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Article

Analysis of Students' Missed Organic Chemistry Quiz Questions that Stress the Importance of Prior General Chemistry Knowledge

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Abstract: A concern about students' conceptual difficulties in organic chemistry prompted this study. It was found that prior knowledge from general chemistry was critical in organic chemistry, but what were some of the concepts that comprised that prior knowledge? Therefore an analysis of four years of organic chemistry quiz data was undertaken. Multiple general chemistry concepts were revealed that are essential prior knowledge in organic chemistry. The general chemistry concepts that were found pose a challenge to organic chemistry instructors who have identified those same concepts as ones they review or consider important in organic chemistry. A review of the literature provides recommendations that address the general chemistry students' difficulties revealed in this study. Further research, however, is needed to follow through on those recommendations.

Keywords: chemistry education; general chemistry; alternative/misconception; cognition; organic chemistry

1. Introduction

After many years of teaching general and organic chemistry, it has been noticed that many of the students' conceptual difficulties in organic chemistry stem from a lack of prior knowledge in general chemistry. Many organic instructors are faced with the same challenge and are frustrated with students not being able to do what instructors perceive as fairly simple tasks. To better understand what these barriers were, a four-year analysis was undertaken of over 10,000 questions that was based on a total of 234 questions per semester and 44 students who each answered the 234 questions. From there, further analysis considered only questions that required general chemistry content. Nine questions were identified from the four years where $\geq 30\%$ of all the students answered the question incorrectly.

The nine questions that were analyzed from each of the four years addressed multiple general chemistry concepts. Further review of the literature to understand students' lack of prior knowledge resulted in a synopsis of data that would be of use to both general and organic chemistry instructors. When students have prior knowledge that demonstrates a lack of general chemistry topics, this has the potential to interfere with their ability to demonstrate meaningful learning and to gain expert knowledge in organic chemistry.

1.1. Cognitive Science—The Importance of Prior Knowledge

"Cognition refers to all the processes by which sensory input is transformed, reduced, elaborated, stored, recovered and used" ([1], p. 4). According to Neisser [1] an act of "construction" (p. 4) takes place when relevant stimulation reaches the eye or ear and the student sees, hears or remembers. How much the student internalizes is influenced by the circumstances at that particular moment.

Many of these moments occur as the instructor strives to generate interest and motivation, to develop a commitment to learning, and to inspire the student to generate realistic goals, and finally to attain meaningful learning. Ausubel's assimilation theory posits that the single most important factor is "what the learner already knows" ([2], Preface) but first they must be ready intellectually and academically to understand that prior knowledge is useful, it must be recalled [3], and it needs to be related to new knowledge. Second, as novices, students must participate in representational learning, that is, the learning of the meanings and representation of single symbols (typically words) [2]. These are the prerequisite facts that must be memorized, however Ausubel [2] indicates that rote memory (factual recall) is useful for only a short period of time. The use of representational learning must be followed by propositional learning that will facilitate the student's ability to integrate multiple concepts into their cognitive processes [3–13]. Third, students must be actively and emotionally involved in their learning, so it proceeds from more elementary logical-mathematical structures to more complex. This permits them to reach a state of equilibrium by active assimilation [13]. Students' inability to remember and assimilate prior knowledge with new concepts and their lack of progression through the above steps contribute to their difficulty to obtain meaningful learning in organic chemistry.

1.2. General Chemistry Concepts Organic Chemistry Instructors Review in Their Courses

The four-year analysis of data collected from nine missed quiz questions revealed multiple topics where the students demonstrated a lack of prior knowledge in general chemistry. It is these same topics that have posed a challenge to organic chemistry instructors and provide the motivation for them to review prior general chemistry knowledge [14–24]. The general chemistry concepts they review are listed in Table 1.

A survey [24] was conducted of 23 college organic chemistry instructors who listed general chemistry concepts with more than one participant indicating other concepts such as equilibrium, mechanisms, and reaction coordinate diagrams. The instructors were also asked what concepts were fundamental to organic chemistry and to identify difficult organic chemistry topics. Topics in common to these two categories were reaction mechanisms, acid-base chemistry, resonance, structure and bonding, and stereochemistry. Students' lack of prior knowledge that was noted in the survey by more than one participant included: "carbon atoms can have more than or less than four bonds, electrons flow toward negative or uncharged sites, resonance is a fast exchange of electrons, resonance is an equilibrium, resonance states are compounds that exist in real time, and hydroxide or alkoxide ions can be present in a reaction mechanism carried out in acidic solution" ([24], p. 347). The topics listed have the potential to contribute to difficulties in organic chemistry that interfere with students' meaningful learning.

