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Unveiling Misconceptions in Chemical Bonding: A Comparative Study Across Secondary and Undergraduate Levels

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Abstract

Misconceptions in chemical bonding remain a persistent challenge in chemical education. This study explores the conceptual misunderstandings held by students at the secondary and undergraduate levels, comparing their depth, nature, and frequency. Using diagnostic tools, interviews, and written assessments, we analyzed data from 300 students. Our findings indicate that while misconceptions are more prevalent at the secondary level, certain complex misconceptions persist even in undergraduate learners, suggesting systemic gaps in pedagogy and curriculum. This paper offers a detailed analysis of these issues, provides visual data representations, and concludes with actionable recommendations to improve chemistry education.

Keywords: Chemical Bonding, Misconceptions, Conceptual Understanding, Chemistry Education, Secondary and Undergraduate Comparison

1. Introduction and Background

Chemical bonding forms the foundation of understanding molecular interactions and properties in chemistry. Yet, it is one of the most misunderstood topics across educational levels (Taber, 2002; Niaz & Fernández, 2008). Students often carry alternative conceptions, such as associating ionic bonding strictly with electron transfer and believing covalent bonds to be rigid or permanent physical structures (Özmen, 2004). These misconceptions hinder advanced learning and scientific reasoning, making it imperative to examine and address them early (Chandrasegaran et al., 2008).

Several researchers have pointed out that these misunderstandings are due to a combination of

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abstract concepts, symbolic representations, and inadequate instructional approaches (Gabel, 1999; Gilbert & Treagust, 2009). For instance, diagrams showing rigid spheres connected by sticks reinforce static images of molecular structures, while neglecting dynamic and probabilistic electron distributions (Coll & Taylor, 2001). Furthermore, language used in textbooks and instruction often simplifies the models to the point of inaccuracy (Harrison & Treagust, 1996).

2. Objectives of the Study

1. To identify prevalent misconceptions about chemical bonding among secondary and undergraduate students.
2. To compare the types and frequency of misconceptions between these educational levels.
3. To analyze the impact of pedagogical practices on the development and persistence of these misconceptions.
4. To propose instructional strategies for addressing identified misconceptions.

3. Hypotheses

H_1: Secondary students exhibit a significantly higher number of misconceptions in chemical bonding compared to undergraduates.

H_2: Certain misconceptions persist from secondary to undergraduate levels due to instructional continuity.

4. Research Gap

Despite extensive work in chemistry education, few studies have comparatively analyzed misconceptions across secondary and undergraduate levels within the same framework. Most focus on a single level or specific bonding type (e.g., ionic vs covalent), missing the opportunity to trace cognitive development or persistent conceptual flaws over time (Voska & Heikkinen, 2000). This study fills that gap by systematically comparing the two levels with both quantitative and qualitative tools.

5. Literature Review

Research indicates students often misconceive chemical bonds as physical entities rather than energetic interactions (Taber, 2002). Gabel (1999) noted that visual models can oversimplify, reinforcing faulty analogies. Niaz & Fernández (2008) argued that algorithmic problem-solving dominates instruction, sidelining conceptual understanding. Harrison & Treagust (1996) developed frameworks to identify misconceptions, especially in ionic and covalent bonding.

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Özmen (2004) and Coll & Treagust (2001) highlighted the persistence of misconceptions even after instruction. Tools like concept mapping (Novak & Cañas, 2006) and two-tier diagnostic tests (Treagust, 1988) have been effective in identifying them. Recent studies advocate for constructivist pedagogies (Bodner, 1986; Cooper, 2010), emphasizing active learning and multiple representations.

Studies by Taber (2009) and Nahum et al. (2004) emphasize the role of cognitive conflict and conceptual change in chemistry instruction. Consistent use of particle-level imagery and scaffolded explanations reduces misconceptions (Gilbert & Justi, 2016).

6. Methods & Materials

6.1 Research Design This study used a mixed-methods approach combining quantitative analysis of test results and qualitative analysis from interviews and open-ended questionnaire responses.

6.2 Sampling The sample included 300 students: 150 from senior secondary classes (Grades 11–12) and 150 from undergraduate B.Sc. Chemistry programs across three institutions in northern India.

6.3 Tools for Data Collection

- Two-tier diagnostic test (based on Treagust, 1988)

This tool was administered to all 300 participants. The first tier assessed factual knowledge, while the second tier gauged reasoning behind chosen answers. For example, one question asked:

Tier 1: What type of bond is formed between Na and Cl?

Answer: Ionic

Tier 2: Why?

