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Misconception Propagation, Clustering, and Score Consistency in Acid-Base Submicroscopic Representations: A Bayesian Network and Machine Learning Approach

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ABSTRACT

Misconceptions in chemistry continue to challenge students' conceptual understanding, particularly in submicroscopic representations such as particle structure, solution properties, ionic interaction, and chemical reactions. This study aims to investigate the propagation of misconceptions, cluster students based on their misconception profiles, and analyze the consistency of scores about these patterns. The participants were 52 second-semester pre-service chemistry teachers who completed a diagnostic test consisting of four particle-level diagrams with open-ended questions. Bayesian Network analysis and Granger Causality testing examined probabilistic and causal relationships between misconceptions. Clustering analysis using K-Means and visualization through t-SNE identified three distinct student groups with varying misconception levels. Score consistency analysis using correlation, ANOVA, and regression revealed that misconceptions in particle structure strongly influenced errors in other concepts and were significantly correlated with lower scores ($r = -0.26$). Sankey diagrams demonstrated how misconceptions in early questions propagated to subsequent concepts, indicating error flow. The findings suggest that early identification and correction of key misconceptions are crucial, and clustering analysis can inform adaptive teaching strategies. This research highlights the importance of integrating causal analysis and machine learning in chemistry education research to understand better and address student misunderstanding patterns.

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1. INTRODUCTION

Misconceptions in chemistry education are still a widespread problem, especially in topics involving the submicroscopic level, and students rarely make links between their macroscopic activities and their symbolic and particulate representations (Putica, 2022; Locatelli et al., 2018). This comprehension gap, compounded by the traditional pedagogical approach focusing on non-active textbook representations and procedural sightings, results in long-lasting misunderstandings and weak problem-solving ability (Park et al., 2017; Dewi, 2022). Johnstone’s (1993) triplet model highlights the need for flexible inter-representation translation between macro, submicro, and symbolic representations if students are to be successful in learning chemistry (Chem-Education Research and Practice). Empirical studies, however, show that students typically face challenges in this regard (Gulacar et al., 2019; Gkitzia et al., 2020). Innovative means of instruction, including the CORE experiment and augmented reality, have increased the students’ representational competence by overcoming this discrepancy and, since then, have supported submicroscopic inquiry (Bruce et al., 2016; Ripsam & Nerdel, 2024). As a result, identifying these misconceptions requires embedding dynamic, multimodal teaching strategies to enhance students’ visualisation skills and understanding of concepts at different levels of representations.

Misconceptions in acid–base chemistry are extremely common and interconnected, including errors in the understanding of particle and ion configurations in solution, the relationship between concentration and pH, ionic treatments in acid–base equilibria, and the treatment of reactions in ionic form (Abell & Bretz, 2018; Locatelli et al., 2018; Rokhim et al., 2024). Students often misunderstand dissolved salts for neutral particles, rather than ions solvated by hydration shells, and depict incorrect ionic representations (Abell & Bretz, 2018). Moreover, some students have limited understanding about how variations in concentration relate to pH or equilibrium. For instance, students commonly hold misconceptions about acid strength and its consistent effect on pH (Novita et al., 2023; Siswaningsih et al., 2020). Ionic versus molecular aspects are also misconceptions, where students generally describe the hydrolysis product or cannot understand buffer systems (Orwat et al., 2017; Kusumaningrum & Kristyasari, 2022). Such misconceptions accumulate, so students' interpretations also experience the same misconceptions in the ionic chemical reaction (Rokhim et al., 2024; Rohmah et al., 2022). Additionally, the literature shows that misunderstandings in one topic, like rates of reaction, may affect understanding in equilibrium, thus demonstrating how errors are interconnected and, in turn, the significance of the implementation of diagnostic instruments to capture these connections (Jusniar et al., 2019; Kurniawan et al., 2020). Dealing with these nested misconceptions is possible by using pedagogical frameworks that couple representational competence with the ability to transition between macroscopic, sub-microscopic, and symbolic levels (Gulacar et al., 2019; Gkitzia et al., 2020).

Studies investigating student misconceptions in acid–base topics in the field of chemistry education have overwhelmingly employed two-tier diagnostic tests and descriptive analysis to understand prevalent errors in ion distribution, pH understanding, equilibrium, and ionic reaction representations (Abell & Bretz, 2018; Şekerci & Erdem, 2022; Bakti et al., 2022). Nonetheless, these studies have focused largely on the rate and form of confusions without considering how these confusions cut across the range of concept domains, constituting a significant void in the literature (Yüksel, 2019). To fill this gap, the Bayesian Network has been used to explore the probabilistic relation between misconceptions, allowing us to explore how misconceptions about basic knowledge at an early stage lead to misconceptions of a higher level (Huangfu et al., 2023).

In addition to this, *clustering algorithms*, such as the *K-means algorithm* and the *Hierarchical Clustering algorithm*, are also being commonly employed to cluster students according to their error patterns and learning profile in the diagnosis system, for the construction of more appropriate, finer-grained differentiations oriented to the teaching strategies (Wei & Lin, 2022; Najah et al., 2023). Furthermore, visualisations of *machine learning technologies* such as *Principal Component Analysis (PCA)* and *t-distributed Stochastic Neighbour Embedding (t-SNE)* have been used to reveal multidimensional structures and intricacies of students' misconceptions (Bakti et al., 2022). Notwithstanding these methodological improvements, few studies have reported entire mapping misconception propagation and clustering analysis with the help of score consistency, underlining the ongoing need for an integrated, data-driven model to efficiently diagnose and remediate stubborn and intertwined misconceptions in acid–base chemistry education (Rokhim et al., 2024).

