
f : number of learners per mental model category
N : total number of learners
(Mesran et al., 2022)

Result and Discussion

Mental model analysis is based on learners' answers using a coding rubric for a four-level test instrument. This coding technique categorises learners into several mental model categories. The mental model categories are scientific model, synthesis-partial understanding A, synthesis-partial understanding B, synthesis-misconception, and initial model

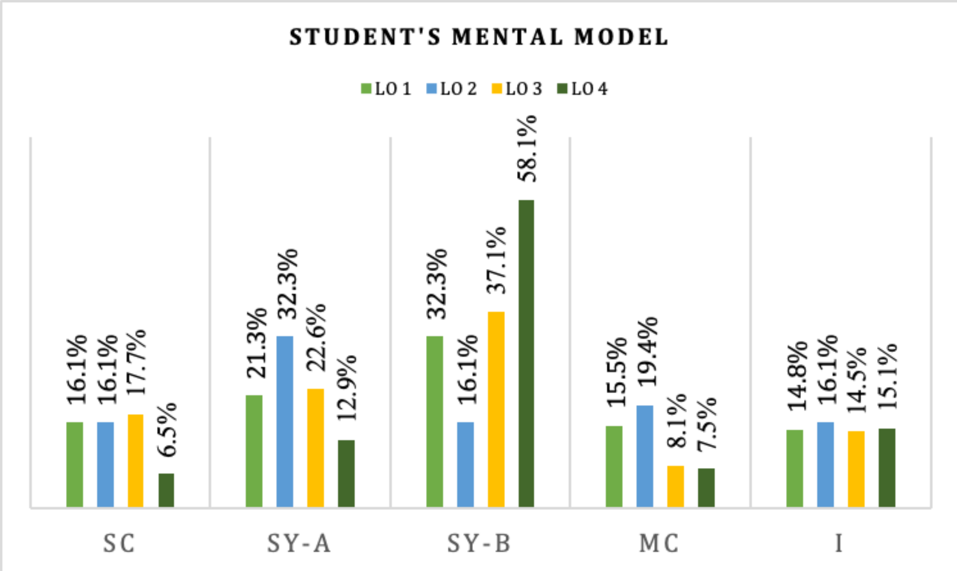
There are 15 items covering four learning objectives on acid-base material, namely the concept of acid-base based on theory, determining the nature of a solution based on indicators, acid-base strength, and the application of stoichiometry of acid-base solutions. The mental model of students is quite varied for each question. Analysis of mental models per question can be seen in Table 2 below.

Tabel 1
Analysis of mental models

Learning Objectives	No	Frequency and Categories of Student's Mental Model									
		SC		SY-A		SY-B		MC		I	
		f	%	f	%	f	%	f	%	f	%
Learning Objectives 1	1	6	19,4%	5	16,1%	11	35,5%	7	22,6%	2	6,5%
	2	2	6,5%	4	12,9%	12	38,7%	3	9,7%	10	32,3%
	3	5	16,1%	10	32,3%	10	32,3%	3	9,7%	3	9,7%
	4	5	16,1%	8	25,8%	9	29,0%	4	12,9%	5	16,1%
	5	7	22,6%	6	19,4%	8	25,8%	7	22,6%	3	9,7%
% 1		16,1%		21,3%		32,3%		15,5%		14,8%	
Learning Objectives 2	6	8	25,8%	12	38,7%	2	6,5%	6	19,4%	4	9,7%
	7	2	6,5%	8	25,8%	8	25,8%	6	19,4%	7	22,6%
% 2		16,1%		32,3%		17,7%		16,1%		19,4%	
Learning Objectives 3	8	7	22,6%	7	22,6%	11	35,5%	2	6,5%	4	12,9%
	9	4	12,9%	7	22,6%	12	38,7%	3	9,7%	5	16,1%
% 3		17,7%		22,6%		37,1%		8,1%		14,5%	
Learning Objectives 4	10	2	6,5%	0	0%	20	64,5%	3	9,7%	6	19,4%
	11	3	9,7%	0	0%	22	71,0%	1	3,2%	5	16,1%
	12	1	3,2%	0	0%	19	61,3%	3	9,7%	8	25,8%
	13	2	6,5%	9	29%	16	51,6%	1	3,2%	3	9,7%
	14	4	12,9%	5	16,1%	18	58,1%	3	9,7%	1	3,2%
	15	0	0%	10	32,3%	13	41,9%	3	9,7%	5	16,1%
% 4		6,5%		12,9%		58,1%		7,5%		15,1%	
% total		12,5%		19,6%		41,1%		11,8%		15%	