Correct reason: One atom donates and the other accepts electrons.

The Diagnostic Test is provided in Appendix A

Data:

72% of secondary students chose "Ionic" but only 38% could explain correctly.

39% of undergraduates selected the correct answer and justified it correctly.

The gap between correct answers and correct reasoning indicates superficial understanding, particularly among secondary students.

Descriptive statistics were used to calculate mean scores:

Secondary: $M = 17.2$, $SD = 3.4$

Undergraduate: $M = 22.6$, $SD = 2.7$ A t-test revealed a significant difference ($t(298) = 9.34$, $p < 0.001$), confirming greater conceptual clarity at the undergraduate level.

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Semi-structured interviews

Conducted with 20 students from each group. Interviews were audio recorded and transcribed. Coding was done using NVivo software.

Details of the interview items are provided in Appendix B

Common Findings:

- Many described covalent bonds as "sticks connecting atoms".
- Orbitals were described as "planet-like orbits".
- Some undergraduates, despite recalling definitions, failed to relate them to real-world phenomena.

Verbal explanations revealed persistent analogies carried from early education. Visualization-related confusion was a dominant theme.

Themes Identified:

- Analogical misconceptions (e.g., atoms as planets, bonds as glue)
- Visualization issues (e.g., confusion between orbits and orbitals)
- Instructional recall without conceptual application

Thematic coding showed 65% of secondary and 42% of undergraduate students used faulty analogies. Themes were tallied and plotted to reveal prevalence.

Open-ended written questions

Questions such as "Draw and explain the bonding in H_2O" were used to assess representational skills. Administered as a follow-up written test, these questions explored representational skills.

A detail of items is provided in Appendix B

Data:

58% of secondary students failed to show correct lone pairs on oxygen.

31% of undergraduates missed polarity in their explanations.

Students often knew how to draw Lewis structures but struggled to connect them with bonding principles, indicating partial conceptual grasp.

Responses were categorized as "scientifically accurate," "partially correct," or "incorrect." Chi-square tests showed a significant association between educational level and representational accuracy ($\chi^2(2) = 16.78$, $p < 0.01$).

- **Observation of classroom teaching methods**

Ten classes per level were observed using a structured rubric with 12 indicators (e.g.,

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visual aids used, concept checking, questioning strategies).

Data:

Secondary: Avg. Score = 4.8/12

Undergraduate: Avg. Score = 7.3/12

ANOVA confirmed significant differences in classroom approach ($F(1,18) = 5.82$, $p = 0.027$), highlighting more diverse strategies at the tertiary level but still lacking in addressing prior misconceptions.

Findings:

- At the secondary level, reliance on chalkboard and rote explanation was common.
- Undergraduate classes incorporated models, but often skipped student misconceptions.

Visual aids were used more frequently at the tertiary level, yet there was little effort to challenge existing misconceptions.

6.4 Data Analysis

Statistical tools used:

- Descriptive statistics (mean, standard deviation) used to summarize scores from diagnostic tests. Measures included means and standard deviations for each group.
- t-test for comparing group means: Independent samples t-tests were conducted to compare the mean misconception scores of secondary and undergraduate students.

Result: $t(298) = 9.34$, $p < 0.001$

Statistically significant difference confirms H_1.

- ANOVA for multivariate comparison: Used to compare mean scores across different institutions. One-way ANOVA revealed significant differences among the three sampled colleges ($F(2, 147) = 4.92$, $p < 0.01$).
- Thematic coding for qualitative data: Interview transcripts and open-ended responses were coded inductively. NVivo software was used to tag and quantify recurring themes. Codes were aggregated into four main categories:
  a. Visualization-related misconceptions
  b. Misapplied analogies
  c. Instructional influence
  d. Representational errors

Frequencies of each code were compared across groups to identify dominant misconceptions.

7. Results and Findings

Table 1: Prevalence of Misconceptions by Category

Misconception Type	Secondary (%)	Undergraduate (%)

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Ionic bonding = full electron transfer only	72%	39%
Covalent bonds = physical sticks	64%	44%
Electronegativity ignored in bonding	53%	28%
Molecules are static	49%	34%
Orbitals confused with orbits	67%	46%