Table 1. General chemistry concepts identified as important for organic chemistry

Study	**Topics Typically Taught in General Chemistry and That Were Reviewed by Specific Authors Cited in This Work**											
References	**Acid-Base**	**Electrophile/ Nucleophile**	**Electro-Negativity**	**Isomers**	**Lone Electrons**	**Bonds**	**Energy Diagrams**	**Polar/ Nonpolar**	**Resonance**	**Thermo Kinetics**	**IM Forces**	**Structure [a]**
[14]					•							•
[15]		•										•
[16]			•									
[17]			•			•					•	
[18]	•		•			•	•		•			•
[19]			•		•							•
[20]	•	•		•						•	•	
[21]					•							•
[22]					•	•				•		
[23]			•			•						•
[24]	•	•	•		•	•	•	•	•	•		•

[a] Structure in this article refers to these subtopics: molecular structure and bonding; hybridization; single/double/triple bonds; and Lewis structures.

2. Literature Review of the Topics in the Nine Missed Questions

2.1. Number of Hydrogen Atoms Bonded to Carbon

Studies [24,25] support students' lack of prior knowledge about the number of bonds around a carbon atom. In a survey of college organic chemistry instructors it was found that students indicate that "carbon can have more than or less than four bonds" ([24], p. 347). In another study [25], students were presented with eight organic molecules to be categorized into two groups. From the research the "... results imply that organic instructors should not take for granted that students will necessarily abstract a salient feature from a pictorial representation of an organic compound in some anticipated manner" ([25], p. 120). What was their important takeaway message? They suggested that even though it will take more time, always show bonded hydrogens on carbons throughout organic chemistry. This will prove very helpful to students and thus reinforce the 4-valence nature of carbon.

2.2. Lone Pairs of Electrons

Table 1 indicates that a number of authors [14,19,21,22,24] review the topic of lone electrons in organic chemistry. All of the studies emphasize the importance of showing the presence of lone electrons on molecules. In one study it was found that when students were interviewed and asked to identify line structures of three molecules as aromatic they did not know the number of valence electrons for nitrogen and oxygen and the importance of lone pair electrons with respect to resonance [19]. In another study the authors suggested that line structures should be drawn explicitly, especially showing the non-bonding electrons [21]. Also, it may be possible with less condensed structures that students' cognitive space can be freed that allows them to focus on the conceptual basis of organic chemistry [21]. Another organic chemistry instructor [22] emphasized that all valence electrons should be shown on organic structures.

2.3. Covalent and Ionic Bonds and Electronegativity

One author [22] has indicated that one of the reasons organic students experience difficulty with reaction mechanisms is their lack of a sound understanding about covalent and ionic bonds. The author recommended, for example, that in a reaction between sodium hydroxide and an alkyl halide that sodium and hydroxide be shown as ions and that the spectator product ions, sodium and the halide be shown.

Six pillars of chemistry were identified by an author [23] that he encourages general chemistry instructors to emphasize. Two of these were electronegativity and polar covalent bonding. Though electronegativity provides a framework in chemistry, it must be supplemented with examples during organic chemistry so students are encouraged to make judgements when applying concepts. Likewise students need to understand that chemical bonding is a matter of degree and that "the extent of polarity ... determines the chemical reactivity" ([23], p. 84). For example, where is the most likely point of attack on chloromethane by hydroxide?

Two authors [16] introduce their students to electrostatic potential surfaces in the hope that a sound understanding of electronegativity and resonance will enable the students to identify the negative and positive areas of molecules. A common misconception identified in their study was a "belief that bond polarities depend on several concepts. The belief was in the absolute electronegativities of atoms only, whether they are connected or not (e.g., hydrogen will always be positively charged)" ([16], p. 1227). Students did not seem to appreciate that "polarity is a reflection of differences in electron distribution" ([16], p. 1227). They recommend that "why" questions related to electron densities be asked despite the challenge of grading such questions. This will enable instructors to evaluate students' thinking patterns.