Based on Table 2 above, the dominant students have a mental model category "synthesis-partial understanding B", with a percentage of 41.1%. Overall, the total percentage for the special category of synthesis is 87.5%. This is supported by previous research, which reveals that in acid-base material, students dominantly have a synthesis mental model (Redhana et al., 2020). Students have a level of understanding, namely partial understanding with an alternative conception, meaning that students do not fully grasp the concept as a whole, as evident in their answers, which are correct at one level, whether at the first or third level. The distribution of students' mental models for each learning objective can be seen in the graph presented in Figure 2 below.

Figure 1
Student's Mental Model



The First Learning Objective

The first learning objective is to explain the concept of acids and bases based on theory. Students are presented with three acid-base theories: the Arrhenius, Brønsted-Lowry, and Lewis theories, which are covered in five questions, specifically questions 1 through 5. Based on the analysis in Figure 2, it is revealed that for this learning objective, the majority of students have a mental model of the "synthesis-partial understanding B" category.

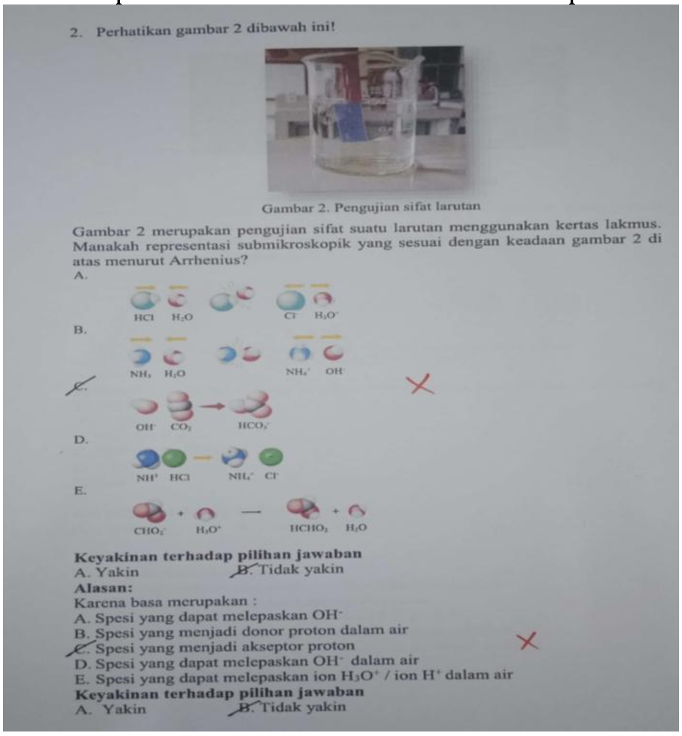
An interesting finding in question 2 is that, although most students within the first learning objective have a "synthesis-partial understanding B" mental model, the "initial model" mental model category has a relatively high percentage of 32.3%, as shown in Table 3. This question focuses explicitly on the Arrhenius acid-base theory. This question presents a macroscopic representation, namely, testing a solution using red litmus paper, where the colour changes to blue after dipping. Students are expected to be able to determine the submicroscopic representation based on the macroscopic representation provided.

However, the percentage in the "initial model" category for this question is relatively high. This is attributed to students' unfamiliarity with the submicroscopic level and their inability to connect the three levels of chemical representation. This is supported by student interviews indicating that the application of the three levels of chemical representation is not fully implemented in schools, as well as previous research by Suja et al. (2021).

Based on the analysis, students also have not fully distinguished between the

Arrhenius and Brønsted-Lowry theories. Generally, students reverse the interpretation of acids and bases in each theory. This is supported by previous research, which states that most students cannot distinguish between the two theories (Mubarokah, 2018).

