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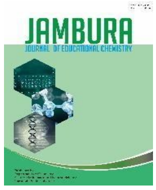

Mapping Students' Misconceptions in Chemical Bonding Using the Four-Tier Diagnostic Test

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Abstract

Students' understanding of Lewis structures and the octet rule remains a fundamental challenge in chemistry learning and is frequently characterized by conceptual difficulties. This study aims to describe the conceptual understanding profile of Chemistry Education students on Lewis structures and related sub-concepts using a Four-Tier Diagnostic Test. A descriptive quantitative research design was employed, involving 17 students from the Chemistry Education Study Program. The diagnostic instrument consisted of 15 items representing valence electrons, Lewis structures–octet rule, formal charge, resonance, octet exceptions, central atom determination, and coordinate covalent bonding.The results indicate that students' conceptual understanding is dominated by non-scientific categories. Only 10.20% of responses demonstrate sound conceptual understanding, whereas misconceptions and lack of knowledge account for 41.57% and 48.24% of responses, respectively. These findings suggest that most students have not yet developed an adequate conceptual understanding of Lewis structures. Item-level analysis reveals pronounced conceptual weaknesses in the Lewis structures–octet rule concept, as well as a complete lack of conceptual knowledge in formal charge, resonance structure determination, odd-electron octet exceptions, and central atom determination. Furthermore, very high proportions of misconceptions (94.12%) are identified in specific diagnostic items related to resonance concepts and coordinate covalent bonding.Overall, the findings demonstrate widespread conceptual difficulties across advanced subtopics related to Lewis structures, highlighting the need for instructional strategies that emphasize conceptual change and strengthen students' representational understanding.

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1. INTRODUCTION

The concept of chemical bonding remains frequently misunderstood by students, including pre-service chemistry teachers; consequently, these formed misconceptions have the potential to persist and impede the comprehension of more advanced chemical concepts (Asequia et al., 2025; Bakti et al., 2025) Misconceptions in chemistry education often arise from learners' inability to bridge macroscopic phenomena with symbolic representations, such as Lewis structures (Bullock et al., 2024). Therefore, the ability to accurately represent these concepts serves as a crucial indicator of proficiency in comprehending advanced chemical principles. (Santos et al., 2024). However, the construction of Lewis structures is not merely a drawing activity but a complex cognitive process. It necessitates the integration of various concepts—including valence electrons, central atom selection, bonding and non-bonding electron pairs, resonance, and stability evaluation based on the octet rule and its exceptions—rendering this topic particularly challenging to master (Vonari et al., 2024).

Various empirical findings indicate that students' difficulties in understanding chemical concepts are predominantly characterized by persistent

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misconceptions and limited conceptual understanding, whereas procedural errors constitute only a minor portion of learning problems (Nkundabakura et al., 2025; Rončević, 2024). Misconceptions arise when students construct alternative ideas that are incorrect yet strongly believed to be valid, making them resistant to correction through purely algorithmic instruction (Karim et al., 2022). This issue is particularly critical in General Chemistry, as it represents the foundational stage for knowledge construction; misconceptions formed at this stage may hinder the subsequent development of students' pedagogical content knowledge (PCK) as prospective teachers. Research has shown that PCK is a complex competency that relies heavily on accurate foundational content understanding (Deng et al., 2024), and an LBCD study involving 210 pre-service chemistry teachers further confirms that PCK develops optimally only when students' conceptual foundations are correctly established from the outset.

The phenomenon of misconceptions in chemical bonding remains prevalent at the secondary school level. A study involving tenth-grade science students at MAN 1 Kota Malang reported low levels of understanding in the octet rule (44.93%), metallic bonding (41.31%), and intermolecular forces (34.78%), with more than 20% of the indicators reflecting conceptual errors (Safitri et al., 2018). These findings are consistent with Musa et al., (2023) who identified high levels of misconceptions across all levels of chemical representation: macroscopic (67.20%), microscopic (67.25%), and symbolic (69.67%), with an overall average of 68.04% (categorized as high). These data underscore that students' understanding of chemical bonding concepts continues to be dominated by conceptual errors, particularly at the symbolic and microscopic levels, which require higher levels of abstraction. Students' difficulties in learning chemical bonding cannot be separated from the presence of misconceptions, both in the core bonding concepts and in foundational topics such as atomic structure and the periodic system (Putri et al., 2024). Given the abstract nature of chemical bonding, misconceptions frequently arise, especially in relation to the processes underlying bond formation (Yovanie, 2024), making this topic a persistent challenge in chemistry education.

