Examining Learning Difficulties and Alternative Conceptions Students Face in Learning about Hybridization in Organic Chemistry

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ABSTRACT: Chemistry education research has demonstrated that chemistry concepts are abstract, complex, and challenging for students to learn and understand. Chemistry is the branch of science that deals with the nature and behavior of atoms, atoms, and molecules, and bond formation and its energetics and hybridization both play a crucial role in the discipline. The concept of hybridization deals with the description of the formation of hybrid orbitals, the prediction of bond angles and molecular geometry, and the reactivity of some organic compounds. The development of a conceptual understanding of hybridization is essential for effective learning about bond formation, molecular structure, bond angle, acidity, and reactivity. This research study aimed to examine alternative conceptions that students hold; the challenges that students face in learning about hybridization; and the strategies they use to solve hybridization problems. The investigation took place at the City College of New York, an urban, minority-serving institute. Our method of data collection comprised a survey made up of Likert-type, open-ended questions as well as a hybridization-related set of problems. The number of research participants was n = 103. Our research findings suggest that developing a conceptual understanding of organic chemistry concepts such as hybridization and resonance structures, then relating it to them to structure of molecules is crucial to its function. The presentation of concepts such as hybridization in an oversimplified manner and students' reliance on memorization in learning can hinder their development of conceptual understanding and meaningful learning. Students misestimate their competencies and abilities, which can negatively impact poor performers and prevent them from addressing deficiencies in learning about hybridization. We suggest that instructors present the topic of hybridization at the three levels of representations, provide students with opportunities for active learning and knowledge construction, and nurture students' visualization of atomic and hybrid orbitals.

Keywords: science education, alternative conceptions, hybridization, atomic orbitals

INTRODUCTION

Alternative Conceptions and Challenges to Learning Hybridization

Chemistry is considered by most students a challenging discipline in science [1]. Organic compound analysis, acids and bases, organic reactions, chemical structures and bonds, functional groups, organic molecules introductions, and isomers are the concepts covered in a traditional organic chemistry course [2]. As per Van Driel and co-workers, students' solid appreciation of fundamental chemistry doesn't ensure their excellent comprehension of organic chemistry [3]. The abstract nature of chemistry, coupled with the notion that students are asked to learn about concepts that they can't see, makes it even more of a challenging subject [4].

Students hold views about ideas, concepts, and frameworks that are not consistent with the scientifically accepted principles, and these views are referred to as misconceptions, alternate conceptions, or naïve conceptions [5]. Alternate conceptions negatively influence students' learning of chemistry [6]. These alternative conceptions are persistent and cannot be easily corrected through traditional lectures [7]. Students possess several alternative conceptions about chemistry which have been found to resist changes in traditional instructional approaches [8]. Alternative conceptions are numerous in the chemistry curriculum at all levels of education [9]. This could be attributed to the abstract nature of chemistry, as it requires students to complete learning tasks at a high cognitive level [10].

If instructors know about alternative conceptions that learners have in a particular topic, they should design successful guidance by deciphering learners' thoughts [11]. Alternative conceptions that exist in students one one crucial factor that assumes a role in inhibiting the comprehension of the concept. The alternative conception is the irregularity of the understanding between the perspectives of instructors and students [12].

Instructors should utilize drawings, pictures, videos, models, recordings, and analogies called instructing methodologies, to assist students in understanding clear organic chemistry ideas [13]. For example, instructors need to think about the positive and negative sides of an organic chemistry model or practice various potential investigations that could be utilized for a specific topic [14].

Identifying learning difficulties in chemistry and discovering methods of addressing them in a meaningful way is essential for the discipline of chemistry and the students' ability to lean the subject effectively [15]. Understanding the alternative conceptions possessed by students is very important to further learn and reduce them. Johnstone and Otis have recommended using concept maps as appropriate devices to learn about students' alternative conceptions as well as to modify their own instruction to improve the learning of chemistry concepts [16]. Furthermore, to improve student learning of chemistry, instructors need to use findings of research about alternative conceptions in chemistry to works with the students on gaining an improved conceptual understanding of the content [17].