Figure 2
An Example of a Student's "Initial Model" Response



Based on Figure 3, students chose option C as the answer to the question regarding the appropriate submicroscopic representation according to Arrhenius' concept, but they were unsure of their choice. Students selected option C because, according to them, bases are proton acceptor species, but they were also uncertain about the reason for their choice.

In this case, the students have not accurately determined the appropriate submicroscopic representation, and they are also unsure about the incorrect answer they selected. Similarly, the chosen reason does not align with scientific concepts, and the students also do not believe in the incorrect reason they provided. Based on the coding rubric, these students are categorised into the "initial mental model."

When testing a solution using red litmus paper, after dipping it, the colour changes to blue; therefore, the solution is a basic solution (Nivaldo, 2011). According to Arrhenius, a base is a species that produces OH- ions in water (Jespersen et al., 2012). However, students are unable to interpret the macroscopic level with existing theories, leading to incorrect choices of submicroscopic representations and, consequently, inappropriate reasons. It can be concluded that students are unable to connect the macroscopic, submicroscopic and symbolic levels.

The high percentage of the "initial model" for question number 2 is due to students being unfamiliar with the submicroscopic level and struggling to connect the three levels of chemical representation. This is supported by the results of interviews with students who stated that the three levels of chemical representation are not fully applied in school. Previous research has indicated that, based on an analysis of student learning, the submicroscopic level is challenging for students to comprehend (Hanif et al., 2013).

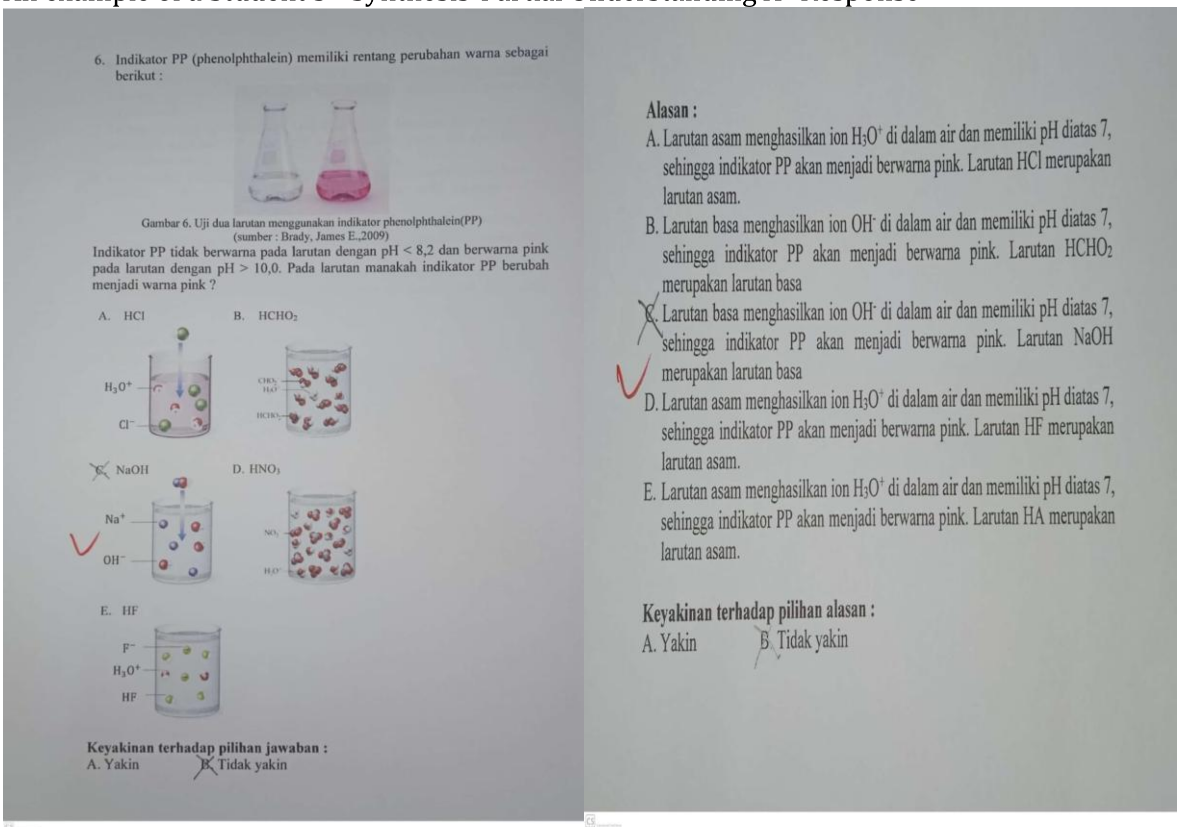
Another study found that students understand the macroscopic level better than the submicroscopic level (Rahayu & Kita, 2010).