In practice, instruction on Lewis structures often emphasizes algorithmic procedures, enabling students to draw structures without fully understanding electron distribution, resonance, formal charge, or stability. Under such conditions, diagnosing conceptual understanding becomes crucial. Recent research indicates that during the 2019–2024 period, the four-tier diagnostic test emerged as the most dominantly used method (30%), surpassing the three-tier format (24%) and other instruments (Istiqomah & Subali, 2025). The four-tier test extends the three-tier format by incorporating confidence ratings for both answers and reasoning, thereby enabling more accurate differentiation among Sound Understanding (PK), Misconception (M), Lack of Knowledge (TT), and Guess (G). Its effectiveness has been supported by several studies, including Budi Bhakti et al., (2022), Atmaca Aksoy & Erten, (2022), serta Trio Ageng Prayitno & Nuril Hidayati, (2022), which demonstrate that the four-tier diagnostic test is valid, reliable, and effective in mapping misconceptions in detail. These findings are further reinforced by Munawaroh & Salirawati, (2025) who reported that a four-tier diagnostic instrument in chemical bonding exhibited good discriminatory power and successfully identified variations in misconceptions as well as the relationship between confidence levels and conceptual understanding among learners.

The novelty of this study lies in its in-depth mapping of pre-service chemistry teachers' conceptual understanding specifically within the Lewis structure and octet rule domain, including resonance, formal charge, octet exceptions, central atom determination, and coordinate covalent bonding, through the use of a Four-Tier diagnostic instrument that has not yet been widely applied in a focused manner to this essential concept cluster. By providing a granular, indicator-level analysis, this study aims to identify the most resistant misconceptions and the weakest conceptual areas as a foundation for designing more targeted and effective remediation strategies in General Chemistry instruction.

2. METHOD

This study employed a descriptive quantitative design aimed at mapping students' conceptual understanding of Lewis structures and the octet rule using a Four-Tier Diagnostic Test. The research was conducted during a General Chemistry class in the Chemistry Education Study Program during a session held after students had completed the relevant instructional content.

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The research subjects consisted of 17 students selected through a total sampling technique, whereby all students enrolled in the class were included as participants. The research instrument was a Four-Tier Diagnostic Test comprising 15 items that assessed the following indicators: valence electrons, Lewis structures and the octet rule, formal charge, resonance, octet exceptions, central atom determination, and coordinate covalent bonding. Each item contained four tiers: (1) a conceptual answer, (2) a confidence level for the conceptual answer, (3) a reasoning answer, and (4) a confidence level for the reasoning. Combinations of accuracy and confidence across the four tiers were used to classify responses into the categories Understanding the Concept (PK), Misconception (M), Lack of Knowledge (TT), and Guess (G).

Content validity was reviewed by experts in chemistry and chemistry education, including evaluations of indicator alignment, conceptual accuracy, item construction, and linguistic clarity. Instrument reliability was calculated using Cronbach's Alpha for the cognitive tiers (Tier-1 and Tier-3), which indicated acceptable internal consistency.

Data collection was carried out by administering the diagnostic test individually to students, after which their responses were compiled and classified according to the Four-Tier categories. Data analysis was performed descriptively by calculating the distribution of PK, M, TT, and G at the class level, per item, per indicator, and per respondent. The percentage for each category was calculated using the formula (1):

$$\%Category = \frac{\sum Category}{N_{Respondents} \times N_{Items}} \times 100\% \quad (1)$$

Where %category is the percentage of the category; Σcategory is the total category score; $N_{Respondents}$ is the number of respondents; and N_{Items} is the number of items.

