ORGANIC SYNTHESIS EXPLORATION THROUGH THE LENSE OF SIGNIFICANT LEARNING FRAMEWORK

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Dedication

To my parents, whose unwavering love, boundless encouragement, and countless sacrifices laid the foundation for every aspiration I've ever had. Your belief in me, even amidst uncertainties, was the constant light that guided me through this demanding journey. This achievement is as much yours as it is mine.

To my late grandfather, Samuel Gatana, you were a beacon of hope who supported and rejoiced with me through every small increment of my education. We were inseparable, and before you closed your eyes forever, I promised you I would finish this journey. Continue resting in peace.

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ABSTRACT

Since the discovery of Organic synthesis as a new scientific field, scientists have been able to synthesize biological and medically essential molecules in laboratories. However, the concept of Organic synthesis has been challenging for many students taking Organic Chemistry courses. Students view the course as an obstacle to overcome as they venture into their career goals. With the cognitive demand of the material appearing to be beyond most students' reach, rote memorization is inevitable for success rather than conceptual understanding. This difficulty poses a barrier to students' academic progress and their development as future scientists. Advancing the principles and techniques of Organic synthesis should be a fundamental priority in science, particularly in chemistry. Research in this field should not only aim at practical applications but also focus on expanding scientific knowledge. Since Organic synthesis plays a crucial role in various scientific and technological advancements, its continuous development is essential for progress in chemistry and related discipline. This study investigated the extent in which experts and novices approach Organic synthesis, as well as values and expectations they hold and how they align with significant learning framework. The implications of this study advocated for the integration of Fink's Significant Learning Framework into Organic synthesis instruction to foster a deeper multidimensional learning experience. By addressing not only foundational knowledge and application but also integration, human dimensions, caring, and learning how to learn, this framework would support students in constructing a coherent understanding of Organic synthesis.

CHAPTER I*:* INTRODUCTION

The majority of students enrolled in General Chemistry across various institutions will eventually take Organic Chemistry courses. Organic Chemistry is a two-semester course taken by most collegiate majors in the areas of Chemistry, Chemical Engineering, health sciences, and Biology. Students from other majors, such as nursing, generally take a one-semester Organic Chemistry course. The course traditionally has a concurrent lab section in addition to an Organic Chemistry lecture. It is in Organic Chemistry II where students primarily encounter Organic synthesis. This portion of Organic Chemistry focuses on the design and synthesis of Organic compounds from simpler starting materials. The importance and emphasis placed on Organic synthesis is heavily influenced by the value of synthetic efforts in developing new and improved pharmaceutical agents and materials.

Rationale for Research Questions

Although there has been a lot of research in and instructional materials created for learning Organic Chemistry, little has been done to better understand how students learn Organic synthesis specifically. From the 1950s to 1970s, instructors taught Organic synthesis as an illustrative representation of actual syntheses approaching each problem in an "*ad hoc way"* (Corey & Cheng, 1989, p. 4). Similar studies found that synthesis activities designed for instruction included scaffolding to develop students' conceptual understanding of synthetic skills based on the author's experience, expertise in synthesis and research in problem-solving (Flynn, 2011, 2014).

Two of the most useful problem-solving approaches used by Organic Chemists include retrosynthesis and a mechanistic approach. A mechanistic approach helps Organic Chemists to understand reaction pathways, reaction intermediates and stepwise changes that occur in a

chemical transformation. The retrosynthetic approach involves transformation of the structure of a synthetic target (TGT) molecule into a simpler structure along the pathway. Through retrosynthesis, learners can use various strategies to solve a problem, either concurrently or independently. These strategies include transform-based, structural, topological, stereochemical, functional group, and recognition of substructural units in the target molecule (Corey, 1991).

The synthetic target molecule is obtained by applying a transform, which is the opposite of the synthetic reaction. This transformation leads to a new molecule, which becomes the synthetic target for further analysis. The repetition of these processes forms a tree of intermediates with chemical structures as nodes and pathways from bottom to top, which correspond to possible synthetic routes (Corey, 1991). In each retrosynthetic step, a structural subunit or retron must be present for the transformation to operate on the target molecule.

During the transformation process in the retrosynthetic approach, there are factors that can make the synthesis process challenging to execute, giving rise to structural complexity (molecular size, functional group content, stereocenter, cyclic connectivity, chemical reactivity, and structural instability) based on the modification of structural elements. This modification complexity is essential, as it determines the type of strategy that will be applied during synthesis. Accordingly, the synthetic success for complex molecules depends on the learner's ability to analyze the problem, develop possible intermediates in the process, apply different independent strategies, and have a broad familiarity of Organic reactions and mechanism (Corey, 1991).

Analyzing any target molecule using a retrosynthesis approach (backward approach) simplifies the problems as there are only a few possibilities compared to the forward approach whereby there is an apparently endless number of starting compounds and Organic reactions that may be used (Bhattacharyya, 2004). The backward approach provides a clear starting point for

solving the problem, although finding the right synthetic pathway "depends on the chemist and the problem" (Corey & Cheng, 1989).