Studies have demonstrated that students have difficulties relating and contrasting the three levels of representations: symbolic, macroscopic, and submicroscopic [18]. Chemical knowledge is learned at three levels: sub-microscopic, microscopic, and symbolic, and the connection between these levels ought to be expressly taught [19]. This implies that the communications and differentiation between the levels are significant attributes of organic chemistry learning and essential for accomplishment in understanding chemical concepts. If a student experiences issues at one of the levels, it might naturally impact the others. Lack of ability of the student to distinguish and relate the three levels also leads to alternative conceptions [20].

Since knowledge is constructed in the learner's mind, it follows then that students use their alternative conceptions and knowledge structures to build new knowledge and develop an understanding of content rather than following the natural continuation of the development of conceptual understanding [21].

The American Chemical Society considers hybrid atomic orbitals as an anchoring concept for the organic chemistry undergraduate curriculum: they argue that hybridized orbitals are essential for bond length, bond angles, and strengths, the description of the molecular geometry, and to explain of sigma bonds [22]. Additionally, hybridization can be used to predict the acidity of a proton [23].

Researchers found that prospective teachers hold onto alternative conceptions about atomic orbitals and hybridization [24]. Students have shown difficulties in learning about hybridization where they assumed that shells and orbitals are the same, could not differentiate between atomic orbitals and molecular orbitals, and confused bonding electrons in hybrid orbitals with s, p, or d orbitals [25]. Furthermore, students do not have a well-developed conceptual understanding of orbital designations and their directions and interchangeably use the terms shells and orbitals [26]. Greater attention should be paid to alternative conceptions in learning about chemistry [27]. Identifying alternative conceptions that students possess about chemistry is crucial in deterring further learning, and instructors should actively work on addressing them to reduce them.

The hybridization of carbon atoms is an essential part of organic chemistry learning, and students use this hybridization to describe the formation of single, double, and triple bonds of carbon. Hybridization occurs when atomic orbitals mix to produce hybrid orbitals, which are not physical objects. Students need to understand that orbitals are nothing more than mathematical solutions to the Schrodinger equation. Students' difficulties in developing a conceptual understanding of hybridization could be an obstacle to learning about the reactivity of chemical compounds in organic chemistry [28].

Students' challenges in learning about hybridization impede their ability to correctly identify molecular structure even though students understand that molecular geometry depends on the understanding of hybridization [29]. Additionally, students in this study could not correctly define the concept of hybridization. Orbitals are abstract in nature, and the mathematics that describes them is rather complicated, which adds to the challenge of learning about them. In another study, researchers found that students struggle in providing explanations of bond formation that rely on hybrid orbital knowledge and in the identification of the hybridization type in organic compounds [30].

Students' Meta-Ignorance

People do not recognize their own expertise level and self-evaluate highly while constantly making errors [31]. It is also reported that low-performing students exhibit reduced metacognitive skills, which prevents them from adjusting their self-perception [32]. Meta-ignorance is defined as ignorance of ignorance, and it mainly affects incompetent students [31]. The double burden of incompetence, according to the Kruger-Dunning effect, is the deficit of expertise and the deficit to recognize when making a mistake [31]. Ignorant or incompetent students will dramatically overestimate their performance and ability compared to their competent peers, and they fail to recognize their actual level of performance and how much they suffer from it [33]. This ignorance of one's poor performance and ability prevent students from taking the required steps to improve their learning and performance. Metacognition is defined as the ability to recognize one's own successful cognitive processing.

Assessing students' understanding of their own learning and studying their metacognitive confidence in their performance provides valuable information for researchers in science education. This can be related to students' problem solving abilities and competencies [34]. Students' inabilities to perform well on given task would also be incapable of metacognitive competencies. The less competent students are about concepts would lead to higher confidence in their self-assessment of their performance. Research in chemistry education reveals that weaker students overestimate their performance on chemistry concepts [35].

Confidence rating refers to one's judgment of one's performance quality [36]. Research demonstrates that students poorly calibrate or miscalibrate the confidence rating of their performance, especially when the assessment problems include topics accessible from students' memory [37]. Poorly calibrated confidence ratings could decrease students' efforts to improve performance and learning [38]. Students need to become aware of their cognitive limitations to improve learning and performance.

METHODS

Guiding Research Questions

Our research was structured to address the following specific questions:

1. What are some of the learning difficulties that students experience in learning about hybridization?
2. What strategies and approaches do students use in learning about and solving hybridization problems?
3. What are the students' meta-ignorance levels compared to their performance in hybridization-related problems?