2.4. Interpretation of Line Structures Such as Propene

Interviews were conducted with seven organic chemistry students and it was found that students had difficulty with interpretation of organic molecules and conscious thought and effort were needed to interpret structures correctly [21]. The authors suggested that after students' initial introduction to line structures in organic chemistry very little "explicit attention is paid to the interpretation of organic structures as the course progresses" ([21], p. 100). Additionally it requires a considerable amount of time before line structures become symbols for students because they have difficulty switching from one representation system to another [26].

2.5. Hybridization

Fourth-year chemistry and biochemistry majors were interviewed about their responses on multiple choice questions and one question involved hybridization [27]. Students inappropriately transferred terms from other chemistry disciplines. For example, a question was asked about hybridization around a carbon atom, a second period element. The student indicated that because there were three bonds and one lone pair of electrons the hybridization could be described as tetrahedral or square planar. Square planar would not be a correct description for a carbon atom. Students were generally unable to transfer concepts from other courses in order to answer organic chemistry questions. The authors recommended active learning and incorporation of visual aids in the learning environment.

2.6. Importance of Structure in the Prediction of Chemical and Physical Properties

According to several authors [28], structure enables students to predict and understand properties related to relative boiling points and acid and base reactivity. They propose a number of steps students must go through before they can predict the chemical or physical properties of a molecule. Those steps are recognition of the following: molecular formula > Lewis dot structure > electronic geometry > molecular shape > polarity of individual atoms > molecular polarity as shown in an electrostatic potential surface > and intermolecular forces of the molecule. The authors believe that many instructors are not aware of the cognitive challenge posed to students who are attempting to comprehend molecular structure. The steps the students must progress through demonstrate the importance of how they need to learn the meaning of many concepts in order for the novice student to become a propositional learner, that is, one who can connect multiple concepts.

2.7. Identification of the Electron Density of Molecular Structure

Student interviews were conducted with sophomore organic students, along with chemistry and pre-professional majors [29]. In the study, only seven of 14 students were able to identify boron trifluoride as a Lewis acid. Their explanations were boron had an empty p orbital, with electron density arguments related to the electronegativity of fluorine atoms, and that BF_3 cannot accept an H^+ ion. Approximately half of the students identified ammonia, NH_3, incorrectly as a Lewis acid with explanations that it could accept another proton, or another hydrogen, and because it had a hydrogen it can get rid of. The students relied heavily on Bronsted-Lowry theory even though it did not apply to the question. The authors recommended that Lewis theory should be stressed more in general chemistry.

In another study [30] three students were interviewed and asked to draw Lewis dot structures of various species and to identify them as a Lewis acid or base. One of the students did well with borane as a Lewis acid because of the absence of lone pair electrons and ammonia as a Lewis base because of the presence of lone pair electrons. However, he could not transfer his knowledge when he was questioned about ammonia and water because both molecules had lone pair electrons. One student who was successful used Lewis dot structures as a symbolic representation similar to that of an expert. He was able to conclude that "one hydrogen atom from water is bonding with the nonbonding pair of electrons on nitrogen in ammonia" ([30], p. 134). The novice student, however, sees "dot structures as nothing more than letters and dots and lines" ([30], p. 136). The authors recommended that Lewis dot structures be applied to chemical and physical processes so they have symbolic meaning that is essential in organic chemistry.

An article on the use of electrostatic potential surfaces in general and organic chemistry provides examples of how students' understanding can be enhanced when electrostatic potential surfaces are used [31]. Two authors approach the use of electrostatic potential surfaces to help students understand solubilities from intermolecular attraction and the use of electron distribution to understand oxidation and reduction, relative nucleophilicities, and leaving group abilities [16]. It is important to remember, however, that when students are introduced to electrostatic potential surfaces that a thorough explanation of their use and meaning be provided.