Organic synthesis requires students to adopt a process-oriented approach to understanding how reactions occur in contrast to the product-oriented approach in General Chemistry. Thus, students must begin to think about the process and gather all the information they need to analyze the problem logically. Organic synthesis also requires the students to retain and apply a range of chemical principles at different stages of the process. To do this, students must construct knowledge by integrating new information with pre-existing knowledge and making sense of it while solving synthesis problems.

Although some studies have proposed different strategies for solving Organic synthesis problems by comparing successful and unsuccessful students or high performing and low performing students, research comparing novices (students) and experts (faculty) is limited. Researchers have proposed several problem-solving strategies to promote students' learning in Organic synthesis. While these accounts focus on the pedagogical approach to problem solving, little is known beyond the anecdotal evidence of how experts engage in these strategies compared to novices.

Unlike novices who rely on linear recall of individual reactions without fully understanding their broader application, experts demonstrate the ability to recognize patterns, apply strategic reasoning and mentally model the reaction pathways. Successful and unsuccessful students, Expert/novice dichotomy, strategies proposed in the literature to alleviate students challenges in Organic synthesis, organization of Organic Chemistry textbooks and Fink's taxonomy of significant learning framework will be discussed further in chapter 2.

This study is reported in two manuscripts (Chapter III and Chapter IV) that addressed the following research questions.

Chapter III: A Significant Learning Perspective on How Novices and Experts Approach Organic Synthesis Problems.

RQ1: How do novices and experts differ in how they organize, and prioritize foundational knowledge during synthesis problem-solving?

RQ2: What strategies do novices and experts use while solving synthesis problems?

RQ3: To what extent do novices and experts connect Organic synthesis with prior learning during synthesis problem solving?

Chapter IV: Understanding Novice and Expert Values and Expectations in Learning Organic Synthesis: A Significant Learning Approach.

RQ1: What instructional methods do experts employ in teaching Organic synthesis, and how do novices use these and other strategies to support their learning?

RQ2: What values and expectations do novices hold toward success in Organic synthesis?

RQ3: In what ways do the expectations of novices and experts align regarding Organic synthesis?

The conclusion in chapter 5 will address the highlights of the implications, future research, limitations and strengths of the study.

Personal Interest

As a college sophomore student, I enrolled in Organic Chemistry I where I had a lot of success. My success in that class led me to start thinking about a future career in medicinal Chemistry, pharmaceutical sciences or as Chemistry faculty. However, in my second semester of Organic Chemistry, the instructor did not expound further on the topics. We spent the time learning the material in the first 8 chapters of the textbook which was the same as we learned in Organic I. Because of my interest in the field, I went to the office to ask the instructor when we would be covering the rest of the material in which he replied, "You shall learn the rest in graduate school". In graduate school after enrolling in Organic Chemistry, while pursuing a master's degree, the challenges of conceptualizing Organic Chemistry II and consequently Organic synthesis were evident. Many times, the instructor would mention that the concepts we were studying should have already learned as an undergraduate student.

These experiences stirred an interest to research the subject from a pedagogical perspective. After joining the Chemistry education program, my interest focused more on Organic synthesis. I found that much of the education research focused on comparing successful and unsuccessful students across various education levels (undergraduate, graduate and postgraduate). However, there was comparatively little research that examined the differences between faculty and students on how they approached synthesis. I observed that students were often referred to as experts based on their success in solving a problem. However, my interest focused on how both the faculty and the students approached Organic synthesis while considering faculty as experts and students as novices.

In an attempt to make these processes explicit, I conducted a pilot study involving several graduate students to understand their perspectives and experiences in Organic synthesis. The

pilot study provided guidance on the type of questions I wanted to address in semi-structured interviews. For the dissertation, I explored the significant learning perspective on how experts and novices approach Organic synthesis. All participants were given Organic synthesis problems (tasks) to solve while thinking aloud.

For the first manuscript, I analyzed this data using the Fink significant learning framework and an open coding system developed by Bode and Flynn (2016) which was modified for this study. Fink's taxonomy is comprised of six different types of learning that are interactive: foundational knowledge, application, integration, human dimension, caring and learning how to learn. The first three components (foundational knowledge, application and integration) were addressed in the first manuscript.

For the second manuscript, I explored the expectations between the novices and the experts through semi-structured interviews. I conducted a survey of students using a student survey tool to explore students' perceptions and expectations in their Organic Chemistry classes. I analyzed and categorized this data within the framework of Fink significant learning model using the last three components (human dimension, caring and learning how to learn). More details about Fink's taxonomy of significant learning will be discussed in chapter 2. The data for both manuscripts were collected simultaneously.

With detailed exploration of expert-novice alignment and expectations, I hope that there can be a better understanding of how to improve the student experience in learning and solving Organic synthesis problems. Beyond improving instruction and student performance, fostering early and meaningful discussion about shared expectations between instructors and students can be highly beneficial. Such dialogue can help effectively address those expectations.

Definition of Terms

For this study, the following terms are defined. These definitions will govern the use of the terms throughout the study.