3. RESULT AND DISCUSSION

3.1. Result

This section presents the results of data analysis, which include the distribution of the Four-Tier categories, students' conceptual understanding patterns, and specific findings for each conceptual indicator.

Table 1. Distribution of students' conceptual understanding categories based on the Four-Tier Diagnostic Test.

Category	Frequency	Persentage
PK	26	10,20%
M	106	41,57%
TT	123	48,24%
G	0	0%
Total	255	100%

In Table 1, the overall distribution of students' responses (N = 17; 15 items; total responses = 255) shows that the majority of responses fall into the TT and M categories, while only a small proportion are classified as PK, and no responses are categorized as G. This pattern indicates that students' conceptual understanding of Lewis structures and octet fulfillment remains low, with many students either not understanding the concept or holding misconceptions.

Table 2. Summary of items with the highest levels of misconceptions and TT

Critical Item Group	Item	Indicator	Dominant Pattern	Proportion
Highest M	3, 11	I2 Lewis structures & octet	Total M	100%
	5	I7 Coordinate covalent bonding	Very high M	94,12%
	7	I4 Resonance (concept)	Very high M	94,12%
	9	I5 Octet deficit/expansion	High M	88,24%
Highest TT	2, 4	I2 Lewis structures & octet	Total TT	100%
	6	I3 Formal charge	Total TT	100%
	8	I5 Octet deficit/expansion	Total TT	100%
	10	I6 Central atom	Total TT	100%
	12	I4 Resonance (number of structures)	Total TT	100%
	14	I5 Odd-electron species	Total TT	100%

In Table 2 overall, the item-level results show that students' difficulties are concentrated in critical items

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related to constructing Lewis structures and applying the octet rule (Items 3 and 11), resonance concepts (Item 7), and coordinate covalent bonding (Item 5), all of which are dominated by high-confidence misconceptions. Meanwhile, derivative subtopics such as formal charge, resonance structure count, odd-electron octet exceptions, and central atom determination are characterized by complete lack of conceptual understanding (total TT). These findings indicate that students' difficulties span two domains simultaneously: resistant misconceptions in core concepts and absence of conceptual knowledge in more advanced subtopics.

Table 3. Four-Tier category profile by indicator

	Indicator	PK	M	TT	G	Total
1.	Total valence electrons	13	4	0	0	17
2.	Lewis structures & octet fulfillment	11	55	36	0	102
3.	Formal charge	0	0	17	0	17
4.	Resonance (number of structures)	0	0	17	0	17
5.	Resonance (concept)	0	16	1	0	17
6.	Octet exceptions (deficit/expansion)	1	15	18	0	34
7.	Octet exceptions (odd-electron species)	0	0	17	0	17
8.	Central atom determination	0	0	17	0	17
9.	Coordinate covalent bonding	1	16	0	0	17

In table 3, the indicator most successfully mastered by students is I1 (total valence electrons), with PK reaching 76.5%, while M accounts for 23.5% and TT for 0%. This finding indicates that the basic concept of valence electrons is relatively well understood by most students.

In contrast, the core indicator I2 (Lewis structures and octet fulfillment) shows the most critical condition, with PK at only 10.8%, while M reaches 53.9% and TT 35.3%. The dominance of misconceptions in this indicator suggests that more than half of the students hold alternative conceptions that are incorrect yet strongly believed to be true, whereas one-third of the students lack clear conceptual understanding.

Four indicators fall under total TT (100%), namely I3 (formal charge), I4 (resonance—number of structures), I5 (octet exceptions—odd-electron species), and I6 (central atom determination). This total TT condition indicates that students do not possess any initial conceptual knowledge of these subtopics.

Indicators that exhibit very strong misconceptions are I4 (resonance—concept) and I7 (coordinate covalent bonding), each with M at 94.1%. The high misconception rates in these two indicators indicate that students' errors are resistant, as they are accompanied by strong confidence in their responses.