This study aims to offer a new and holistic framework to help resolve existing difficulties concerning disseminating misconceptions through submicroscopic acid–base chemistry. In understanding the relationships among misconceptions, the paper combines the analysis from the *Bayesian Network* with *Granger causality*, highlighting probabilistic and temporal connections for the misconceptions, to provide an extensive view of their inner relationships (Huangfu et al., 2023; Wei & Lin, 2022). For even more detailed accuracy, *clustering* (i.e., *K-Means*) and *dimension reduction* (i.e., *t-SNE*) may be used to classify students according to their common patterns of misconceptions and to derive more targeted pedagogical support (Najah et al., 2023; Bakti et al., 2022). This work further investigates how the profiles of misconceptions are consistent into scores and how academic achievement can fit onto this score and to what extent can this model explain students' achievement through examination of consistency (under *regression* and *ANOVA*, (Şekerci & Erdem, 2022; Yüksel, 2019), and backed with the qualitative confirmation of the evidences of students' reasoning of why (Golestaneh & Mousavi, 2024; Omilani & Elebute, 2020) to supplement the comprehensive explanation. As such, this study attempts to identify how students' misconceptions spread across the classes, categorize students according to their misconceptions, and investigate the relationship between the misconception patterns and their achievement, supplemented by qualitative research. By combining these approaches in the same framework, this study is an original contribution to chemistry education research. We provide a coherent model for diagnosing and addressing the interrelatedness of misconceptions that has not been hitherto used within submicroscopic acid–base representations.

2. MATERIAL AND METHOD

Research Design and Participants

The research process applied in this study is presented in *Figure 1*. The procedure commenced by preparing and validating the instrument to check whether the tools are valid and reliable to trace misconceptions in four basic core chemistry topics at a sub-microscopic level: particle structure, solution properties, ionic interaction, and chemical reaction. Subsequently, data were collected in a teacher-supervised classroom, with

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students working through open-ended diagnostic tasks. Two independent raters coded the responses qualitatively to classify them as *correct*, *partial*, or a *misconception*.

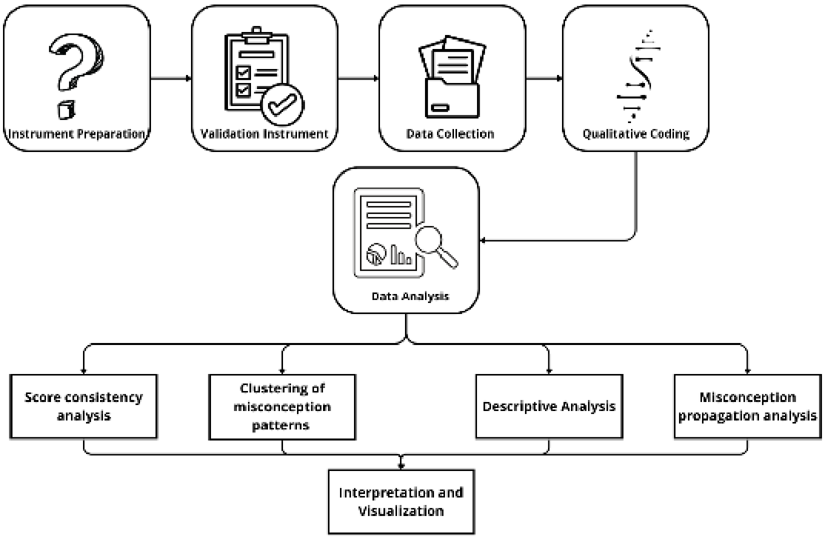

Figure 1. The Research Workflow Diagram

Subsequently, the coded data proceeded to the data analysis phase, which consisted of multiple components. Descriptive analysis was performed to identify the frequency and distribution of misconceptions across the four key topics. This was followed by misconception propagation analysis, using Bayesian Network and Granger Causality techniques to map causal relationships between conceptual errors. The study also performed clustering analysis through K-Means and t-SNE clustering methods to group students based on their misconception profiles. In addition, score consistency analysis using correlation, regression, and ANOVA was applied to relate misconception patterns to student performance. Finally, all analytical outcomes were integrated into the interpretation and visualization phase, using tools such as Sankey diagrams and t-SNE plots to present error flow and cluster patterns. As presented in Figure 1, this structured workflow ensured a comprehensive and systematic approach to diagnosing, analyzing, and interpreting the dynamics of misconceptions in chemistry education.

The participants were 52 second-semester chemistry teacher candidates at a public university in Indonesia who were part of one cohort group and were chosen using *total sampling*. Most students were 18–20 years old and had taken first-semester general chemistry, suggesting a common knowledge base. Students came from various academic profiles (*low*, *medium*, *high*) and thus from a wide range of achievement levels, making it possible to examine performance across levels. All students were informed why they were involved in the study and, before completing the diagnostic test, were first introduced to the purpose of the investigation and asked to give their informed consent for using their anonymized responses in the present study, which was obtained.

Instruments and Measurement

The instruments used in this study were an open-ended diagnostic test utilizing particle diagrams, based on the established framework proposed by *Taber* (2002). The test instrument consisted of four diagrams (Diagrams 1–4) that depicted various conditions of acid solutions through condensed submicroscopic visuals. Each diagram was followed by two open-ended questions: (1) the first asked students to identify the types of particles present in the diagrams (HA molecules, H_2O molecules, A^- ions, H_3O^+ ions), and (2) the second asked students to explain the properties of the depicted solution and compare it with other diagrams.

This diagnostic instrument assessed students' knowledge of central chemistry concepts, including particle structure, solution behavior, ionic interactions, and chemical reactions, as evidenced by their ability to interpret and reason through submicroscopic diagrams. The instrument's content was validated by two experts in chemistry education and a curriculum reviewer to ensure that it was grounded in theoretical constructs and educational relevance. The use of particle diagrams as a diagnostic tool in this study follows the approach advocated by Taber (2002), who emphasizes the value of visual representations in uncovering students' conceptual understanding (and their misconceptions) of chemistry.