The Second Learning Objective

The second learning objective showed that 30.6% of students had a mental model of "synthesis-partial understanding A." This category indicates that students have a correct understanding but are not yet confident in that understanding, as seen in questions 6 and 7. Question 6 is related to determining the properties of a solution using an indicator. In this question, students are given a scenario involving the testing of a solution's properties using the PP indicator (phenolphthalein). Based on Table 3, it was found that 11 out of 31 students answered correctly at the first and third levels but were unsure about their answers and the reasons they chose, indicating lingering uncertainty about the concept. The following is an example of a student's answer with a "Synthesis-partial understanding A" mental model for question number 6 presented in Figure 4 below.

Figure 3

An example of a Student's " Synthesis-Partial Understanding A" Response



Based on Figure 4, students interpreted that the solution, which would turn pink when dropped with the PP indicator, is a sodium hydroxide (NaOH) solution. However, even though this answer was correct, students were unsure of their initial choice. The reason students gave for choosing NaOH was that it is a basic solution, which produces OH- ions and has a pH above 7, and that adding PP indicator results in a change to pink. Nevertheless, students expressed uncertainty about this reasoning. Based on the coding rubric, these students demonstrate a partial understanding of the concept, categorised as a "synthesis-partial understanding A" mental model.

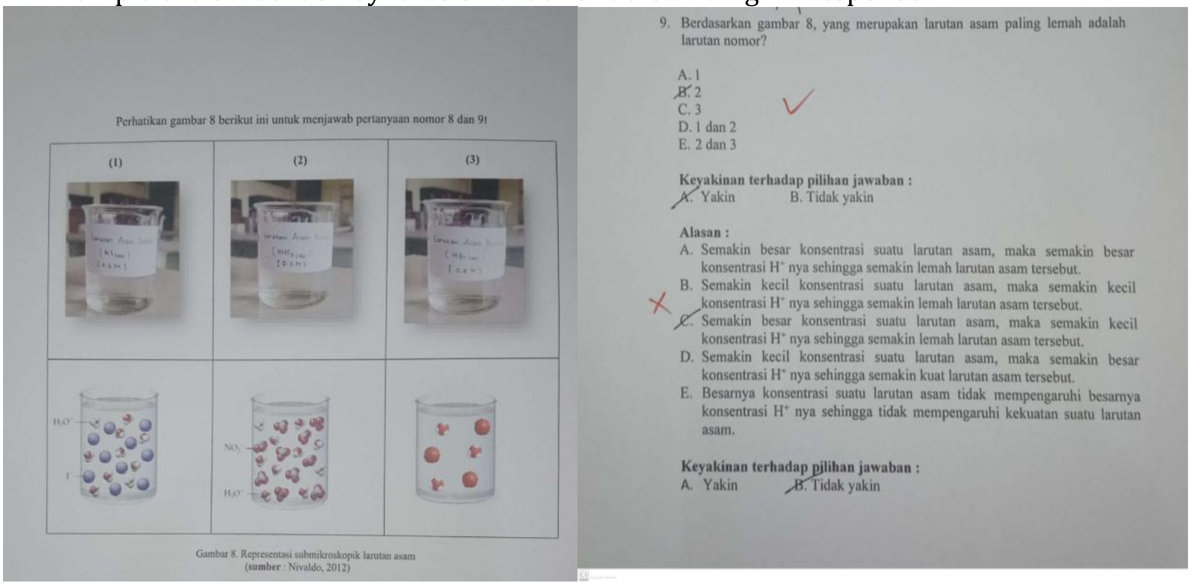
When the PP indicator is added to a solution with a pH > 10, it changes to pink (Chang, 2011). Therefore, a solution with a pH above 10 is a basic solution. Among the given options—HCl, $HCHO_2$, HNO_3, HF, and NaOH—only NaOH is a basic solution. The student correctly selected this option but was unsure of the answer. Thus, it is confirmed that the student possesses an understanding consistent with the concept, but there is still uncertainty regarding their comprehension.