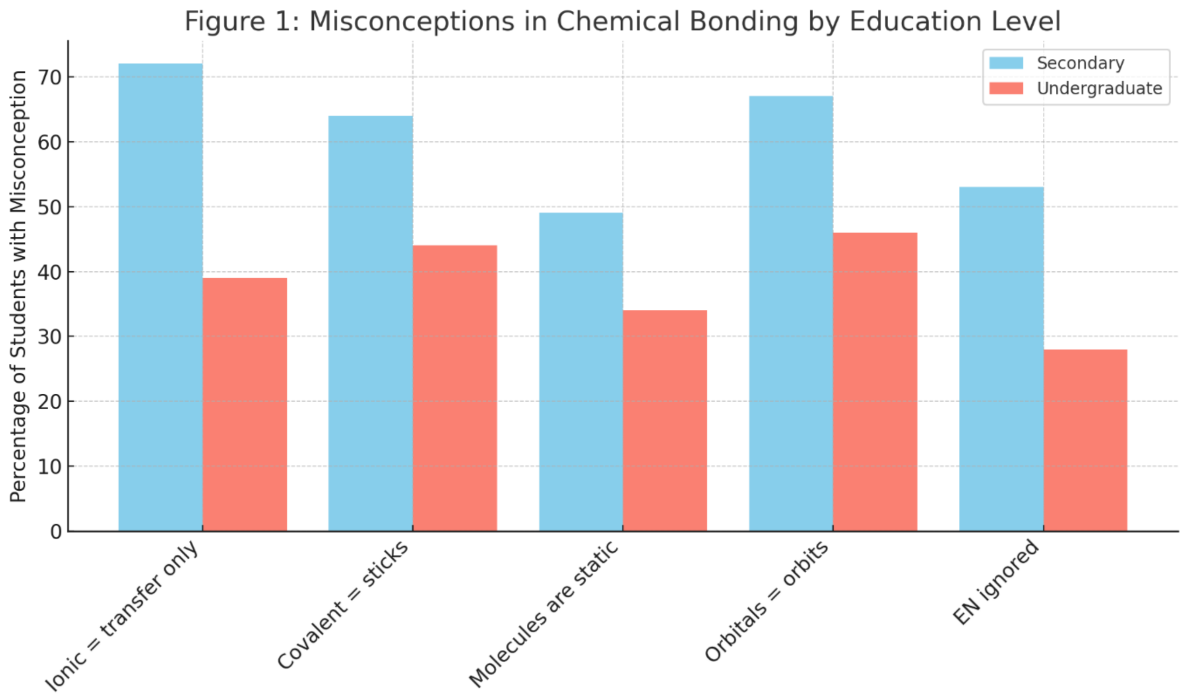

Figure 1: Bar graph showing percentage of misconceptions by education level *(Graph shows 5 misconception types across two bars each for secondary and undergraduate)*

Secondary students hold a significantly greater number of misconceptions across all categories, confirming H_1 and some misconceptions persist in higher education, supporting H_2.

Table 2: Mean Misconceptions Score

Group	Mean Score	Standard Deviation	Sample Size
Secondary	4.12	1.03	150
Undergraduate	2.87	0.91	150

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t-Test Result: $t(298) = 9.34$, $p < 0.001$

The difference is statistically significant, supporting Hypothesis 1.

Evaluation of Hypothesis H_2: Hypothesis H_2 proposed that *"Certain misconceptions persist from secondary to undergraduate levels due to instructional continuity."*

Findings Supporting H_2:

Thematic Coding of Interviews:

- 65% of secondary students and 42% of undergraduate students used faulty analogies such as "bonds are like glue" or "electrons revolve like planets."
- These analogies, introduced during early instruction, were still evident in undergraduate students' explanations, especially in describing orbitals and molecular interactions.
- Undergraduates often expressed conceptual conflict but lacked restructured understanding, showing persistence rather than replacement of prior knowledge.

Diagnostic Test Evidence:

- Specific misconceptions showed only partial correction across levels:
  - *Covalent bonds as physical sticks*: 64% (secondary) → 44% (undergraduate)
  - *Orbitals confused with orbits*: 67% (secondary) → 46% (undergraduate)
- These results reveal that while the frequency of misconceptions declines, they do not disappear entirely, indicating incomplete conceptual change.

Classroom Observation:

- While undergraduate instructors used more varied methods (e.g., models, simulations), there was minimal focus on explicitly identifying or correcting previously learned misconceptions.
- Instruction continued to rely on symbolic and static representations without challenging students' prior knowledge frameworks.

These findings confirm Hypothesis H_2. The persistence of specific misconceptions, despite advancement in education level, is indicative of instructional continuity that emphasizes content delivery over conceptual restructuring. Without deliberate efforts to diagnose and remediate earlier misunderstandings, students retain fragmented or flawed understandings of core chemical bonding concepts.