Table 1. Final Instrumenent Structure

Indicator	Example Questions
Identify the types of particles in the solution as shown in the diagram.	What types of particles are shown in the solution represented in this diagram?
	How would you describe this solution?
Describe the properties of the solution by comparing the particle composition in the current diagram with that of Diagram 1.	What types of particles are shown in the solution represented in this diagram?
	How would you describe this solution (compared to diagram 1)?
Describe the properties of the solution by comparing the particle composition in the current diagram with Diagrams 1 and 2.	What types of particles are shown in the solution represented in this diagram?
	How would you describe this solution (compared to diagrams 1 and 2)?
Describe the progression of solution properties by comprehensively comparing the particle composition in the current diagram with Diagrams 1, 2, and 3.	What types of particles are shown in the solution represented in this diagram?
	How would you describe this solution (compared to diagrams 1-3)?

Data Collection

The diagnostic test was administered in a teacher-guided (classroom) setting, with students given 45 minutes to answer eight open-ended questions that targeted an understanding of acid–base chemistry through particle diagrams (Taber, 2002). Data were gathered, transcribed, and analysed thematically. Two raters coded each response as being correct (understanding completely, understanding partially) or incorrect (misconception) in terms of accuracy, completeness, and conceptual clarity (Bakti et al., 2022; Widarti et al., 2017). Inter-observer reliability was assessed using a *Cohen's Kappa correlation* coefficient of 0.82, reflecting strong agreement, and any disagreement was discussed to achieve uniformity and validity in the categorization process (Wahyono & Susetyorini, 2021).

Data Analysis

Using a multi-faceted approach, the data analysis in these studies revealed the prevalence, spread, and effect of the student misunderstandings, from a student misconceptions perspective in acid–base chemistry. Descriptive statistics were then used to determine the frequency and distribution of each misconception category. Bayesian Network analysis (in R: Free Educational Software for Statistics; and using the bnlearn package in R) and Granger causality testing (in Python: Statsmodels; statsmodels: Econometric and statistical modeling with Python) were then applied to statistically map probabilistic and temporal relationships between misconceptions and to reveal how misconceptions about basic particle structures drive misconceptions about more complex mechanisms of reaction (Corter & Lee, 2024; Sasongko et al., 2020). Clustering analyses (via K-Means and hierarchical methods in Scikit-Learn) enabled the clustering of misconception severity with the aid of dimensionality reduction techniques (PCA and t-SNE) for a better visual understanding (Pang et al., 2023).

For the assessment of how these misconception patterns influence learning outputs, consistency analysis of scores by correlation coefficients (Pearson, Spearman, and Kendall's Tau), ANOVA, and Kruskal–Wallis were employed to determine any statistically significant differences in scores among batches of learners (Farozin et al., 2022; Otu & Sefotho, 2024). We used linear regression models that yielded predictive information about associations between misconception levels and educational performance. Visualizations (heatmap, swarm plot, violin plot, dendrogram, and Sankey diagram) were produced using Matplotlib, Seaborn, and Plotly and provided a clear representation of the interplay and diffusion of processes across multiple regions (Matovu et al., 2023; Vos & Frejd, 2022).

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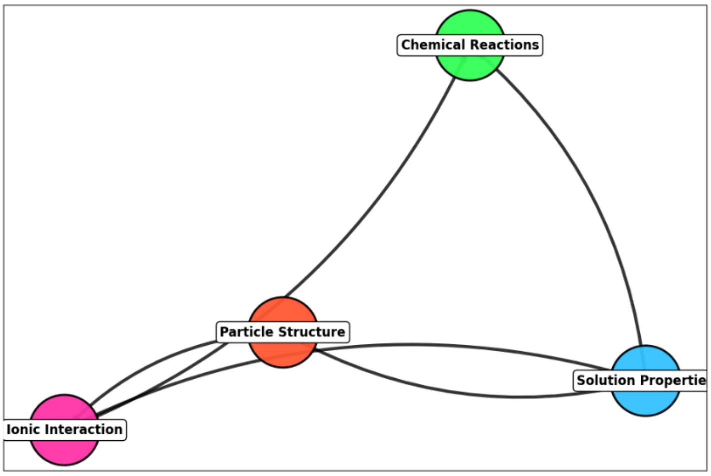
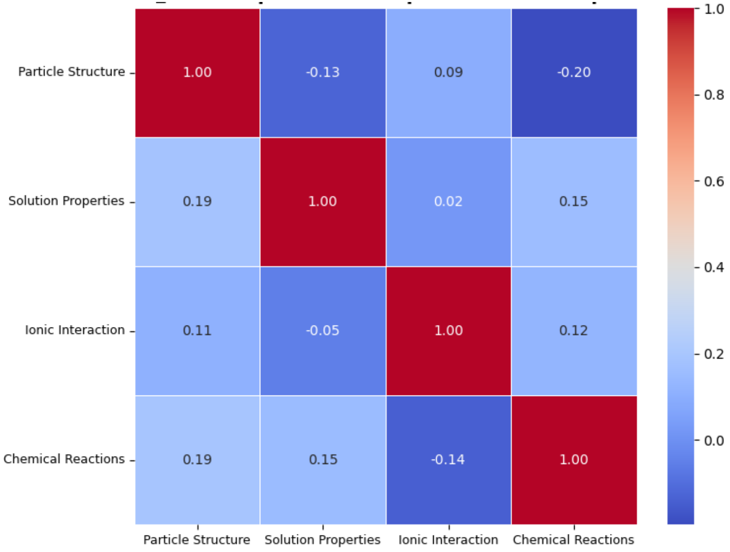
3. RESULTS

Misconception Propagation Analysis



□ Each node represents a misconception in a specific concept.
□ Arrows indicate the relationships between misconceptions.