The Third Learning Objective

The third learning objective, focusing on the subtopic of acid-base strength, an analysis of students' mental models (based on Figure 2), reveals that students predominantly hold a mental model in the "synthesis-partial understanding B" category, with a percentage of 37.1%. This is supported by the results of interviews with students, who still have an incomplete understanding of this concept. When asked whether a compound is strong or weak, students still answered incorrectly. This is consistent with previous research, which found that students experienced difficulty in determining whether a compound is an acid or a base.

Figure 4

An Example of a Student's " Synthesis-Partial Understanding B" Response



The image above displays one of the students' answers to question number 9. According to the student, the weakest acid solution is acid solution 2, HNO_3 0.2M, and the student was confident in their choice. The reason given for choosing the 0.2M solution was that as the concentration of an acid solution increases, the concentration of H+ decreases, making the acid solution weaker. However, the student was not confident in this reasoning.

The student misinterpreted the relative concentrations: 0.6 M, 0.2 M, and 0.4 M. According to the student, 0.6M is smaller than the others, and 0.2M is the largest. Additionally, the student's understanding of the relationship between concentration and the strength of an acid solution is not yet accurate. Concentration is directly proportional to acid strength; therefore, the higher the concentration of an acidic solution, the stronger the solution, and vice versa. In other words, they are still unable to determine acidity fully. This is also reflected in the results of interviews with students, who are still unable to fully distinguish between strong acids/weak acids and strong bases/weak bases. Referring to the coding rubric, these students have a mental model of the "synthesis-partial understanding B" category.

The Fourth Learning Objective

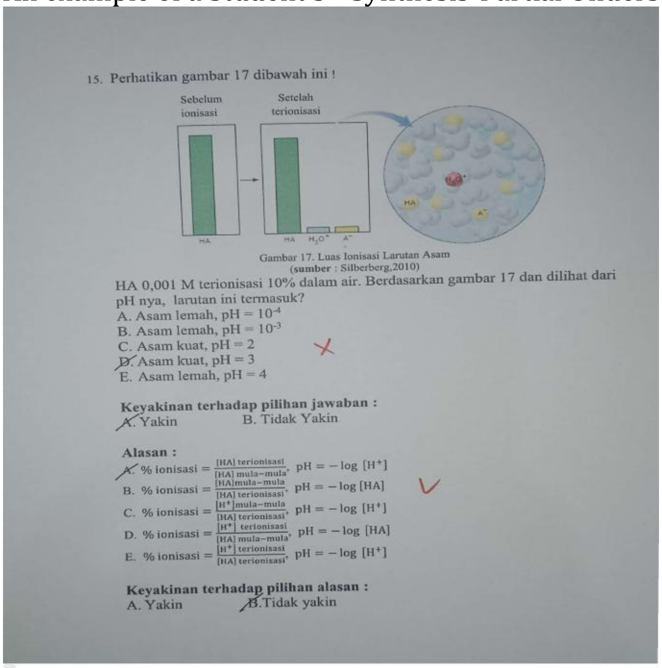
Based on Figure 2, it can be observed that in the fourth learning objective, the majority of students had a mental model of "synthesis-partial understanding B," with a significantly higher percentage compared to learning objectives 1, 2, and 3. Learning objective 4 focuses on the stoichiometry of acid-base solutions, which aligns with research by Utami et al. (2020) reporting that students also experienced moderate difficulty in this subtopic.