- Activities- Dynamic part of the mechanism that deals with the transformation of the entity. For example, breaking or forming bonds.
- Chiron approach – A synthesis approach in Organic synthesis involves the disconnection of strategic bonds in a target molecule. The technique capitalizes on conserving stereochemistry from a target molecule chiron to the chiron template (Hanessian, Franco, & Larouche, 1990).
- Experts – An expert has a coherent, extensive, and consistent knowledge base acquired in a domain through experience, which affects how they notice and interpret information in their environment.
- Novices- A novice has incoherent and unconnected knowledge fragments with several inconsistencies and minimal exposure to the domain.
- Organic synthesis- Preparation of Organic compounds from other compounds (Bruice, 2014).
- Problem - A task that requires analysis, reasoning, and high order cognitive skills to bridge the gap between the reference point and the target.
- Exercise – A task that requires well-practiced procedures. The path is clear from the beginning.
- Problem-solving- A system of generating acceptable solutions that involve cognitive operations influenced by motivation and behavior factors (Smith, 1998; Anderson 2005; Yuriev, Naidu, Schembri, & Short, 2017).

- Retrosynthesis- Working backward from a target molecule to the available starting material.
- Retron- The structural subunit of a target structure.
- Synthon – Fragments (typically one positive and one negative) formed because of disconnection in retrosynthetic analysis. Synthons are not real compounds.
- Target molecule (TM)- The desired product of Organic synthesis.
- Transform- Retrosynthetic operation that deals with the transformation of a target molecule to a synthetic precursor.

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CHAPTER 2: Literature Review

INTRODUCTION

Students' attitudes towards learning Organic Chemistry have been a significant concern over the years (Zaplatynski, 2006; Adams, Wieman, Perkins, & Barbera, 2008; Dunlap, & Martin, 2012; Cha, & Kim, 2016; O'Dwyer & Childs, 2017). Most students regard this course as an obstacle to overcome as they venture into their career goals (Bhattacharyya, 2004; Anderson & Bodner, 2008; Fishback, 2010). According to Salame (2021), most students fear Organic Chemistry because of its reputation as a barrier to their academic success. Seymour and Hewitt (1997) attributed this reputation to students' perception, faculty reference, and teaching methodologies designed for higher achieving students (as cited by Salame, 2021). With the cognitive demand of the material appearing to be beyond most students' reach, most students rely on memorization instead of conceptual understanding (Bhattacharyya, 2004; Anderson & Bodner, 2008; Fishback, 2010; Lafarge, Morge & Meheut, 2014; Early, 2018).

This chapter presents a comprehensive review of educational literature that will help to establish a theoretical foundation for analyzing the data. This study aims to explore how significant learning has been applied in the teaching and learning of Organic Chemistry, with a particular emphasis on mastering Organic synthesis as reflected throughout the literature. The chapter is organized into five key sub-sections that collectively inform this foundation: (1) categorization of students as successful and unsuccessful; (2) the expert-novice dichotomy as it pertains to problem-solving and knowledge organization; (3) proposed methods in the literature for teaching and learning Organic synthesis; (4) the structure of Organic Chemistry textbooks and proposed methods for students' success; and (5) an overview of Fink's Taxonomy of Significant Learning. Each section addresses a critical component of how students should acquire and apply knowledge.

Successful and Unsuccessful Students

The purpose of the following section is to examine how students approach problem solving in Chemistry with a focus mainly in Organic synthesis. The following studies investigate the cognitive, metacognitive and procedural strategies that differentiate students who succeed in conceptual problem solving from those who rely on algorithmic methods without deeper understanding. By exploring problem solving in Chemistry across various students levels (from undergraduate to postgraduate), the section will shed light on significant learning gaps.

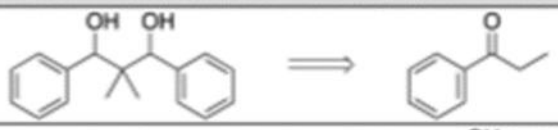
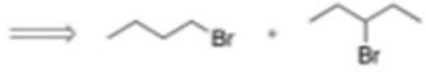
Pickering (1990) while conducting his study, on conceptual learning versus problem solving categorized students into two groups: those who can solve conceptual problems successfully and those who can do mathematical problems without having a molecular understanding. Students who solve the problems algorithmically lack a sufficient level of conceptual understanding. Similarly, Domin and Bodner (2012) classified the students as successful and unsuccessful based on accuracy, abstractness and completeness while solving problems on 2D-NMR concepts.

Based on the think-aloud protocol analysis, the unsuccessful problem solvers showed the incorporation of prior knowledge but never used it while solving the problems. The successful problem solvers' representations resembled how the instructors presented the concepts during instruction on accuracy and completeness, although they lacked abstractness. The students grounded their representations to the instructional material and incorporated information that was not presented in class, implying the individual's cognitive schema (Pickering, 1990).

Using Ausubel and Novak's theory of meaningful learning, Bode and Flynn (2016) conducted a study in an Organic II Chemistry course at research-intensive universities in Canada. The investigators were interested in the strategies both successful and unsuccessful students use

in solving synthesis problems. The participants involved in the study consisted of students from two classes taught by different instructors at the university. The instructors gave the students a target molecule with a starting material and additional instructions to solve synthesis problems (Bode & Flynn, 2016, p.595), as the following table depicts.