Figure 2. Bayesian Network – Misconception Propagation



	Particle Structure	Solution Properties	Ionic Interaction	Chemical Reactions
Particle Structure	1.00	-0.13	0.09	-0.20
Solution Properties	0.19	1.00	0.02	0.15
Ionic Interaction	0.11	-0.05	1.00	0.12
Chemical Reactions	0.19	0.15	-0.14	1.00

Figure 3. Heatmap of Misconception Relationships

The misconception spread analysis based on *Bayesian Network* modelling and *correlation heatmap* provides a global impression about how a student's misconceptions in one concept area may spread to others. Figure 3 shows the pairwise correlation of misconceptions in the four related chemical topics of *particle structure*, *solution properties*, *ionic interaction*, and *chemical reactions*. Despite a weak to moderate correlation, they show a large systematic error spread. The strongest positive correlations are between *particle structure* and *solution properties* (r = 0.19) and between *particle structure* and *chemical reactions* (r = 0.19). This reveals that those students who exhibit misconceptions at the particle level are also more likely to exhibit difficulties in interpreting the macroscopic behavior of solutions and reaction mechanisms. Additionally, since the relationship between *solution properties* and *chemical reactions* is positively correlated (r = 0.15), it implies that students lack a correct understanding of solution behaviour, which subsequently affects their ability to conceptualize chemical reactions correctly.

One interesting difference occurs when comparing *chemical reactions* with *particle structure* (r = -0.20) and *ionic interactions* (r = -0.14), which means that some students might separate these concepts without integrating their understanding among these and across different representational levels. The partial

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compartmentalization is problematic since students cannot develop solid conceptual bridges between particle-level behavior and macroscopic phenomena.

The *Bayesian Network* diagram (see Figure 2) sheds additional light on these associations and shows the directionality of misconception flow. Arrows downstream from the *particle structure* node toward *solution properties*, *ionic interactions*, and *chemical reactions* convey that misconceptions at the particle level are fundamental and manifest at higher levels of conceptual organization. It shows that erroneous preconceptions about how particles move and interact at the molecular scale give rise to specific systematic misinterpretations of solution concentration, ion making, and reaction dynamics. A student who does not understand that weak acids ionize only partially at the particle level may have difficulty explaining why a solution has a higher or lower pH and may incorrectly balance chemical equations or predict reaction outcomes.

This conceptual mode of fragility is consistent with the results of Gulacar et al. (2020) and Golestaneh & Mousavi (2024), who found that the organisation of chemical knowledge in students is hierarchical and can be significantly disrupted by students' early misconceptions. In the absence of targeted instructional interventions (e.g., scaffolding (see Desjean-Perrotta et al., 2023), cognitive conflict strategies (Ningrum et al., 2022), and visual model-based learning (Matovu et al., 2023), these misunderstandings might become canalized and generalized to advanced topics, and learners' performances may end up restricted to simple problems. These findings highlight the importance of instructional approaches that improve submicroscopic conceptual comprehension. The timely identification of particle-level misconceptions using diagnostic testing and clustering analysis is essential. Breaking through these misconceptions helps teachers to provide differentiated learning involving visual models, hands-on experiences, and explicit reasoning. This will ultimately be conducive to realizing *representational competence*, facilitating student transitions between particle-level explanations with macroscopic phenomena and symbolic representations that will power deeper, more accurate understanding of chemical phenomena.

Misconception Clustering

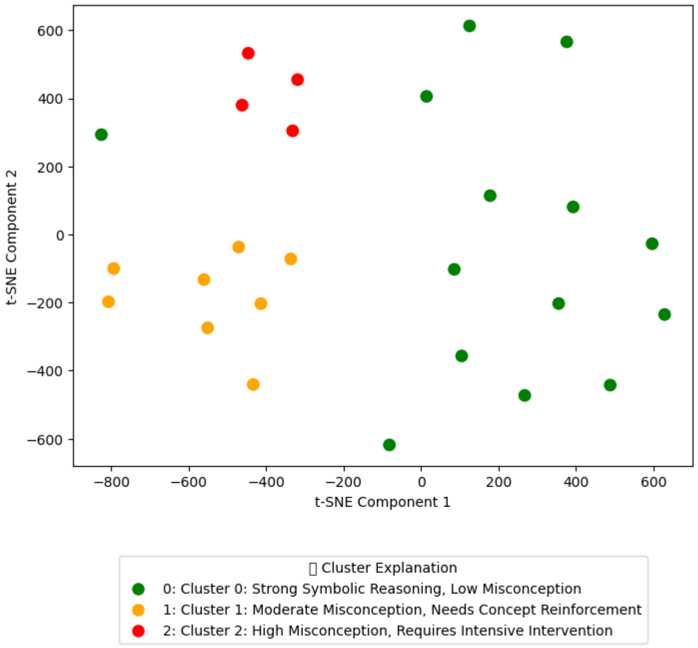

Figure 4. t-SNE Plot of Misconception Clustering

The *t-distributed stochastic neighbour embedding* (*t-SNE*) clustering analysis revealed three clusters of students according to their misconception patterns (Figure 4). *Cluster 0*: Green points correspond to students with strong symbolic reasoning and few misconceptions. These students can coordinate submicroscopic, macroscopic, and symbolic levels and comprehend acid strength, ionization, and equilibrium behavior well. *Cluster 1*: Represented by the orange color, represents students with a medium level of misconceptions. They exhibit some conceptual understanding but have difficulty fully understanding the relationship between ion interaction and equilibrium, for which reinforcement of directed learning and guided self-learning may be indicated. Most importantly, *Cluster 2* is a group of students with high misconceptions and fragmented reasoning levels, shown in red. These nonmechanistic responses with a purely phenomenological explanation refer only to the macroscopic behaviors and the symbolic equations and leave out the particular relationships between the particles and the macroscopic appearances.

The clear separation between clusters in Figure 4 indicates that misconceptions manifest as structured clusters, not singular mistakes. These trends mirror varying learning needs that demand diverse pedagogies. For students in *Cluster 2*, intensive support from explicit instruction and scaffolding is required to construct submicroscopic knowledge. These results are from those of Widarti et al. (2017) and Adu-Gyamfi & Ampiah (2019) concerning using cognitive conflict strategies, directed feedback, and utilizing various representations to address misconceptions. Hence, the development of cluster-based diagnostic tools can be a valuable resource for educators in designing adaptive learning interventions that gradually complement students as they construct a more coherent and scientifically accurate understanding of acid strength and related chemical phenomena.