Method of Quantitative Analysis

This project was designed to investigate the challenges that students face in learning about hybridization and confidence in solving these problems. The project took place at the City College of New York (CCNY) during the spring and fall semesters of 2020 and spring of 2021. The City College of New York is an urban, minority-serving public college with a commuter student body. All participants in this project have either completed one semester or were enrolled in an organic chemistry course. Students learn about hybridization and bond formation in molecules in organic chemistry as a prerequisite to understanding bond angles, lengths, and strengths. Research participants have studied hybridization early in the semester as part of the course. We created a survey made up of Likert-type, open-ended questions as well as a hybridization problem set in order to gather data about student conceptions, practice, and confidence about hybridization problems. The survey was reviewed by two experts in assessment who verified that the questions adequately and objectively evaluated student understanding of hybridization in organic chemistry. A test-retest reliability analysis produced a reliability coefficient of 0.85 for our survey.

The survey was administered to and collected from 103 participants with approval from the CCNY Internal Review Board (IRB).

The Likert-type questions were on a five-point scale using numerical values as follows: Strongly disagree (1), disagree (2), neutral (3), agree (4), and strongly agree (5). We performed a single factor ANOVA on our Likert-type questions in order to understand the variability of the student responses to them. Insufficient variability in student responses to a question would indicate that it either did not accurately reflect student experience or that student experience of the issue at hand was too uniform to be informative. The average numerical value of student responses for each question was calculated and displayed in histograms.

For open-ended questions —as in the Likert-type questions — these values were averaged and displayed in histograms. Responses to two of these questions were diverse enough that a bar chart was used to display the various student responses.

RESULTS AND DISCUSSION

A single factor ANOVA method was performed on the Likert-type questions section of the questionnaire. P was calculated and found to be $P<0.05$, which indicates evidence against the null hypothesis and shows a strong relationship between variables. Furthermore, the data analysis shows that the mean-square between groups is 8.631, significantly larger than the mean-square within groups of 0.782. The ratio between groups-mean square and within-groups mean square is 54.06, which is large enough to reject the null hypothesis with confidence.

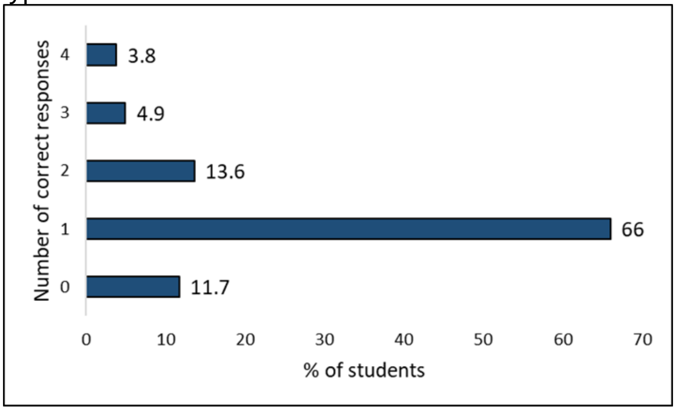

FIGURE 1. Students' percentages of a number of correct answers to the hybridization-related problems.

Figure 1 presents the percentages of students with the number of correct answers to hybridization provided problems. The problem set involved resonance hybrids and understanding how resonance affects hybridization. The majority of students (66%) had only one correct response. Only a small percentage of students — about 9% — were able to answer 3-4 problems correctly. One possible explanation is that students follow a prescribed set of rules taught to them and presented in textbooks to solve hybridization problems. The problem set presented to the students has a lone pair allylic to the □ bond and is delocalized because it participates in resonance, which impacts its hybridization and molecular shape. Developing a conceptual understanding of organic chemistry and understanding the structure of molecules is crucial. Recognizing resonance structures and their role is essential for learning and developing a conceptual understanding of many topics in organic chemistry. Understanding the □ bond and its delocalized electrons plays a role in learning about numerous concepts in organic chemistry, including hybridization.