For indicator I5 (octet exceptions—deficit/expansion), the TT category (52.9%) is slightly more dominant than M (44.1%), while PK is only 2.9%. This pattern shows that many students do not understand the concept of octet exceptions, although some have begun forming alternative conceptions that are incorrect.

Overall, the indicator-level findings emphasize that the greatest weaknesses lie in the core concept of Lewis structures and the octet rule (I2), as well as its advanced related concepts, including resonance, octet exceptions, formal charge, and central atom determination. These findings serve as the basis for the theoretical discussion on the sources of misconceptions and conceptual gaps in the subsequent section.

Table 4. Results per respondent

Category	Mean (items)	SD (items)	Min–Max (items)
PK	1,53	0,72	0 – 2
M	6,24	0,97	4 – 8
TT	7,24	0,56	7 – 9
G	0,00	0,00	0 – 0

3.2. Discussion

The Four-Tier findings indicate that students' conceptual understanding of Lewis structures and the octet rule remains limited. The dominance of the TT and M categories suggests that most students either lack conceptual knowledge or hold alternative conceptions with varying levels of confidence. The absence of responses in the Guess category further implies that students' errors were not random but stemmed from genuine conceptual uncertainty or firmly held misconceptions. These results confirm that the identified difficulties are conceptual rather than procedural in nature. Consistent with four-tier diagnostic literature (Rohmah et al., 2022), the instrument effectively distinguishes between lack of understanding and high-confidence misconceptions. Theoretically, this study clarifies the structure of students' conceptual difficulties within the Lewis structure–octet rule domain. Practically, the findings highlight the need for targeted instructional strategies in General Chemistry, particularly through

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multi-representation approaches, scaffolding of electron-structure reasoning, and conceptual-change interventions addressing resonance and coordinate covalent bonding.

At the indicator level, the most critical weakness appears in I2 (Lewis structures and octet fulfillment), with PK at 10.8%, M at 53.9%, and TT at 35.3%. Even at the item level, this indicator yields extreme patterns: total misconception for Items 3 and 11 (M = 100%) and total TT for Items 2 and 4 (TT = 100%). These patterns strongly indicate that Lewis structures–octet is the root source of students' difficulties. Theoretically, understanding Lewis structures requires the integration of multiple prerequisite concepts simultaneously (valence electrons, electron-pair distribution, central-atom selection, and stability evaluation). According to (Kristiana et al., 2020) misconceptions are particularly high in determining symbols and Lewis structures. When instruction is predominantly procedural and oriented toward "drawing steps" only, students form simplified heuristics that lead to systematic misconceptions. This condition has been widely reported among first-year chemistry students (Karonen et al., 2021). his is consistent with (Islami et al., 2019) who report high levels of misconceptions in chemical bonding, particularly in the sub-concepts of Lewis structures and the octet rule.

In addition to the core concept, indicators I4 (resonance—concept) and I7 (coordinate covalent bonding) reveal particularly strong misconceptions. These patterns indicate that students struggle to develop a coherent conceptual framework for advanced aspects of Lewis structures. Theoretically, misconceptions in I4 arise when students fail to distinguish between resonance structures as contributing representations and the actual molecule as a resonance hybrid. The CERP literature consistently identifies resonance as a fundamental yet frequently misunderstood concept in introductory and organic chemistry . (Barakat & Orgill, 2024). Similarly, misconceptions in I7 regarding coordinate covalent bonding often stem from an excessive focus on the origin of the electron pair, leading students to perceive it as a different or weaker bond type, even though once formed, it is equivalent to an ordinary covalent bond

Misconceptions in coordinate covalent bonding stem from excessive focus on the origin of the electron pair, leading students to perceive coordinate bonds as a different (or weaker) type of bond, even though once formed, they are equivalent to ordinary covalent bonds. Such misconception patterns are consistent with findings from four-tier studies on chemical bonding (Rohmah et al., 2022)