Score Consistency and Correlation Analysis

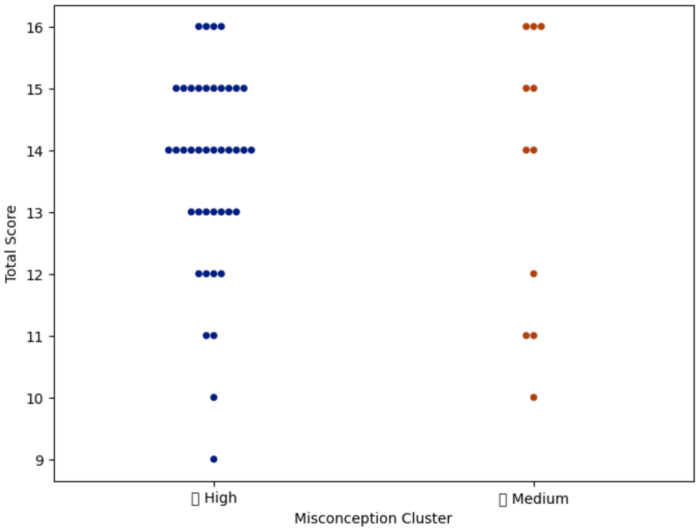

Figure 5. Swarm Plot of Score Distribution Across Clusters

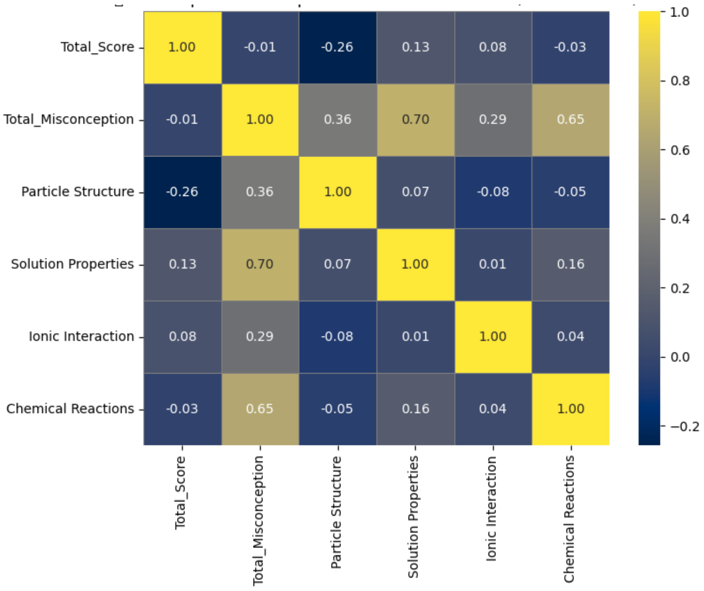

Figure 6. Heatmap of Score and Misconception Correlation

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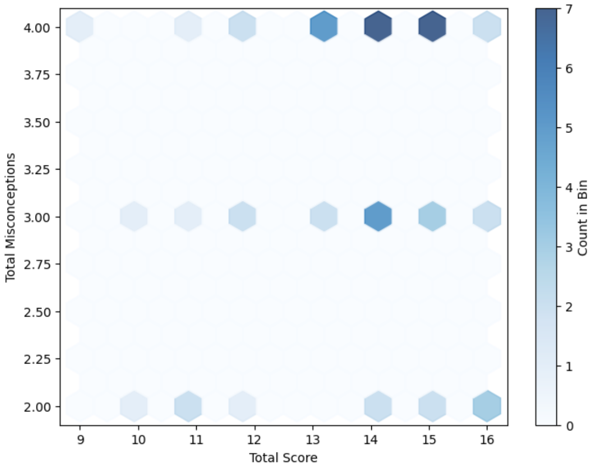

Figure 7. Hexbin Plot (Score vs. Total Misconceptions)

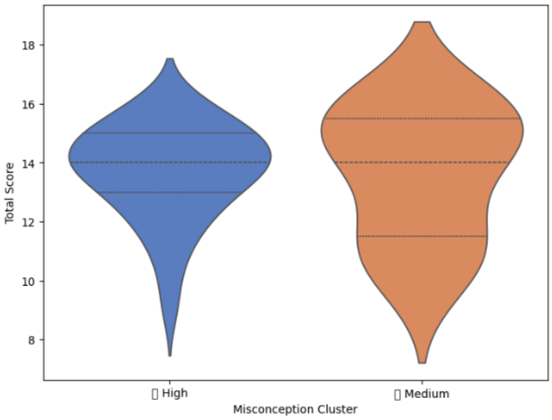

Figure 8. Violin Plot of Score Distribution by Misconception Cluster

Analysis of score distribution over the misconception clusters shown in the swarm plot (Figure 5) provides a clear distinction in students' level of performance belonging to the different sets of misconceptions. Students in the high-misconception cluster most commonly scored between 9 and 14, with many scores clustering around 12–13. This small range and little deviation show continued challenges and confirm that these students struggle with foundational concepts. On the other hand, learners in the medium-misconception group displayed diverse score distributions between 10 and 16, with some scoring over 14. This indicates that these students have some conceptual holes, but retain partial understanding that can be worked further upon. The violin plot in Figure 8 gives a more graphical insight into this discrepancy; the high-misconception cluster has a concentrated distribution toward the left direction, gathered around lower scores, whereas the medium-misconception group has an evenly spread complete score, right-biased (higher median line), indicating better academic performance and conceptual understanding.