Learning objective 4 comprises six related questions (questions 10-15), specifically addressing acid equilibrium constants (Ka), base equilibrium constants (Kb), degrees of ionisation, and determining the pH of acids and bases. Analysis of students' answers reveals that while students are familiar with the formulas for determining pH, they struggle to apply them correctly in questions. This is evident from students' answers, which are generally correct at the third level (symbolic representation). In contrast, their responses to the main questions at the first level (macroscopic representation) are still inaccurate. This is supported by previous research stating that students lack proficiency in mathematical operations (S. Utami et al., 2022).

Additionally, students are also unable to determine submicroscopic representations and connect the three levels of chemical representation. This inability is attributed to the incomplete implementation of the three levels of representation in schools (Suja et al., 2021; Herawati et al., 2013). However, the application of the three levels of representation is crucial and significantly influences students' mental models (Murni et al., 2022). Previous research results and analysis of learning outcomes indicate that the submicroscopic level is particularly challenging for students to understand (Hanif et al., 2013). The following is one of the students' answers for learning objective 4, question 15 presented in Figure 6 below:

Figure 5

An example of a Student's " Synthesis-Partial Understanding B" Response



15. Perhatikan gambar 17 dibawah ini !

Sebelum ionisasi — Setelah terionisasi

HA | HA H_3O^+ A^-

Gambar 17. Luas Ionisasi Larutan Asam
(sumber : Silberberg,2010)

HA 0,001 M terionisasi 10% dalam air. Berdasarkan gambar 17 dan dilihat dari pH nya, larutan ini termasuk?

A. Asam lemah, pH = 10^{-4}
B. Asam lemah, pH = 10^{-3}
C. Asam kuat, pH = 2
D. Asam kuat, pH = 3
E. Asam lemah, pH = 4

Keyakinan terhadap pilihan jawaban :
A. Yakin   B. Tidak Yakin

Alasan :
A. $\% \text{ ionisasi} = \frac{[HA]\text{ terionisasi}}{[HA]\text{ mula-mula}}$, $pH = -\log [H^+]$
B. $\% \text{ ionisasi} = \frac{[HA]\text{ mula-mula}}{[HA]\text{ terionisasi}}$, $pH = -\log [HA]$
C. $\% \text{ ionisasi} = \frac{[H^+]\text{ mula-mula}}{[HA]\text{ terionisasi}}$, $pH = -\log [H^+]$
D. $\% \text{ ionisasi} = \frac{[H^+]\text{ terionisasi}}{[HA]\text{ mula-mula}}$, $pH = -\log [HA]$
E. $\% \text{ ionisasi} = \frac{[H^+]\text{ terionisasi}}{[HA]\text{ terionisasi}}$, $pH = -\log [H^+]$

Keyakinan terhadap pilihan alasan :
A. Yakin   B. Tidak yakin

Based on Figure 6, the student believed that the HA solution shown is a strong acid with a pH of 3, and they were confident in their answer. The reason given for choosing a pH of 3 was to use the ionisation percentage formula is,

$$\% \text{ ionization} = \frac{[HA]\text{ ionization}}{[HA]\text{ initial}}$$

pH =- log [H+]

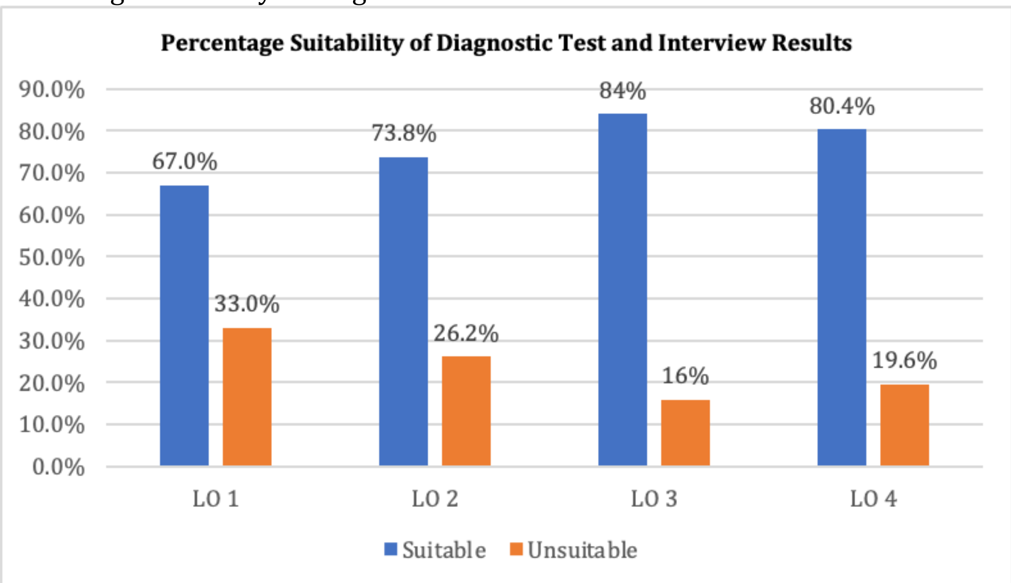
However, the student was unsure about the reasoning at the level three (symbolic representation) stage. Based on the coding rubric, these students have a mental model of "synthesis-partial understanding B."