Table 2.1. Synthesis Problems with Specified Requirements

Course code and question number	Synthetic problem	Requirements (in addition to a proposed synthesis)
A		• Brainstorming • Analysis
B1		
B2	3-ethyl-3-heptene 	• Brainstorming • Analysis • Use Wittig reaction

For some questions, the instructors expected the students to engage in brainstorming, which consisted of right and wrong ideas, analysis, and proposed synthetic pathways. During the coding process, the investigators categorized the answers as either successful (correct synthetic proposal and minor errors) or unsuccessful (significant synthetic errors and missing critical synthetic steps). To analyze their results, Bode and Flynn used a chi-square test of independence to compare the strategies used by both successful and unsuccessful students. From the students' results, specific procedures were more associated with successful answers than unsuccessful (p. 598). These strategies included:

- Identified newly formed bond in the target molecule,
- Identified atoms added to the starting molecule to form the target,
- Identified key regiochemical relationships,

- Mapped the atoms of the starting material onto the target,
- Used a partial or complete retrosynthetic analysis,
- Drew reaction mechanism.

The investigators based the criteria for distinguishing student success on the number of strategies used and not whether they got the whole problem correct. Most of the unsuccessful answers did not demonstrate any fundamental techniques. Bode and Flynn proposed that synthetic pathways are more successful when learners use multiple strategies.

The same concept of categorizing students as successful or unsuccessful has also been used in Physics. Ali et al. (2014) conducted a study to determine the metacognitive ability between successful and unsuccessful students in solving Physics problems. The participants consisted of 21 students at the university level who had a Physics background associated with their ability to solve problems from the Physics problem-solving achievement test (PPSAT). The investigators divided the students into two groups, field one and field two, to study the participants. The students performed the task while at the same time thinking aloud. After grading the task, the investigators put both groups together to determine the successful and unsuccessful students. Students who performed below 40%, with many procedural errors and less conceptual understanding, were classified as less successful from their results.

Another criterion that the investigators used to organize the students as unsuccessful was the ability to demonstrate cooperation in solving the problem while thinking aloud. The investigators classified the students who stopped trying to solve the problems or completely withdrew from the process as unsuccessful, while those who performed above the 40% threshold with fewer or no procedural errors and high conceptual knowledge levels as more successful. According to the investigators, their study results support previous literature on categorizing

students as successful and unsuccessful in problem-solving based on incorporation of prior knowledge, resemblance of instructors presentation and correct synthetic proposals with minor errors.

High achieving students, just like experts, can organize their approach method in solving the problems, unlike low achieving students. In their research, Gulacar et al. (2014) investigated 18 students (nine high achieving and nine low achieving students) from a midwestern university in the United States. The investigators selected the students based on their pre-knowledge of stoichiometry concepts using a stochiometric proficiency test. The investigators subjected the students to various tests such as logical thinking (students reasoning ability), digit backward test (tested working memory), and Longeot test to determine their cognitive development. Additionally, the investigators gave the participants other tests for assessing students' conceptual understanding of the mole concept and their abilities to solve stoichiometric problems. Gulacar et al. (2014) used a systematic coding method with eight codes to classify students based on whether they got a question correct or missed any step.

Their findings revealed significant differences between the two groups in solving complex problems. As Gulacar et al. reported, "The lower-achieving students did nonsense calculations or made guesses based on irrelevant data when they did not know what method they needed to follow or what subproblems needed to be done" (p. 965). The low achieving students were less successful as they solved some problems incorrectly and were more than likely to make mistakes than high achieving students. High achieving students were more successful, made few errors, and demonstrated formal reasoning and problem-solving skills, which helped them solve stoichiometric problems efficiently.

Since there were no significant differences between high and low-achieving students on cognitive abilities, Gulacar et al. argued that working memory is not a factor in solving Chemistry problems despite students having significant differences in their reasoning abilities. From their conclusion, Gulacar et al. argued that most students struggle with complex problems because they cannot make connections between the subproblems. As the problem becomes more complex, the difference between high and low-performing students' problem-solving behavior increases.

Problem-solving behaviors have been categorized based on the students' approach (deep or surface approach). Ausubel's work of meaningful learning and rote memorization helps to understand these differences. Students who demonstrate deep problem-solving behaviors are identified as those seeking an understanding, looking for meaning, making connections between the concepts, and showing intrinsic motivation (Teichert et al., 2019; Bunce et al., 2017). Students who demonstrate surface problem behaviors tend to focus on idiosyncratic features of the problem and rely on memorizing algorithmic procedures and formulas without understanding the concept (Teichert et al., 2019; Bunce et al., 2017). They also match the attributes of the problem to what they are familiar with without analyzing the uniqueness of the problem.

Bunce et al. (2017) conducted a study on 990 students who enrolled and completed the General Chemistry course at the US Naval Academy, focusing on their study methods. The researchers categorized the students into four groups based on whether they used surface or deep approach methods while studying using the Modified Approach and Study Skills Inventory survey (M-ASSIST). Students in Level 1 were highly concerned with "getting answers" as they associated the time they would spend studying with how they expected to perform on their exam. Level 2 students used rote memorization or algorithms for solving problems. Level 3 students

worked on problems individually and cooperatively with their peers, while Level 4 students acted as teachers to their peers by monitoring and evaluating their understanding (Bunce et al., 2017).