This is further supported by the correlation heatmap (Figure 6), which reveals a moderate negative correlation (r = –0.26) between total misconceptions and total scores, indicating that as misconceptions increase, academic outcomes decrease. In particular, ignorance of particle structure has the largest negative correlation with performance (r = –0.26), followed by solution properties (r = –0.13). Furthermore, the high correlation coefficients between misconceptions of the whole and solution properties (r = 0.70) and chemical reactions (r = 0.65) indicate conceptual co-representations in these areas, where misunderstandings in one concept may produce mistakes in the other. This is consistent with the previous study by Widarti et al. (2017), which revealed particle-level reasoning as one of the key basic skills for understanding macroscopic and symbolic representations. This cumulative effect also seems to be visually corroborated by the hexbin plot (Figure 7), which shows dense areas of high score (14–16) students who also have a lower number of misconceptions (around 2), while those with a higher count of misconceptions (3.5–4) are relatively denser in lower scores. These

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trends indicate that misconceptions are structured and spread over linked chemistry areas, such as acid strength, ionization equilibrium, and solution properties.

These converging data patterns, observed across visualizations, indicate a reliable and robust prediction of students' academic achievement by misconception profiles. This suggests an important pedagogical implication: interventions should give precedence to remediating the misconceptions about particle structure and the properties of solutions, for these two are primary sources of misapprehension. It has been reasserted in some studies (Widarti et al., 2017; Omilani & Elebute, 2020) that to develop a strong conceptual understanding, scaffolding, multi-representation mode of instruction, and cognitive conflict, without neglecting treatment of foundational misconceptions, are necessary. Teachers should use diagnostic clustering and consistency analysis as assessment forms and as the foundation for developing adaptive teaching tactics. Low misconception groups may also benefit from potential reinforcement of submicroscopic and symbolic connections. High misconception groups will likely need enriched activities like guided inquiry, visualization tools, and repeated conceptual reinforcement. Attending to and strategically addressing these weak points enables educators to facilitate more robust and stable student conceptions, resulting in their improved capacity to accurately reason within the macroscopic, submicroscopic, and symbolic dimensions inherently associated with their mastery of acid-base chemistry.

Question-Wise Error Flow (Error Propagation Effect)

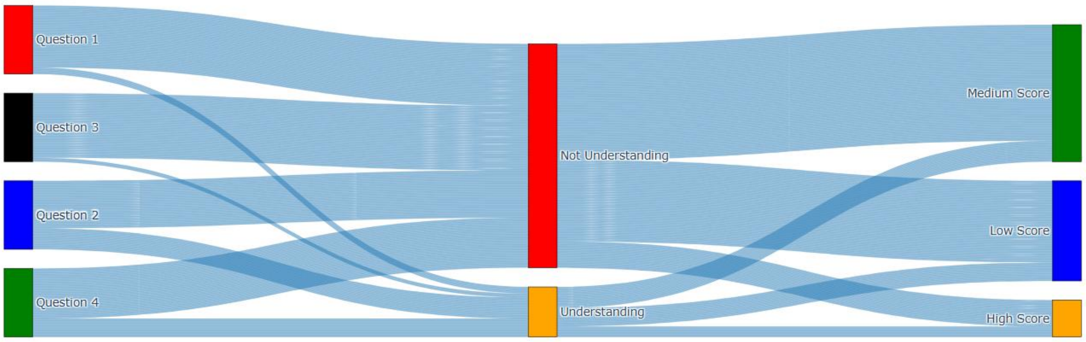

Figure 9. Sankey Diagram (Question Understanding & Score Impact)

The Sankey diagram (*Figure 9*) illustrates the process of error through student responses between four critical item questions and how this ultimately drives performance levels. The figure represents the passage of understanding from each question (Q1–Q4) toward categories of "Understanding" or "Not Understanding" and then toward the grouped performance (high, medium, and low scores) according to the performance outcome of each student.

This diagram indicates that sources of incorrect responses mostly resulted from Q1 and Q3, which assessed high-level cognition processes, specifically submicroscopic reasoning and integration between macro- and symbolic levels. The high mass of incoming answers through these questions into the "Not Understanding" node shows these basic questions' immense influence in supporting or frustrating student understanding. Further scrutiny of the diagram indicates that students who showed a lack of understanding on both Question 1 and Question 3 are more likely to fall into the low- and medium-score categories as well, which implies a cumulative effect of early errors on final performance results. However, in Question 2 and Question 4, which are less complex, correct and partial understanding often results in medium or high scores. This trend highlights a domino effect: students who cannot reason on the particle level or conceptualize equilibrium processes can also not accurately translate these conceptual understandings into chemical equations or other symbolic forms (Matovu et al., 2023).

The visualization cues us to the misunderstanding that the content of early, high-cognitive-demand items never occurs in isolation. However, transects and affect reasoning on latter items, emphasizing the cumulation of misconception processes. These results serve as a caution that educators need to carefully order

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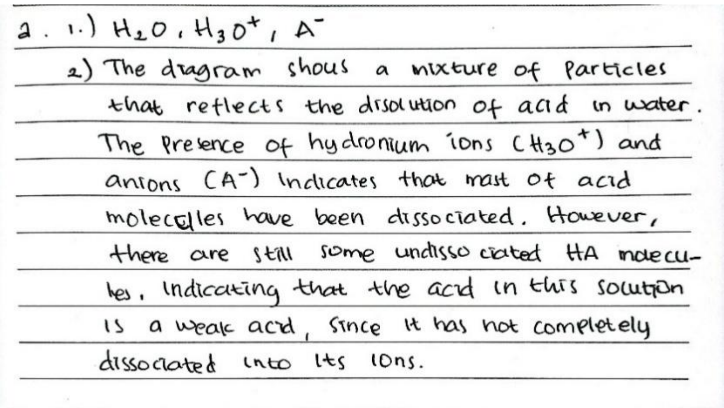
instruction, starting from the particulate view and gradually scaffolding in the representational integration. It supports early intervention with scaffolding approaches in order to avoid the dissemination of misconceptions. It is correlated with the results from Widarti et al. (2017) and Gkitzia et al. (2020), showing that teaching strategies, such as guided inquiry, multiple representations, and conceptual conflict activities, are necessary to enable the development of coherent representational competence and to prevent cognitive load. The evidence indicated by the data from the Sankey diagram suggests the need for targeted, focused teaching interventions on core submicroscopic reasoning weaknesses to enhance overall performance in acid-base topics.