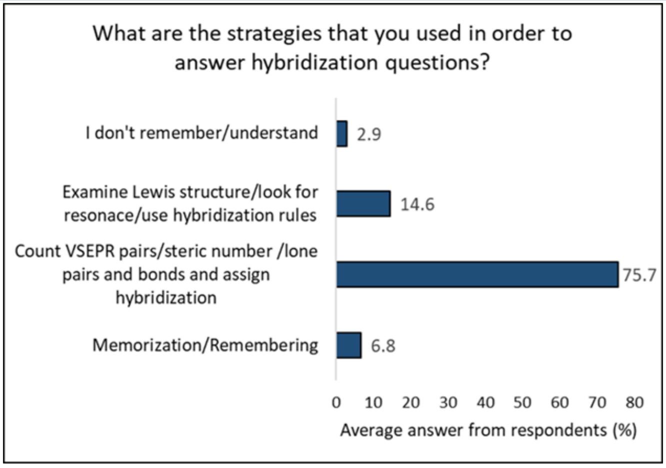

FIGURE 2. Student responses to open-ended questions about the strategies they used to solve hybridization-related problems fell into four basic categories. Counting VSEPR pairs or a steric number and assigning hybridization based on rules was the dominant response.

Students' responses to strategies used in solving hybridization problems are presented in Figure 2. The data show that the majority of students (75.6%) regurgitate counting of VSEPR pairs or steric numbers to arrive at the hybridization with no emphasis on examination of structure or investigation of the presence of resonance hybrids. This could be explained by how the concept is covered in textbooks and taught in a traditional lecture format. The over-simplistic presentation of hybridization in organic chemistry and relating it to count a steric number of VSEPR pairs does not lead to meaningful learning and conceptual understanding of hybridization. If students were exposed to meaningful learning of Lewis dot structures, bond polarity, molecular shape, resonance, and hybridization, it would translate to a conceptual understanding of molecular structures and their characteristics [39].

Figure 2 also shows that 6.8% of students rely on memorization and recollection in order to solve hybridization problems. Memorizing rules and steps to solve problems hinders students' development of conceptual understanding and meaningful learning. We should note that a fraction of the students (14.6%) discuss the examination of Lewis structures and investigating resonance hybrids, and applying hybridization rules to solve problems. Hybrid orbitals and hybridization is an abstract concept to students and should be presented at the three levels of representation; students should be allowed to be actively engaged in the learning process, the development of conceptual knowledge, and the visualization of atomic and hybrid orbitals. Definitions and demonstrations of the three levels of representations should be specified for the students [40].

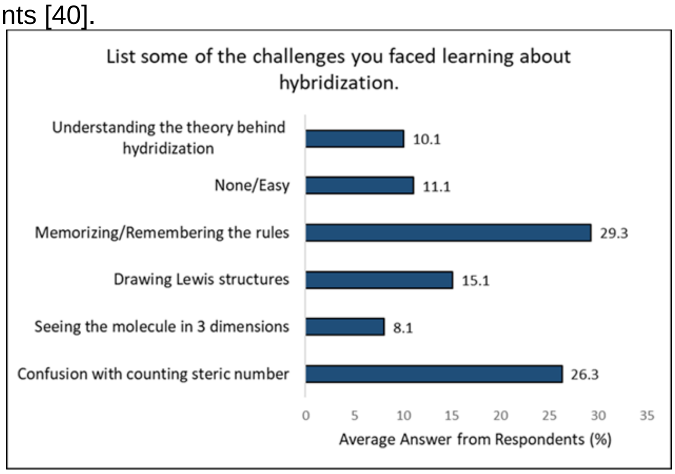

FIGURE 3. Student responses to open-ended question about the challenges they faced in learning about hybridization-related problems were broken down into six principle categories. The distribution of these responses was fairly uniform, but remembering the rules and confusion about counting the steric number were dominant responses.

The challenges that students face in learning about hybridization are presented in Figure 3. The data show that students (29.3%) find difficulties memorizing and remembering the rules presented in textbooks about hybridization. Reliance on memorization in learning hybridization is counterproductive to students' development of conceptual understanding. Students depend on memorization in learning about chemistry concepts, including hybridization, which does not translate to meaningful learning [41]. 26.3% of students in our research investigation also report that they face confusion about counting the steric number or VSEPR pairs while learning about hybridization.

We should note that 10.1% of the research participants reveal that understanding the theory behind hybridization poses a challenge to their learning. This might have to do with the abstract nature of hybridization and the need to relate the three levels of representations to understand the concept. It is especially challenging for students to understand the submicroscopic level of hybridization and hybrid orbitals. Research supports our findings in that students have difficulties learning about abstract concepts at the sub-microscopic level [42]. In one study, researchers suggest that for students to develop a conceptual understanding of hybridization, teaching and learning should focus on nurturing students' ability to visualize atomic and hybrid orbitals [43].