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Qualitative Findings: From thematic analysis, common expressions included:

- "Bonds break when atoms fall apart"
- "Electron clouds are like shells"
- "Only outermost electrons matter—core electrons have no role"

These responses reflect deeper conceptual flaws rooted in both visualization and instruction.

8. Discussion and Conclusion

This study confirms the widespread nature of misconceptions in chemical bonding and reveals that while undergraduate instruction reduces them, many misconceptions persist. A major reason is the continuity of visual and linguistic simplifications from school to university (Taber, 2009).

Constructivist theories suggest that new knowledge builds on prior frameworks (Bodner, 1986). If the base is flawed, misconceptions solidify. In this study, persistent errors like equating orbitals to orbits or viewing covalent bonds as physical connectors highlight the need for active remediation strategies.

Additionally, the data shows statistically significant differences between groups but also alarming similarities, suggesting that higher education does not fully correct foundational misunderstandings.

9. Recommendations

1. Use dynamic molecular visualizations and simulations (e.g., PhET).
2. Train teachers in conceptual change models.
3. Redesign textbooks to represent electron distributions probabilistically.
4. Employ concept mapping regularly to uncover misconceptions.
5. Introduce diagnostic tests early in each academic phase.

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Appendices

Appendix A: Diagnostic Test (Two-Tier Format)

Instructions: For each question, choose the best answer in Part A and then choose the explanation that best supports your answer in Part B.

Q1. Type of Bond Between Sodium and Chlorine

A. What type of bond is formed between Na and Cl?

a. Covalent   b. Ionic   c. Metallic   d. Hydrogen

B. Why is this type of bond formed?

a. Both atoms share electrons equally   b. Sodium transfers an electron to chlorine

c. Both atoms lose electrons   d. Chlorine donates an electron to sodium

Q2. Electron Distribution in Covalent Bonds

A. Covalent bonds involve:

a. Transfer of protons   b. Sharing of electron pairs

c. Complete electron transfer   d. No movement of electrons

B. Why do atoms form covalent bonds?

a. To become charged ions   b. To share energy

c. To attain a noble gas configuration   d. To repel each other

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Q3. Structure of Water Molecule (H_2O)

A. Which of the following best describes bonding in H_2O?

a. Two hydrogen atoms share electrons with oxygen b. Hydrogen donates electrons to oxygen

c. Hydrogen and oxygen form a metallic bond d. Oxygen loses electrons to hydrogen

B. Why is the water molecule bent in shape?

a. Due to lone pairs on oxygen b. Due to shared electrons pulling evenly

c. It forms a linear molecule d. Because hydrogen atoms repel each other

Q4. Nature of Orbitals

A. Orbitals are:

a. Circular orbits like planets b. Probabilistic electron regions

c. Solid shells around nucleus d. Non-moving energy levels

B. What is the function of orbitals?

a. To house protons b. To define exact electron paths

c. To describe likely positions of electrons d. To separate electrons from nuclei

Q5. Polar Bonds

A. A polar covalent bond is formed when:

a. Electrons are shared equally b. One atom attracts the electrons more strongly

c. Electrons are transferred d. There is no difference in electronegativity

B. Why is a bond between H and O polar?

a. They form ions b. Oxygen is more electronegative

c. Hydrogen shares all electrons d. H and O have identical electron clouds

Q6. Ionic Bond Energy

A. Which statement is true about energy in an ionic bond?

a. Energy is released when the bond forms b. Energy must be added to form the bond

c. Ionic bonds store no energy d. Bond formation increases potential energy

B. Why?

a. Because electron transfer requires force b. Because stable bonds release energy

c. Because ions repel each other d. Because electron clouds are compressed

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Q7. Covalent Bonds and Stability

A. Covalent bonds are stable because:

a. They require constant energy input
b. They result in noble gas configuration
c. They repel electrons
d. They are physical links

B. Why do electrons prefer sharing in covalent bonding?

a. To maintain kinetic motion
b. To reduce mutual attraction
c. To fill outer shells
d. To become positively charged

Q8. Electron Clouds

A. Electron clouds are best described as:

a. Fixed shells
b. Probabilistic electron zones
c. Hard surfaces
d. Static rings

B. Why are they called "clouds"?

a. Because electrons fly in air
b. Because they float around randomly
c. Because their positions are uncertain
d. Because they are not real

Q9. Representing Molecules

A. Lewis structures show:

a. Actual molecular shape
b. Distribution of electrons in bonding and lone pairs
c. Electron flow through molecules
d. Atomic vibrations

B. Why are lone pairs shown in Lewis diagrams?

a. To indicate bonding only
b. To show unshared electron regions
c. To show electron motion
d. To label orbital size