These results enabled the investigators to conduct further research regarding the relationship between the study approach and course achievement as measured by the grade. They placed the students into three groups: successful (A/B), intermediate (C), and unsuccessful (D/F) based on their course letter grade. There were significant differences in the deep factor between A/B and D/F and A/B and C students from their analysis, but no significant difference in the C and D/F students' surface factors. A/B students demonstrated deep study approaches compared to other groups, while C students demonstrated a surface approach like D/F students.

For the surface approach, all groups had significant levels of latent means, with A/B students having the smallest and D/F the largest, with C students representing a latent mean of surface approach between the two groups. As a result, Bunce et al. concluded that high performing and middle achieving students are more than likely to report or agree with items representing a deep approach from their studies, while low performing students report using the surface approach. For Bunce et al., these results could be used to view students who are unsuccessful as lacking better study approaches or indicate a mismatch between how instructors teach and how students approach learning.

Teichert et al. (2019) used the same approach (deep vs surface) to investigate the problem-solving behavior employed by middle achieving students in a General Chemistry course compared to the top and bottom students. To help answer their research questions, Teichert et al. used a population sample of 72 students in their first year in a General Chemistry class at the US Naval Academy, where they conducted think-aloud interviews as students solved the problems, a

total of 4 multiple questions out of 25 selected from their exam. The researchers divided the items into two categories, two algorithmic and two conceptual problems with a difficulty level between 65% and 87 %. The investigators focused on the problem-solving process and students' explanations during think-aloud interviews and not on whether they correctly answered the questions.

From their findings, the bottom students exhibited surface problem-solving behaviors (overreliance on algorithms, lack of conceptual understanding, and many procedure errors) while the top and middle students had surface and deep behaviors on the conceptual questions. The higher achieving students manifested deep problem-solving behaviors (correct use of the concept, practical problem-solving skills and effective test-taking strategies, and appropriate scientific language). The bottom-level students had challenges explaining their rationale in solving the problems as they mainly relied on recall. The top and middle-level students were able to explain the concept and apply expert-like terminologies.

While solving the problems using an algorithm, the top and the middle group had fewer errors, checked their answers, and used deep test-taking strategies compared to the bottom students. As a result, Teichert et al. proposed that to help students become more successful and use a deep approach while solving problems, instructors should analyze what students do correctly in terms of algorithmic and conceptual understanding before applying any intervention. For large classes, instructors can use free-response questions or clickers and listen to students' use of chemical language while solving the problems.

Lastly, Teichert et al. recommended that instructors' focus should be on why solving problems is necessary rather than how or what students' solutions are. The focus on students' ways of thinking would help them adapt to the instructor's expectation of their learning.

Across multiple studies as observed above, successful problem solvers integrate cognitive, metacognitive, and conceptual strategies, enabling more effective and adaptable learning. Moreover, successful students exhibited strong foundational knowledge, strategic problem solving (application) and connection of prior knowledge to the new problems (integration) unlike the unsuccessful students. While intrinsic motivation was discussed in one of the studies, there was limited focus on how students developed empathy and identity which are key components of the human dimension. Although successful students care more about conceptual understanding (deep approach) there was little emphasis on developing interest or valuing the discipline (caring).

Expert/Novice Dichotomy

In the literature, an expert is defined as someone who has acquired knowledge in a domain through experience and has a highly structured, consistent, and organized knowledge base (Ardac, 2002; Galloway et al., 2017; Stains & Talanquer, 2008). Also, they have extensive knowledge (network of information) that affects how they notice and interpret information in their environment (Gulacar et al., 2019); and an extreme amount of practice on a circumscribed set of tasks in their work environment (Feltovich, Prietula, & Ericsson, 2006). This information network consists of collections of isolated facts created from previously learned knowledge and stored as schemas.

The storage of information as schemas allows the expert to retrieve it with little attentional effort and includes its context where applicable (Persky & Robinson, 2017). To support this claim, Kozma and Russell (1997) mentioned that “the knowledge of experts consists of a large number of interconnected elements that are stored and recalled as extended, coherent chunks of information organized under underlying principles” (p. 950). However, the ease of

information retrieval does not mean that experts are faster problem solvers, but that they can recognize patterns and features that might lead them to make connections with familiar information (Heyworth, 1989; Kozma & Russell, 1997).

Conversely, a novice is someone who has minimal exposure to a domain (Galloway et al., 2018); and possesses a fragmented and incoherent knowledge base with several inconsistencies (Ardac, 2002; Persky & Robinson, 2017; Galloway et al., 2018). Literature has also stated that novices use nonformal concept interpretation modes to trigger existing standards from long-term memory (Ardac, 2002). These terms expert and novice have been used inconsistently in the literature; for example, in some studies, students have been categorized as experts based on their success on a given topic.

Adams et al. (2008) modified the Colorado Learning Attitude about Science Survey originally designed for Physics to identify the characteristics of novices and experts in Chemistry. These characteristics were classified based on beliefs on three fundamental aspects Chemistry, as table 2.2 illustrates. Understanding these beliefs among the novices and how instructions affect them would improve teaching and learning in Chemistry.

Table 2.2: Contrasting Novice and Expert Beliefs Fundamental Aspects of Chemistry.