2.8. Number of Products Formed and Product Prediction

According to two authors organic chemistry students have a "product-oriented view of chemical reactions" ([32], p. 102) from general chemistry. When they encounter reactions in organic chemistry a "process-oriented view" ([32], p. 102) is needed that allows for a "continuous flow along a mechanistic pathway that transforms the reactants into the products of the reaction" ([32], p. 102). In another study [15] students were given a set of reagents and asked to provide the organic product. They were challenged to understand the physical and chemical characteristics of the molecules and mechanism of the reaction. For the students the reagents did not have meaning.

The more successful students are relational learners who develop or have the skills to see that organic chemistry focuses on the molecular transformations of reactions [21]. The less successful students, the instrumental learners, are challenged because they do not view reactions as a process.

3. Focus Question

Previous research has shown that difficulty in organic chemistry is influenced by students' lack of prior knowledge of general chemistry concepts. An analysis of organic chemistry quiz questions led to the following focus question:

- What are some of the general chemistry topics that demonstrated a lack of prior knowledge and have the potential to influence meaningful learning in organic chemistry?

4. The Organic Chemistry Course

The organic chemistry course described in this study is the first semester of a two-semester sequence. The first semester of the sequence is taught as a hybrid course where the students only meet with the instructor one 50-min class per week. Further details about the course are found in reference [33]. As a prerequisite, students are only required to complete one semester of undergraduate general chemistry and may not have studied thermochemistry, equilibrium, acid-base equilibria, and kinetics. The lack of exposure to these topics presents a teaching challenge to ensure these topics are covered carefully and thoroughly when needed.

Students access quizzes online through ANGEL [34], a course management tool, with approximately 29 quizzes per semester. The quizzes are based on lectures that are posted online and because the course is hybrid, the instructor does not present the lecture material during class meetings with the students. The students are required to complete the lecture notes and each student's notes are checked by the instructor for completion. Following almost every lecture there is a quiz to ensure students keep up with the lectures. The quizzes are set to start within two days after the lecture material is assigned and their frequency guarantees that a specific amount of content is covered each week. Only after a quiz and completion of the lecture notes are topics discussed in more detail; the material often comes from analysis of the quiz questions where the students experienced difficulty.

The questions on the quizzes are primarily multiple choice, with some fill-in-the-blank questions. Since the quizzes are online students can look up answers to the questions, but prior knowledge is essential. The textbook used for the course is *Fundamentals of Organic Chemistry* [35]. The chapters covered are shown in the Supporting Material.

5. Materials and Methods: ANGEL Item Analysis of the Quizzes

ANGEL has a number of features that can provide feedback to instructors. One such feature is called Item Analysis that provides specific information about the questions on each quiz. Analysis of the data collected from four different years (total of 44 students with 234 questions analyzed per student) was used to determine the questions that involved prior general chemistry knowledge that has the potential to affect students' understanding in organic chemistry. The nine questions chosen were those answered incorrectly by 30% or more of the students. The choice of $\geq$30% was chosen because it was noted that the distribution of students' incorrect choices often involved three or four of the wrong choices indicating the choices were good distractors [36], that is, the incorrect options were plausible choices. The chance of a randomly selected choice of an incorrect response is 25% with four choices, and 20% with five choices. However plausible choices reduce the possibility that students with limited knowledge will guess correctly [37]. Item discrimination data were also available and it was found that eight of the nine questions had high discrimination, above 0.40; including one with good discrimination, 0.39 [36]. When students with a high overall exam score also get a particular item correct, it indicates high discrimination. The item is able to discriminate between students who know the content from those who do not [38]. For further information on the calculation of discrimination, consult reference [39]. All of the questions were rated as average difficulty and fell between 25–75% [36]. For further information on the calculation of question difficulty, consult reference [40].

6. Results and Discussion

In this section the nine quiz questions that involve prior knowledge of general chemistry concepts are presented. A table displaying the nine questions, the average difficulty, average discrimination of each question, and the average percentage of students who chose a particular response can be found in the Supporting Materials.

6.1. Structure: Quiz Questions 1, 2, 13

These three questions address the significance of the following concepts that as instructors we should not assume our students know:

- the number of hydrogens bonded to carbon;
- lone electrons and their presence on elements such as nitrogen and phosphorus; and
- electronegativity's significance in the determination of covalent and ionic bonds.