4. DISCUSSION

Students' Misconceptions Regarding Acid Strength



2 . 1.) H_2O , H_3O^+ , A^-

2) The diagram shows a mixture of particles
that reflects the dissolution of acid in water.
The Presence of hydronium ions (H_3O^+) and
anions (A^-) Indicates that most of acid
molecules have been dissociated. However,
there are still some undissociated HA molecules,
Indicating that the acid in this solution
is a weak acid, since it has not completely
dissociated into its ions.

Figure 10. Example Student Answer 1

The patterns of conceptual errors shown in the *Bayesian Network* (Figure 2) and other correlations (Figure 3) explain that most misconceptions are due to weak bases in particle structures and their direct connections with acid strength and extent of ionization. These initial misconceptions at the submicroscopic level will then manifest into misconceptions at macroscopic states of matter and other related areas, such as solution properties, ionic interactions, and chemical reactions. The low to moderate correlation among these areas indicates that the difficulties in "seeing" particle-level phenomena drive the inconsistencies in more generalized learning where conceptual understanding is concerned (Siswaningsih et al., 2020). This is similar to the result of Djarwo and Kafiar (2023), which stated that the "smoking guns" of student misunderstanding lie in ionization degree and acid-base strength concepts.

These propagation routes are further illustrated by the *Bayesian Network* diagram (Figure 2), which includes arrows with directions, indicating flows from misconceptions at the particle level toward those in solution properties and reactions. These pathways highlight that errors in fundamental particle-level reasoning propagate to more complex contexts, including equilibrium and ionic interactions. This is best exemplified in a student's answer as illustrated in Figure 10. This student rightfully looks for water (H_2O), hydronium ions (H_3O^+), and anions (A^-) in the solution, and recognizes the presence of undissociated HA molecules as an indicator of partial ionization and weak acid character of the solution. However, the justification is not clear and is only superficial. The reader is not informed about dynamic equilibrium, ionization constants, or the nature of partial dissociation. It demonstrates a lack of understanding and is a common fallacy to confuse acid strength with concentration or pH (Widarti et al., 2017).

In order to tackle these prevailing trends, submicroscopic reasoning abilities should be given greater emphasis in instructional tactics. To support students in making explicit connections between particle diagrams, symbolic chemical equations, and macroscopic observations, teachers should use visual models (*partial representations*), particulate simulations, and guided concept-mapping activities. Misconceptions can be identified earlier via diagnostic tests before they become set and spread. Further, in-class interventions should include guided inquiry that forces students to describe beyond observations and provide mechanism-based explanations of why these phenomena work. Only when a deeper appreciation at the particle level is reached can teachers disrupt the domino effect of misconceptions that finally affect students' reasoning at several representational levels in acid-base chemistry.

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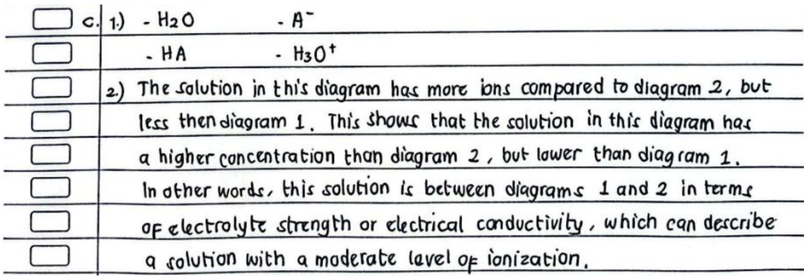
The Connection Between Representations in Understanding Acid Strength



☐ c. 1.) - H_2O - A^-
☐ - HA - H_3O^+
☐ 2.) The solution in this diagram has more ions compared to diagram 2, but
☐ less then diagram 1. This shows that the solution in this diagram has
☐ a higher concentration than diagram 2, but lower than diagram 1.
☐ In other words, this solution is between diagrams 1 and 2 in terms
☐ of electrolyte strength or electrical conductivity, which can describe
☐ a solution with a moderate level of ionization.

Figure 11. Example Student Answer 2

The clustering analysis, as visualized in the t-SNE plot (Figure 4), could parse groups of students that effectively connect macroscopic, microscopic, and symbolic representations when accounting for acid strength. In line with this, Cluster 2 students (with the most misconceptions) appear to pay attention to superficial macroscopic cues (e.g., concentration and conductivity) without associating them with submicroscopic mechanisms (e.g., particle interaction or dynamic equilibrium). This fragmented concept, in turn, may be a product of a representational disconnect, in which students may ‘know’ the macroscopic phenomena in terms of what they see but cannot explain why and how those phenomena happen at the particle level or represent these phenomena in chemical equations (Akkuzu & Uyulgan, 2021; Gkitzia et al., 2020).

The student response in Figure 11 is a clear example of this representational gap. The student identifies key particles — H_2O, HA, H_3O^+, and A^- — but then compares ion counts between diagrams and makes inferences about concentration and conductivity. The statement, “the solution in this diagram has more ions compared to diagram 2 but less than diagram 1,” demonstrates an ability to observe and compare data but does not reflect understanding of the underlying dissociation process or equilibrium positioning. The student’s conclusion that the solution has a “moderate level of ionization” is made purely on observable data rather than explaining the reversible nature of weak acid dissociation or referencing equilibrium constants (Ka). There is no discussion of how ion formation is balanced by recombination reactions or how shifts in equilibrium could change conductivity or pH values.