Novice beliefs characteristics		Fundamental aspects of Chemistry		Expert beliefs characteristics
Isolated pieces of information	⟸	Chemistry content and structure	⟹	A coherent framework of concepts
Handed down by authority, no connection to the real world	⟸	Source of Chemistry knowledge	⟹	Describe nature, established by experiment
Pattern matching to memorized arcane recipes.	⟸	Problem-solving in Chemistry	⟹	Systematic, concept-based strategies; widely applicable.

Many approaches have been implemented to classify experts and novices based on the following criteria: results of concept tests (Lopez, Kim, Nandagopal, Cardin, Shavelson, & Penn, 2011; Hrin, Milenković, & Segedinac, 2016), analysis of think-aloud interviews (Camacho, & Good, 1989; Pate, & Miller, 2011; Madden, Jones, & Rahm, 2011; Stieff, 2011; Shanahan, Shanahan, & Misischia, 2011; Overton, Potter, & Leng, 2013; Lopez, Shavelson, Nandagopal, Szu, & Penn, 2014; Randles & Overton, 2015; Caspari, Kranz, & Graulich, 2018; Webber & Flynn, 2018); beliefs on fundamental aspects in Chemistry (Adams, Wieman, Perkins, & Barbera 2008); responses to clicker questions (Flynn, 2011), and results from card sorting games (Krieter, Julius, Tanner, Bush, & Scott, 2016; Galloway et al. 2018). Table 2.3 illustrates some of the criteria used to classify individuals as experts or novices from literature.

Table 2.3. Criteria of Classifying Faculty and Students as Experts and Novices.

Criteria (s)	Experts	Novices
Experiences Simon and Simon (1978); Chi, Feltovich, and Glacier (1981); Snyder (2000); Kozma and Rusell (1997).	University professors who have been teaching and conducting Physics research for at least 10 yrs.	Students who had completed one semester of classical mechanics at the introductory level.
Background knowledge Simon and Simon (1978); de Jong and Ferguson-Hessler (1986); Heyworth (1999); Snyder (2000); Kohl and Finkelstein (2008).	Students who hold at least a bachelor's degree Professional chemist, graduate students, faculty	Eleventh-grade students Undergraduate students
Performances Heyworth (1999); de Jong and Ferguson-Hessler (1986); Hardiman, Dufresne, and Mestre, (1989); Stavy, (1991); Kohl and Finkelstein (2008); Priest and Lindsay (1992); Nehm and Ridgway (2011).	Students who had a good conceptual understanding and made no procedural errors. Higher percentage of correct and fastest solution times. High test scores and consistent use of key concepts	Students who had a poor conceptual understanding and made many errors. Low percentage of correct and slowest solution times Low test scores, inconsistent use of key concepts

One of the significant differences between novices and experts is how they approach the problem. Experts and novices have been categorized based on the methods they use in solving problems, such as the deep and surface approach (Krieter et al. 2016). Other methods include comparing the achievement of students among different groups (bottom, middle, and top levels); (Teichert et al., 2019) or their study approaches (Bunce, Komperda, Schroeder, Dillner, Lin, Teichert, & Hartman, 2017). In her research on developing problem-solving skills through

retrosynthesis using clickers, Flynn (2011) described some of the characteristics experts and novices demonstrate while solving problems, as the following table illustrates.

Table 2.4 Novice and Expert Problem-Solving Characteristics.

Novice Problem Solvers	Expert Problem Solvers
Disengage	Engage
This is too hard	Curious
Jump to answers	Explore and plan
Pick out an equation	Brainstorm
See information as a distinct set of facts	Group information by principles of patterns
Move to the end	Review at the end
	Evaluate and assess learning.

Experts in Organic synthesis use the knowledge of structure, functional groups reactivity, and reaction mechanism to organize and produce a synthesis. While writing essays and designing Organic synthesis, experts engage their peers in the process through a form that Bhattacharyya, Calimsiz, and Bodner (2003) referred to as “shop talk” (p.321). Like professional writers who endeavor to connect with their readers, experts (synthetic Chemists) do the same by proposing synthesis problems to make them feasible in the laboratory and produce a product that is acceptable to the consumers.

While designing synthesis problems, experts plan on paper accounting for flexibility just in case they want to make any changes. They also focus on convergent synthesis by breaking the target molecule into smaller fragments, reducing the problem’s complexity. Experts utilize the process of retrosynthesis because it simplifies the problem and provides an exact starting point for attacking the problem (Bhattacharyya et al., 2003).

Experts form mental representations of the problem, which they use to infer relationships and define the situation and its constraints (Persky & Robinson, 2017). These mental representations provide latitude for experts to understand the problem and identify a clear solution. Ultimately, experts want to understand the nuances and the constraints of the problem instead of just plugging in the number to get an answer. These representations help them to explain the reasons behind using any given technique. They also have a high metacognitive awareness that enables them to differentiate what they know and what they do not understand (Persky & Robinson, 2017).

Ali, Ibrahim, Abdullah, Surif, and Saim (2014) defined metacognition as both metacognitive knowledge (knowledge about variables or persons, tasks, strategies) and metacognitive experience (skills such as planning, monitoring, and evaluating activities). This metacognitive ability allows the experts to monitor their thinking, ask various questions for concepts that appear difficult, and self-test to correct any misconceptions.