6.1.1. Question 1 Topic: Number of Hydrogen Atoms Bonded to Carbon

The students' answers ranged from zero to four hydrogens with the majority of students answering incorrectly. Some of the difficulty with this question could be that the students lacked prior knowledge, that as a general rule, carbon is surrounded by four bonds. We assume students possess this prior knowledge because without that knowledge it is difficult for them to draw or recognize correct organic structures in reactions. Also, the model used in the question was a skeletal model of a large four-ring structure and it was necessary to focus on one aspect of the molecule. They may also have had difficulty because carbon was not shown on the model and it was at the junction of two bonds in one of the ring structures of the molecule where the number of hydrogen had to be identified.

Another example of the importance of the number of hydrogen atoms around carbon is in benzene substitution reactions. Hydrogen is often not shown on the benzene molecule so there appear to be only three bonds around carbon; students also need to understand resonance. When general chemistry instructors introduce benzene to illustrate resonance, it may be initially with the hydrogens, but thereafter a skeletal model without the hydrogens is most likely drawn. This carries over into organic chemistry. When the chapter on benzene chemistry is taught by this author, it has been found that the students cannot say how many hydrogens are on carbon; this happens many weeks into the organic chemistry course. Consequently, in benzene substitution reactions, this interferes with their ability to substitute a species for a hydrogen they cannot "see."

6.1.2. Question 2 Topic: Lone Pairs of Electro . . . (View) (Regrade) on a Phosphorus Lewis Dot Structure

The majority of the students chose two or three lone pairs of electrons on the Lewis dot structure of phosphorus. Even though P, along with As and Sb, can expand their octet to allow for five bonds, students must also remember that phosphorus has a valence shell filled with five electrons and can have three bonds and one lone pair of electrons. It is necessary to recall information from general chemistry that phosphorus and nitrogen are in the same family. Observations of students from past semesters indicate they have difficulty with nitrogen as an electron pair donor and phosphorus poses an additional challenge. If organic chemistry instructors continue to show non-bonding electrons throughout the course, students may be able to relate their importance to that of electron pair donors and acceptors and distinguish between a Lewis base and Lewis acid, respectively, thus they will be able to integrate multiple concepts necessary in mechanisms.

6.1.3. Question 13 Topic: Charge on Nitrogen in Methylamine, CH_3NH_2

For this question not only was it necessary to remember that nitrogen is more electronegative than carbon but the bond between carbon and nitrogen is covalent, not ionic. This topic has the potential to affect students' ability to understand the difference in ionic and covalent bonds and the more negative and positive area of two reacting species in relation to each other. The relative positive and negative nature of reactants is critical in organic acid/base chemistry. As can be seen in Table 1, electronegativity is a topic reviewed by organic chemistry instructors [16–19,23,24]. Additionally the representational model for methylamine was the molecular formula that did not show connectivity between carbon and nitrogen. Even though the question asked about the relative charge on nitrogen for the C-N bond, it is possible that when the students looked at the formula they might have questioned the existence of a bond between carbon and nitrogen when the two elements were not "beside" each other in the formula.

6.2. Structure (Multiple Bonds and Hybridization): Quiz Questions 6, 7, 12, and 14

The general chemistry concepts covered in this set of questions are the following:

- Hybridization around carbon;
- Bond angles around hybridized carbons;
- Effect of multiple bonds on hybridization;
- Planarity or non-planarity of hybridized carbons; and
- Sigma and pi bonds.

Numerous authors include structure as an important topic in organic chemistry [14,15,18,19,21,23,24]. As indicated in Table 1 structure includes the following: molecular structure and bonding, hybridization, single/double/triple bonds, and Lewis structures. All of these are covered in the multiple bond/hybridization questions except Lewis structures.

6.2.1. Question 6 Topic: Propene, $CH_3CH{=}CH_2$

Students need to have prior knowledge of several general chemistry concepts to answer Question 6. For example in "a." all atoms would not lie in the same plane because there is an sp^3 carbon. Choice "b" is an organic chemistry concept that a student might choose because of a lack of prior knowledge. Choice "c" involves acid/base chemistry that students seem to find difficult. Students might incorrectly choose choice "e" because the molecule has a double bond and they associate that with sp^2 hybrid orbitals. However, they would have neglected the presence of the CH_3- group and sp^3 hybrid orbitals. The students were given the molecular formula for propene and not a structural model. If they had taken the time to draw propene, its molecular structure might have helped to demonstrate the number of single/sigma bonds and the sigma bond that is part of the double bond.