The derivative indicators that show total TT (100%), namely I3 (formal charge), I4 (resonance—number of structures), I5 (octet exceptions—odd-electron species), and I6 (central atom determination), indicate that students lack initial conceptual knowledge of these subtopics. These derivative concepts are abstract and strongly dependent on foundational understanding of Lewis structures. When this foundation is weak, students lack the conceptual pathway to evaluate stability using formal charge or determine the number of resonance structures, resulting in TT responses. From Johnstone's representational framework, these topics require the integration of macroscopic, submicroscopic, and symbolic levels; failure to coordinate these representations can lead to cognitive overload and fragmented understanding (Johnstone, 1991). Furthermore, according to Ausubel's theory of meaningful learning, new knowledge can only be meaningfully assimilated when relevant prior concepts exist within the learner's cognitive structure (Ausubel, 1968). This prerequisite dependency within the Lewis model is also emphasized in studies on molecular structure difficulties at the university (Abd Ghani, 2026)

Conversely, indicator I1 (determination of total valence electrons) demonstrated the highest level of mastery, with a success rate of 76.5%. Empirically, this indicates that the concept of valence electrons is relatively well-understood, likely due to its procedural nature and frequent reinforcement through periodic table rules in earlier education. However, this achievement must be interpreted critically. In line with the analysis by Stroumpouli & Tsaparlis, (2022), algorithmic skills often constitute cognitive constructs distinct from deep conceptual understanding; thus, high proficiency in procedural aspects does not automatically guarantee success in visual representation. This discrepancy is corroborated by Karonen et al., (2021), who found that failures in constructing Lewis structures frequently stem from students' reliance on heuristic strategies rather than logical reasoning regarding electron distribution. Consequently, a demonstrable disconnect emerges: while students are capable of calculating valence electrons as isolated values, they fail to integrate this procedural knowledge with principles of molecular stability when constructing the final structures

Based on these findings, instructional implications for General Chemistry must target two goals simultaneously: reducing TT through conceptual development and reducing M through conceptual change. Strengthening I2 requires a multi representational approach and scaffolded instruction beginning with valence-electron counting, argument-based central-atom selection, electron distribution, and checking stability and the octet. To reduce resistant misconceptions in resonance and coordinate covalent bonding, targeted cognitive-conflict strategies are necessary, along with emphasizing the distinction between “model vs. reality” for resonance, and “formation mechanism vs. final bond properties” for coordinate covalent bonding. Such intervention directions are consistent with recommendations from studies on misconceptions in bonding and resonance (Barakat & Orgill, 2024)

This study has several limitations. First, the number of respondents is limited to 17 students in a single class, restricting the generalizability of the findings. Second, the study employed a descriptive quantitative design without qualitative triangulation, resulting in explanations of misconceptions and TT being drawn primarily from four-tier response patterns and theoretical review. Third, the instrument consisted of only 15 items and focused specifically on Lewis structures–octet and their derivative concepts, thus limiting the coverage of General Chemistry content evaluated. Nevertheless, the Four-Tier data provide a strong diagnostic picture of students’ conceptual profiles and the specific areas requiring instructional intervention (Rohmah et al., 2022)

4. CONCLUSION

The findings indicate that students’ conceptual understanding of Lewis structures and the octet rule remains low. The Understanding Concept category accounts for only 10.20%, whereas Misconception (41.57%) and Lack of Knowledge (48.24%) dominate the overall responses. The most prominent weaknesses appear in the core indicator of Lewis structures–octet, reinforced by patterns of total misconception and total lack of knowledge in several items. Advanced concepts such as formal charge, resonance structure count, octet exceptions, and central atom determination are not mastered at all, whereas resonance concepts and coordinate covalent bonding exhibit high-confidence misconceptions. These findings confirm that students’ difficulties are conceptual and resistant in nature, requiring instructional interventions that target conceptual development and conceptual change through multi-representation approaches and gradual scaffolding. Future research is recommended to involve a larger number of respondents, incorporate qualitative triangulation to explore the sources of misconceptions, and develop structured remediation tools based on these diagnostic findings..

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