Despite experts having a high metacognitive ability, Persky and Robinson (2017) argued that they are at risk of metacognitive biases for things they once "knew" (p.78). Since knowledge degrades over time, it is easier to miscalculate the decline rate and only notice domain-specific knowledge gaps. To reduce this metacognitive error, Persky and Robinson (2017) claimed that experts should always learn and practice in their domain to avoid ending up in the arrested development stage. If experts lack pedagogical knowledge, they may depend on textbooks on how to teach students, but the textbook authors may not be familiar with the students and their prior knowledge, classroom environment, and other factors that may impact their learning (Persky & Robinson, 2017).

Nevertheless, if experts want to improve their pedagogical skills, they will have to dedicate time and energy to learning, practicing, and implementing effective classroom practices.

According to Gulacar et al. (2019), experts use the breakdown method to chunk the problems into sub-problems, making it easier to identify the underlying concepts that compose the problem. Experts are also impacted by their affective domain (values, attitudes, motivation), influencing how they solve the problems. To determine the extent to which different expert groups differ in their success with sub-problems and their characteristics while dealing with stoichiometric problems, Gulacar et al. (2019) conducted research using three diverse expert groups. The participants were 17 graduate students (2-5 years of experience in graduate school), three Chemistry instructors with a Ph.D. degree in Chemistry, and six graduate students in Chemistry with 5-20 years' experience working in the industry. Also, the industrial chemists had an educational background ranging from undergraduate to graduate degrees in Chemistry.

The investigators gave the participants five closed-ended textbook-style problems of varying levels of difficulty. Each question required different background knowledge to solve it. The investigators allotted the experts' 30-35 minutes for all five questions with the assumption that they would not need much time to solve those problems through thinking aloud interviews. From their analysis, Gulacar et al. (2019) found that there was no significant difference between the expert cohorts in attempt success rate (participants' ability and knowledge to deal with sub-problems) and completion success rate (interconnections of sub-problems). However, graduate students had a higher success rate, followed by professors and industry participants. The investigators argued that the higher success rate for graduate students was based on instructors' expectations for them to provide detailed information to students as teaching assistants on problems similar to those used in the study.

Additionally, the investigators attributed the industrial participants' low scores to less demand in solving these types of problems for their careers.

The experts exhibited similar characteristics while solving problems during their think-aloud interviews. There was the use of extensive knowledge in forms of familiarity and chunking. Gulacar et al. observed the participants' perseverance in that whenever they encountered a roadblock, they continued to attempt to solve the problem. Despite graduate students having a higher score on completion rate, there was no significant difference between the expert groups' means on either the attempted or completed solve rate.

Imagistic reasoning has been indicated as the primary problem-solving strategy in Organic Chemistry due to the domain's content (Stieff & Raje, 2010; Stieff, 2011). Experts use imagistic reasoning while solving problems that require interactions between complex three-dimensional objects since these problems cannot be perceived directly (Stieff & Raje, 2010). However, it is not clear to what extent the experts rely on the generation of mental images during problem-solving.

Stief and Raje (2010) researched experts with 5 to 30 years of teaching experience in Chemistry. Each participant was given ten tasks at the beginning of the interview, which they had to complete while thinking aloud. Four out of ten tasks required the participants to generate a new representation of a given structure; for the next three tasks, they had to predict the product of a reaction, while for the last three, they had to explain how to synthesize certain molecules. The analysis produced unexpected results as the participants relied heavily on algorithmic strategies to generate novel structure but less on imagistic reasoning when evaluating the molecule's structure. Further analysis of each task revealed that experts applied algorithmic diagrammatic strategies rather than spatial imagistic strategies.

Although the use of spatial thinking in Organic Chemistry remains unclear (Stieff, Ryu, Dixon, & Hegarty, 2012), research has demonstrated the use of spatial ability among experts in other fields as a strategy in problem-solving; for example, the use of mental images to determine the relationship between similar molecules (Steif, 2007), the use of spatial perspectives to inspect imagined anatomical structures in medicine (Keehner, Montello, Tendick, & Hegarty, 2006), and animations of dynamic spatial transformations of weather maps to predict the storm trajectory (Trafton, Trickett, & Mintz, 2005).

To understand how students and Organic Chemists learn Organic Chemistry, Bhattacharyya et al. (2003) proposed an analogy to compare the process of solving Organic synthesis problems and writing essays. They based these comparisons on previous studies on graduate students enrolled in a graduate course in Organic synthesis and undergraduate students finishing a year-long Organic Chemistry course.

According to Bhattacharyya et al. (2003), the writing of essays and the designing of synthesis are goal-oriented recursive activities that produce a more significant product than individual elements. These activities can be challenging for novices as they must put together the elements to produce the product. Novices are challenged in writing essays since they focus on individual sentences and have difficulties putting them together into a coherent essay. Like in writing essays, they tend to focus on individual reactions but have a challenge in putting them together to form a rational synthesis. In a social context, novices barely discuss writing essays with their peers, and whenever the conversation occurs, it has nothing to do with the content.