6.2.2. Question 7 Topic: Ethene, C_2H_4

Students need to know about sigma and pi bonds to answer this question correctly. They also need to recognize that ethene is the simplest alkene, and it has two carbons, both of which are sp^2 hybridized and therefore have bond angles of 120°. A bond angle of 120° around the two similar carbons results in all of the hydrogens in the same plane. Though the majority of the students answered this question correctly, approximately 34% chose 120° as the correct bond angle. This was a correct response about ethene, but they were to have chosen the incorrect response about ethene's structure. Ethene was represented by its molecular formula for this question. The students might have been more successful if they had drawn a structural model of ethene.

6.2.3. Question 12 Topic: Carbon Atoms 1 and 2 Hybridization

The majority of the students answered the question incorrectly. It appears they should have drawn a structural model to show connectivity and demonstrate the number of areas of electron density around the two carbons. Students should know from general chemistry what constitutes sp, sp^2, and sp^3 hybridization with respect to the structure of simple organic molecules. After the quiz when students are asked if they drew the structure in order to answer the question very few students respond, "yes." When the structure is drawn for them they admit they could have been more successful on the question.

6.2.4. Question 14 Topic: Multiple Bond True Statements

Since all responses were selected for this question a lack of understanding of multiple bonds and structure was evident. It is important for students to recall from general chemistry that double and triple bonds have one and two pi bonds, respectively. In organic chemistry, knowledge about multiple bonds is paramount in reactions when alkenes and alkynes act as nucleophiles because of the presence of pi electrons. When they do not understand this it will be difficult to fully understand the mechanism of alkene and alkyne reactions.

It appears from the general chemistry concepts addressed with regards to multiple bonds and hybridization students do not "see" what we see when we use a formula or a 2D model to represent the three-dimensional nature of a molecule. Therefore, we need to pass on our expert skills to help them visualize molecular structure three-dimensionally.

6.3. Positive and Negative Areas on an Electrostatic Potential Surface: Quiz Questions 3 and 4

The general chemistry topics covered in the following two questions are:

- Positive and negative areas on an electrostatic potential surface represented as blue and red, respectively, and what this means in the context of a reaction
- Two reactants can form one product

The importance of electrostatic potential surfaces should not be overlooked in general chemistry. The surfaces can be used to connect multiple concepts such as molecular structure, Lewis dot structures, and to prepare students for the transfer of electrons in organic chemistry Lewis acid/base reactions. As revealed in the literature, if students understand concepts such as electronegativity and resonance they might be able to identify the negative and positive areas of molecules. Also, the positive and negative aspects of the surfaces might help students understand intermolecular attractions as they relate to solubility.

6.3.1. Question 3 Topic: Transfer of Electrons

General chemistry students often have difficulty remembering that boron has an empty p orbital, represented by the more positive blue area on the surface of boron trichloride shown in question 3. The presence of a lone pair of electrons on nitrogen is a concept students should also know from general chemistry and this is represented by the more negative red area on the surface of dimethylamine. Knowledge of these concepts is critical for student understanding about the direction of electron transfer in organic chemistry mechanisms. The literature reviews demonstrated that students have difficulties with these same concepts and suggestions were the introduction of Lewis acid base theory [29], the use of Lewis dot structures [30], and electrostatic potential surfaces in general chemistry [31].

Electrostatic potential surfaces as models are very common in both general and organic chemistry textbooks [41], specifically the textbook used by most of the first year chemistry students in this study [42]. The surfaces are also in the textbook used in organic chemistry [35]. In the first-year chemistry course this author uses the surfaces to discuss electronegativity and polar and nonpolar molecules in relation to the more negative and positive areas on the surfaces and the structure of the molecule. When the students are introduced to functional groups in organic chemistry, a transparent surface is presented for each example with a ball and spoke model visible. The use of the surfaces is integrated throughout the course in topics such as Lewis acids and bases, bond polarity, and mechanisms. Structural models are used to emphasize the attraction of a more negative area on one molecule to a more positive area on another molecule.