Students reveal that drawing Lewis structures (15.1%) and seeing the molecule in three dimensions (8.1%) are the most challenging part of learning about hybridization. Understanding Lewis's structure and shape of a molecule in organic chemistry is crucial to learn about its function and reactivity. Finally, 11.1% of students reported that hybridization learning was not challenging.

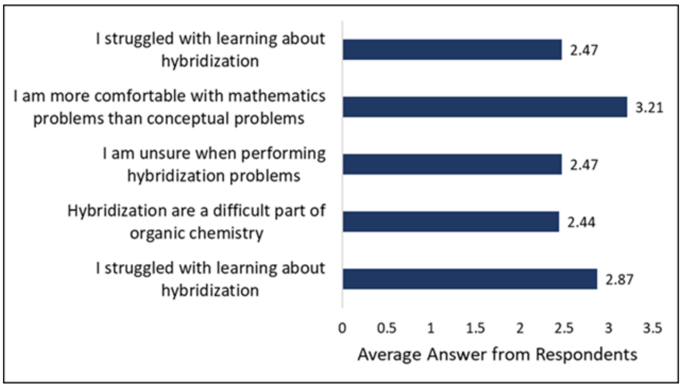

FIGURE 4. Average responses of students to Likert-type questions in our survey. The range of answers was: strongly disagree (1), disagree (2), neutral (3), agree (4), and strongly agree (5).

Responses to our Likert-type questions (Fig. 4) revealed students' perceptions of hybridization-related problems. The figure shows that students' perceptions of hybridization problems are that they do not struggle with the learning of hybridization and are unsure about the concepts of hybridization, classifying hybridization as a problematic part of organic chemistry. Students seem to be neutral on struggling with learning about hybridization, and they are more comfortable with mathematics problems than conceptual ones. This might have to do with one of two possible explanations, the first relating to how hybridization is presented in organic chemistry textbooks and taught in traditional lectures. Here, the concept is oversimplified into rules related to a steric number. This might lead the students to believe that the hybridization concept is not challenging to learn and provides them with a sense of false confidence about their ability to learn and perform on problems related to hybridization. The second possible explanation is meta-ignorance, which is ignorance about being ignorant of one's knowledge, competence, and ability. Students do not know that they do not know about hybridization and thus might have the perception that they are able to learn and perform well on hybridization problems. This overestimation of one's abilities and competencies leads to the often-misplaced confidence in one's performance and self-assessment.

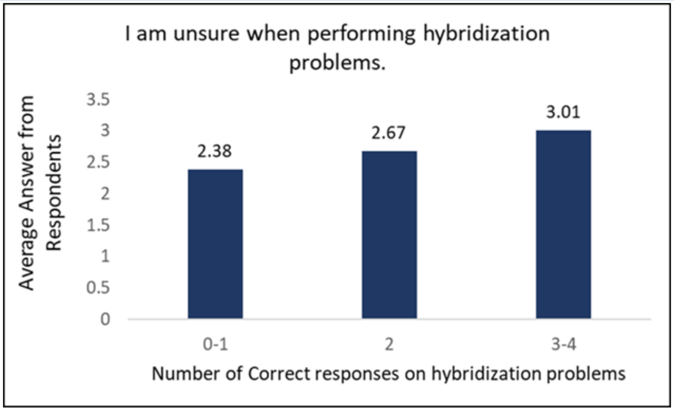

FIGURE 5. Students’ responses to Likert-type questions on confidence with performing hybridization problems and their performance on the assigned problem set.

Figure 5 depicts students' confidence level in their performance in hybridization problems. The figure shows that low performers tend to self-assess with higher confidence in their performers. On the other hand, the figure also shows that high performers exhibit lower confidence levels in their competence, ability, and performance. Our data suggest that both low and high performers misestimate their performance level. This is consistent with research in psychology that reports that bottom and top performers misestimate how well they do. While bottom performers overestimate how well they did, top performers underestimate how well they did [31].