This descriptive treatment illustrates that the student 'knows' at the macroscopic level (ion number and conductivity) but does not 'translate' this knowledge into a microscopic explanation for the behaviour of the substance. This is based on the fallacy that electrolyte strength is dictated only by the visible count of ions, without considering the dynamic equilibrium dependencies of the generation of ions. Teachers should develop lessons focusing on connecting particle diagrams, symbolic equations, and measurable properties (e.g., pH and electrical conductivity) to close this gap. Tasks that require building and interpreting particle-level models while also writing equilibrium expressions may aid students in linking across representations. In addition, leading questions about why specific ions are present and how ion concentrations are affected by equilibrium dynamics can facilitate deeper learning. Figure 11 thus demonstrates the student's struggle of shifting between observational description and mechanistic explanation, which provides evidence for the importance of a scaffolding teaching strategy to construct conceptual coherence and representational fluency when understanding acid strength.

Dominant Misconception Patterns and Pedagogical Implications

The findings of this study show that misconceptions about acid strength are not simple isolated errors but are complicated, pervasive, and interlinked misconceptions. However, these misunderstandings are not restricted to ionization but also extend into dynamic equilibrium and the complex relationship between behavior at the particle level and macroscopic chemical properties. As shown in the Sankey diagram (Figure 9), the spread of these errors is almost visible: initial failures to understand tasks integrally (especially the high-cognitive-demand ones — those that require submicroscopic reasoning, in this case, Questions 1 and 3) lead to conceptual failure throughout later tasks themselves. Similarly, if students only relate acid strength to concentration or pH, and if they do not distinguish between full versus partial ionization of strong versus weak acids, they may fail to understand that the equilibrium colored by an arrow is not a changeover, but a mix, with one end of the reaction

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in some sense "opposing" the other. This falsehood in thinking frequently results in a simplified and misleading perception of acid-base behavior, where all acids are considered as reactive as the same material, regardless of the dissociation constant (Ka), the concentration, and the continuity (molecular shape) of the structure (Widarti et al., 2017; Gulacar et al., 2020).

This cognitive vulnerability is not specific to one concept but subserves other areas of chemistry knowledge, as indicated by performance data from different analyses. The distribution in the violin plot (Figure 8) shows that the students of the high-misconception cluster displayed consistently lower scores, although concentrating in a narrower dispersion, demonstrating the existence of long-lasting and widespread conceptual deficits. Similarly, as shown in Figure 6, the correlation heatmap shows a negative correlation (r = –0.26) between misconceptions, specifically about particle structure and solution nature, and students’ performance during the academic year. Evidence from this study supports that misconceptions of fundamental principles inhibit students’ scientific reasoning ability, not only regarding single tasks but across macroscopic, microscopic, and symbolic levels. The hexbin plot (Figure 7) provides further evidence of this reading, showing that low rates of misconceptions tend to form a cluster at the high scores. In contrast, cumulative misunderstandings are strongly related to lower academic achievement.

The findings of this study from a pedagogical viewpoint highlight the necessity of structured and scaffolded teaching that makes explicit connections across multiple levels of representation. To achieve this goal, teachers should also support students in integrating visual models of particle behavior; systematically connect these models to macroscopic phenomena, such as pH, conductivity, and reaction rates; and promote mechanistic, rather than superficial, observation. Functions of diagnostic assessments — like clustering — provide sound instruments for the recognition of misconception profiles, and these can be used to tailor individual, adaptive interventions aimed at moderate and high-risk learners (Akkuzu & Uyulgan, 2021; Omilani & Elebute, 2020). Instructional methods combining different means of representation (representational, symbolic, macroscopic) are necessary to correct defective mental models through cognitive conflict and for flexible thought transfer between representations (Widarti et al., 2021). Additionally, students' involvement in metacognitive reflection may surface and correct hidden misconceptions by expressing and justifying their reasoning. Through intentionally confronting these patterns of misconceptioned understanding via scaffolded, multimodal instruction, teachers create opportunities for students to develop representational competence and conceptual coherence that make possible not only credible but also transmissible understandings of acid-base behavior.

This study does have a few limitations, despite its contributions. The small sample size (n = 52) and the use of a single institution sampling frame may have affected the applicability of the results to other contexts. Although open responses to diagnostic items produced rich, fine-grained information, they are also inherently subjective to code, even with robust inter-rater reliability. Furthermore, the cross-sectional design limits inference of causality; however, Bayesian Network and Granger Causality analyses provide insight into probabilistic relationships. Future work should mitigate these limitations by working with more diverse and representative samples, using longitudinal designs that capture learning trajectories over time, and by triangulating data sources to increase the rigor and robustness of findings.

5. CONCLUSION

This study highlights that students’ misconceptions about acid strength are primarily caused by inadequate understanding of ionization processes at the submicroscopic level. The Bayesian Network analysis indicates that misunderstanding of particle structures leads to misconceptions concerning solution properties, ionic interactions, and equilibrium reactions. Cluster analysis indicates three different kinds of students, in which the students in the high-misconception cluster tend to have fragmented reasoning, lacking coherent use of macroscopic, microscopic, and symbolic representations. Anecdotal data from student responses to exam questions suggest that many students fail to distinguish between acid concentration and strength and do not know that weak acids only partially ionize. Such fallacious arguments impair their capacity to interpret pH shifts

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and equilibrium states precisely. Results from score consistency and correlation plots suggest that misconceptions are a serious learning obstacle. The Sankey diagram shows how errors formed at the fine-grained level of particle-incorrect ideas translate into macroscopic ones, thus gradually developing misconceptions, supporting early prevention. These results highlight the importance of scaffolded instruction that links particulate-level visualizations, symbolic equations, and macroscopic observations. Diagnosis and misconceptions clustering should be considered against teaching to differentiate support for various students' profiles. Educators can address persistent misconceptions and promote a deeper, coherent understanding of acid strength and related chemical phenomena by combining guided inquiry, visual modeling, and cognitive conflict strategies.

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