Analysis of the response to question number 15 reveals that the student does not yet have a complete understanding. The submicroscopic representation of the acid solution shows that it is not fully ionised, with only 10% ionisation. According to chemical concepts, a partially ionised acid solution is a weak acid (Nivaldo, 2011). However, the student incorrectly believed that the acid solution was a strong acid with a pH of 3. This indicates a misconception, as the student assumed that a partially ionised solution is a strong acid. While the student successfully identified the correct scientific formula to use, they made an error in the mathematical operation to determine the pH of the solution. Thus, the student's primary challenge lies in mathematical operations, which aligns with the findings of S. Utami et al. (2022).

As explained earlier, this study also involved student interviews. These interviews served to reconfirm the students' test answers, verifying whether the results were based on their genuine understanding, cheating, or even guesswork. The interviews were divided into five groups, with each group being asked four questions representing each learning objective related to acids and bases. The results of the interview aligned with the four-tier diagnostic test, showing over 65% consistency. Thus, the diagnostic test analysis accurately reflects the students' understanding. Below is a graph showing the percentage of alignment between the test and the interview presented in Figure 7.

Figure 6

Percentage Suitability of Diagnostic Test and Interview Results



Based on Figure 7, the diagnostic test results showed a 65% alignment with the learning objectives assessed in the interviews. This high percentage confirms that the diagnostic test results accurately reflect the students' understanding. However, some students displayed discrepancies between their diagnostic test scores and interview responses. We assume this occurred because students either guessed their answers or copied from peers. Another contributing factor was the ineffective implementation of daily interviews (Tuesday-Friday) after the Final Semester Assessment (FSA), which likely led to reduced student focus.

Interview results from 31 students indicate that chemistry learning utilising the three levels of chemical representation hasn't been effectively implemented. This was evident in students' varying familiarity with the macroscopic, symbolic, and submicroscopic representations when questioned. This condition suggests that the general introduction of these concepts to students hasn't been consistently carried out in the learning process. Furthermore, interviews revealed that students' understanding of acid-base concepts was not comprehensive, as evidenced by their hesitation when asked to confirm their answers.

Based on the analysis of students' mental models regarding acid-base material, this can serve as valuable evaluation material for teachers in designing improved future learning processes. The aim is to cultivate students who not only memorise but also scientifically comprehend concepts, thereby facilitating their storage in long-term memory. A crucial method to achieve this is by effectively implementing the three levels of chemical representation in the learning process.

Conclusion

The analysis of students' mental models regarding acid-base material indicates that their understanding has not yet fully reached the expected scientific model. In reality, students' mental models varied across categories: scientific models, synthesis-partial understanding A, synthesis-partial understanding B, synthesis-misconception, and initial models. However, an interesting finding is that most students (41.1%) fell into the "synthesis-partial understanding B" category. In this case, students are still unable to connect the three levels of chemical representation. This study is expected to serve as a reference and evaluation material for educators to design integrated learning that effectively incorporates the three levels of chemical representation. This includes carefully planned strategies, models, methods, learning media, instructional materials, and evaluations. The primary aim of this effort is to improve students' mental models of the scientific model. This integrated understanding isn't only about mastering acid-base material but also equipping students with a more mature scientific framework for thinking when facing other chemical concepts.

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