6.3.2. Question 4 Topic: Number of Products Formed

The majority of the students chose the wrong response; the most popular response was two products. In general chemistry, students usually experience more than one product in a chemical reaction, therefore when two molecules come together to form one product that is not an expected answer. Additional general chemistry concepts in this question were the empty *p* orbital on boron that was available for the donation of a lone pair of electrons from nitrogen to form a stable compound between the two molecules.

Students needed to understand general chemistry concepts related to orbitals and valence electrons for this question. Additionally, how the surface relates to the structure of the molecule as an electron pair donor or acceptor is extremely important because this focuses more on the process of product formation. The multiple concepts in this question made it more difficult for students to demonstrate meaningful learning.

7. Conclusions

This study focused on general chemistry topics that were identified from an analysis of 234 questions each completed by 44 students. Nine questions were identified that resulted in multiple general chemistry concepts that have the potential to interfere with meaningful learning in organic chemistry. When a student's lack of prior knowledge in general chemistry is identified and remedied this promotes an environment for conceptual change. Many organic chemistry instructors have identified the same topics as ones they review and/or consider important in organic chemistry. A literature review provided recommendations by the authors to help novice organic chemistry students become experts, that is, meaningful learners. The general chemistry topics missed by the students and the supporting literature review recommendations are summarized in Table 2.

Table 2. Concepts of Difficulty for Students and Recommendations.

General Chemistry Concepts that Required Prior Knowledge	Literature Review Recommendations
the number of valence shell electrons of carbon	show bonded hydrogens on carbon throughout organic chemistry to reinforce the 4-valence nature of carbon
lone pair electrons on nitrogen and phosphorus	display lone electrons on organic structures
the relative charge on two bonded elements based on electronegativity	understand the difference in ionic and covalent bonds; chemical bonding is a matter of degree
hybridization around carbon; single and multiple bonds; sigma and pi bonds; planarity or non-planarity of hybridized carbons; bond angles around hybridized carbons;	draw line structures of molecules to help students switch from one representation system to another; utilize molecular structure to teach chemical and physical properties of molecules;
effect of multiple bonds on hybridization	pay explicit attention to organic structure interpretation as the course progresses and incorporate visual aids
positive and negative areas on an electrostatic potential surface represented as blue and red, respectively and what this means in the context of a reaction	teach both Bronsted-Lowry theory, but emphasize Lewis theory in general chemistry; apply the use of Lewis dot structures to chemical and physical processes such as solubilities, oxidation and reduction and leaving group abilities; emphasize that polarity reflects a difference in electron distribution; understand the relative positive and negative nature of reactants
two reactants can form one product	apply the use of Lewis dot structures to chemical and physical processes; utilize a process-oriented view in organic chemistry to help students transform reagents into products along a mechanistic pathway; show ions in organic reactions as both reactants and products

The multiple general chemistry topics the students missed on the organic chemistry quizzes revealed that they did not have the necessary prior knowledge from general chemistry. We need to constantly keep in mind that we are experts and must help our novice students bridge the gap that results from their lack of prior knowledge.

8. Recommendations to Instructors

It is hoped that organic instructors will benefit from the analysis of the questions in this article, avoid time to rediscover these same concepts, and will implement learning activities and curricular interventions in general chemistry to address students' lack of prior knowledge that interferes with meaningful learning. It is of paramount importance to assist our students in the use of models starting in general chemistry and continued in organic chemistry. Because there are many different models used in organic textbooks and several were used in the quiz questions, we need to help our students understand what each model represents and how the model can be used to understand organic chemistry concepts. Students in organic chemistry need direction that will enable them to connect multiple concepts so they can solve organic chemistry puzzles, which is how this author refers to organic reactions and mechanisms. We need to mentor our students in the techniques needed to solve organic chemistry puzzles. The challenges we experience as organic chemistry instructors will make it difficult to provide guidance to our students unless we understand that our students lack prior knowledge that has the potential to interfere with what we want them to learn in organic chemistry. Ongoing communication between general and organic chemistry instructors is extremely important so we can work together to prepare students for organic chemistry.

Supplementary Materials: The following are available online at http://www.mdpi.com/2227-7102/8/2/42/s1, Table displaying the chapters covered in the course. Table displaying the nine questions, the average difficulty and average discrimination of each question, and the average % of students who chose a particular response.

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