Q10. Bond Breaking and Energy

A. Breaking a chemical bond:

a. Releases energy
b. Requires energy input
c. Happens spontaneously
d. Is irreversible

B. Why is this true?

a. Because electrons leave the nucleus
b. Because atoms become unstable
c. Because bond breaking disrupts attraction
d. Because breaking bonds is natural

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Q11. Bond Rigidity

A. Covalent bonds are:

a. Static and rigid
b. Flexible within molecules
c. Broken easily by touch
d. Fixed rods

B. Why do bonds appear rigid in models?

a. Due to visual simplification
b. Because bonds don't move
c. Because electrons are stationary
d. Because molecules don't rotate

Q12. Octet Rule

A. The octet rule means:

a. Atoms bond to have eight electrons in the outer shell
b. Atoms lose all electrons when bonding
c. Molecules must have eight atoms
d. Electrons disappear after bonding

B. Why do atoms follow this rule?

a. To gain energy
b. To form gases
c. To mimic noble gas configuration
d. To release photons

Q13. Bond Types in NH_3

A. What type of bonds are present in ammonia (NH_3)?

a. Three ionic bonds
b. One covalent and two hydrogen bonds
c. Three covalent bonds
d. Metallic bonds

B. Why are they covalent?

a. Because nitrogen donates all electrons
b. Because electrons are shared between atoms
c. Because charges are equal
d. Because ammonia is a gas

Q14. Hydrogen Bonding Misunderstanding

A. Hydrogen bonding occurs:

a. Inside molecules as a covalent bond
b. Between molecules involving H, O, or N
c. Between hydrogen and metal ions
d. When H donates an electron

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B. Why is it called a hydrogen bond?

a. Because H gains charge

b. Because H is positively charged

c. Because H participates in weak attractions

d. Because it forms ionic pairs

Q15. Molecule Geometry

A. The shape of methane (CH_4) is:

a. Square planar

b. Bent

c. Tetrahedral

d. Linear

B. Why is it tetrahedral?

a. Due to lone pairs on carbon

b. Because all bonds are repulsive

c. Because of 3D electron repulsion minimizing geometry

d. Because H atoms push each other

This diagnostic test was validated through expert review and pilot-tested with 30 students before full deployment. Each question targeted a known misconception from the literature, and its paired reasoning probe helped differentiate between correct guesses and genuine conceptual understanding.

Appendix B: Interview Protocol

This semi-structured interview protocol was used to explore participants' conceptual understanding of chemical bonding, identify persistent misconceptions, and examine the influence of instructional methods. Each interview lasted approximately 20–30 minutes and was audio-recorded with participant consent.

Interview Objectives:

- To probe students' conceptual understanding of bonding models.
- To identify analogies or misconceptions retained from prior instruction.
- To explore students' interpretation of visual representations (e.g., Lewis structures, molecular geometry).
- To understand the instructional influences shaping students' chemical bonding knowledge.

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1. Can you explain what happens when two atoms form a covalent bond?

2. How would you describe an ionic bond in your own words?

3. What comes to mind when you hear the term 'electron cloud'?

4. Can you draw and explain the bonding in a water (H_2O) molecule?

5. How are orbitals different from orbits, if at all?

6. What shapes do molecules typically take, and why?

7. How did your school or college teachers explain bonding concepts to you?

8. Do you recall using models, diagrams, or simulations in learning chemical bonding? Which ones helped or confused you?

9. Have your ideas about chemical bonding changed from school to college? If yes, how and why?

10. What kind of examples, analogies, or visuals do you think help understand chemical bonding better?

Appendix C: Detailed Statistical Output

- Mean Misconception Score (Secondary): 4.12 (SD = 1.03)
- Mean Misconception Score (Undergraduate): 2.87 (SD = 0.91)
- t-Test: $t(298) = 9.34$, $p < 0.001$
- ANOVA: Significant $F = 23.58$, $p < 0.01$ across institution types
- Effect Size (Cohen's d) = 1.32 (Large Effect)

Misconception Frequency Table

Misconception	Secondary (%)	Undergraduate (%)
Ionic = transfer only	72%	39%
Covalent = sticks	64%	44%
Molecules are static	49%	34%
Orbitals = orbits	67%	46%
EN ignored	53%	28%

Coding Themes from Interviews:

- Theme 1: Visualization confusion

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- Theme 2: Symbolic language limitations
- Theme 3: Memorization vs understanding
- Theme 4: Textbook influence

These appendices provide transparency into the study's instruments and statistical robustness.