Additionally, our research findings are supported by research in chemistry education. In one study about illusions of competence in introductory chemistry courses, the researchers revealed that low-performing students overestimate their performance and ability, whereas high-performing students underestimate their own performance and ability [44]. Confident students who perform poorly might not be inclined to work harder to address their learning deficiencies since they do not perceive such deficiencies. This could lead to a detrimental effect on their learning and can hinder their abilities to improve their achievement.

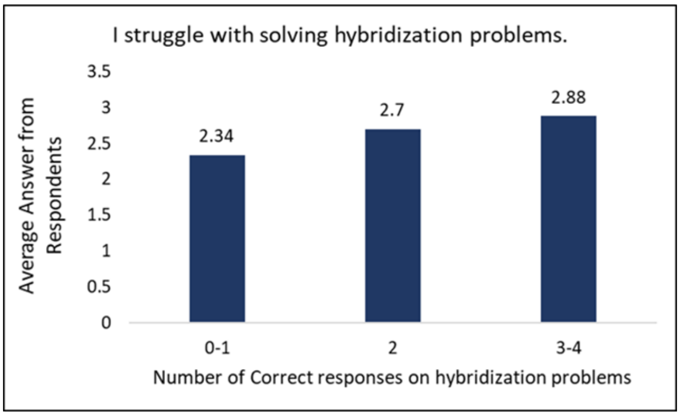

FIGURE 6. Students’ responses to Likert-type questions on difficulties with performing hybridization problems and their performance on the assigned problem set.

Figure six presents a correlation between the number of hybridization problems solved correctly and the students' level of struggle with these problems. Students who perform poorly report few challenges and difficulties in learning about hybridization, whereas students who perform well reveal that they struggle and face difficulties learning about hybridization problems. Students who do not perceive difficulties or challenges in learning about a concept are less likely to seek help or attempt to address the issue, which can negatively impact their performance in science. One's perceptions about one's ability and competence in a field can determine performance in the field [45]. Students who are low performers could also exhibit more alternative conceptions. Chemistry education research concerns students' alternative conceptions and learning difficulties in understanding scientific concepts [46]. In one research study, students were found to hold onto their misconceptions about certain chemistry concepts and are unaware that they hold such misconceptions [47].

CONCLUSIONS

Developing a conceptual understanding of organic chemistry concepts such as hybridization and resonance structures and relating it to the structure of molecules is important the development of conceptual understanding in organic chemistry. The concept of hybridization is oversimplified in its presentation in organic chemistry textbooks and by traditional teaching instructors; it's taught as something relying solely on identifying a steric number and counting VSEPR pairs, which hinders the development of conceptual understanding and meaningful learning of the topic.

Students rely on memorization in learning about hybridization, which can be an obstacle to meaningful learning and conceptual understanding. It is difficult for students to develop an understanding of the submicroscopic level of hybridization and hybrid orbitals because it is challenging for students to visualize the orbitals. Hybrid orbitals and hybridization are abstract concepts to students, which poses many difficulties to them; thus, instructors should present them at the three levels of representation; provide opportunities to students to be actively engaged in the learning process and knowledge construction; and nurture students' understanding and visualization of atomic and hybrid orbitals.

This investigation reveals that high performers exhibit lower confidence levels in their competencies, abilities, and performances, whereas low performers overestimate the level of their performances. Students who perform poorly but exhibit confidence might not be inclined to work harder to address their learning deficiencies since they do not perceive such deficiencies, which could be an obstacle to improving their learning and achievement. Low-performing students report that they faced few challenges and difficulties in learning about hybridization. The perceptions the students have about their abilities and competencies while learning about a concept can hinder them from seeking help or attempting to address the issue, and this can negatively impact their performance and learning in chemistry.

Instructors should (1) nurture the development of conceptual understanding of hybrid orbitals, their shapes, and their relationship to molecular geometry; (2) be aware of and emphasize the learning of the differences between shells, orbitals, and energy levels; (3) incorporate learning and teaching strategies that challenge and cause changes to students' alternative conceptions about hybridization in a meaningful way; (4) engage students in learning about hybridization and orbitals at both the symbolic (visualization of orbitals) and microscopic (bonding) levels; (5) ensure that students learn the connections between three levels of the chemical representations which would cause an improvement in conceptual understanding and reduction of alternative conceptions; and (6) provide students with learning opportunities to construct knowledge and gain competency about the driving force behind hybridization and the reasons that it occurs in atoms.

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