Bhattacharyya et al. (2003) found that novices (students) consider writing essays and designing synthesis as a personal activity while viewing them as classroom-based exercises. They propose synthetic paths without thinking whether the route they have suggested would be

possible in the lab. In his study, Bowen (1990) found a similar pattern whereby novices hardly applied any practical considerations nor paid close attention to laboratory representations while planning synthesis. Novices are less elaborate in their planning and mostly use retrosynthesis haphazardly because their instructors tell them that is what Organic Chemists use. So, they use retrosynthesis when they run out of other options without understanding how retrosynthesis simplifies the problem. As Bhattacharyya et al. (2003) put it, "it is unreasonable to expect students to be vested highly in a technique they do not really trust" (p.324).

Making connections with previously learned information challenges novices as they see knowledge as context dependent. They encounter challenges in deconstructing and applying that knowledge in different contextual boundaries. When learning new material, there is a significant burden placed on working memory. However, they can reduce this burden through several repetitive retrieval practices leading to long-term memory storage. Moreover, instructors can help the novice achieve this by using effective instructional techniques, but the "effectiveness of these techniques depends on the learner's expertise" (Persky & Robinson, 2017).

Research has shown that novices are not only more successful in solving algorithmic problems, but they are more than likely to rely on algorithmic procedures to solve conceptual problems. Several studies have found that despite most students having success in solving numerical problems, in stoichiometry and gas laws, they have difficulties answering conceptual problems from the same topic (Nurrenbern, & Pickering, 1987; Sawrey, 1990; Nakhleh, 1993; Nakhleh & Mitchell, 1993; Phelps, 1996). According to Phelps (1996), the gap between algorithmic problem solving and conceptual understanding persists because instructors allow students to mask their conceptual understanding by accepting numerical answers, which is not a clear indication of a true understanding.

Novices' interpretations of scientific concepts are poor since their conceptual knowledge is incoherent and consists of various unconnected knowledge fragments (Reif, 1987; Kozma & Russell, 1997; Persky & Robinson, 2017). These knowledge fragments can be retrieved quickly with little processing, resulting in wrong or inconsistent answers. When instructors confront the novices with problems, they build mental representations using surface features since their internal representation is composed of recognizable visible objects referenced to the problem (Heyworth, 1989; Kozma & Russell, 1997). Thus, novices may tend to solve the familiar part of a challenging problem that connects with their internal representations.

The low level of metacognitive awareness among novices leads them to ask questions on superficial aspects of the problem and ignore ideas that are difficult to understand (Persky & Robinson, 2017). They may also be less likely to monitor their learning and fail to assess whether they have understood or mastered the information. Additionally, novices may not self-test or question themselves as feedback sources to correct any misconception or change any learning strategies (Persky & Robinson, 2017).

Heyworth (1989), in his study investigating problem-solving strategy in volumetric analysis, found that novices relied primarily on means-end analysis to connect to the problem using the information given. When they were unsuccessful with that method, they could switch to a working forward approach, which Heyworth referred to as a "groping forwards strategy" (p.66). In this strategy, the novices used formulas with which they were not familiar, hoping to navigate the steps until they reached the goal. If the second method fails, they terminate solving the problem.

Stains and Talanquer (2008) investigated how students at different levels of expertise could classify chemical reactions at both symbolic and microscopic levels. The participants in this study involved students ranging from first-year General Chemistry students to fifth-year students in a Ph.D. program at a research one institution in the Southwestern region of the United States. The instructors had already taught the topic of chemical reactions to the participants.

The researchers gave the students nine reactions in which they expected the students to classify three questions of the nine at the symbolic level and six questions at the microscopic level. Data collection involved semi-structured and think-aloud interviews on both microscopic and symbolic tasks. Using ground theory for analysis, Stains and Talanquer (2008) found that students at all levels used both explicit (representation of chemical reaction) and implicit (underlying characteristics of substances involved) features.

Further analysis showed variability in the types and the numbers of chemical reactions the participants created based on the preparation level. The investigators classified these responses into two groups: discipline-based and non-discipline-based groups. Results indicated a significant difference in the grouping of reactions between undergraduate and graduate students. Based on their grouping and accuracy in classifying chemical reactions, Stains and Talanquer separated the students into different expertise levels, i.e., novice, intermediate, and advanced.

From their findings, most students at the undergraduate level functioned at the novice level while graduate students functioned at the intermediate level. Novice students used specific features to classify the reactions and lower their cognitive demand. They also used implicit features to make sense of chemical processes and build reaction categories. Graduate students used more implicit features to develop groups and specific rules to classify the task methodically.

Overall, all the participants used explicit features for sense-making while classifying reactions at the microscopic level rather than the symbolic level.

However, some novices and intermediate students were more inclined to rely on recall and memorization to classify the reactions at the symbolic level (Stains and Talanquer, 2008). In other studies, researchers used the ability to solve problems to classify novices as either successful (high-performing) or unsuccessful problem solvers (low-performing) based on correct synthetic proposals (Bode & Flynn, 2016), knowledge gaps and misconceptions, (Camacho, 1989) and oral verbalization (Pate & Miller, 2011) during problem-solving using think-aloud interviews.

Proposed Methods for Learning Organic Synthesis

While dealing with synthesis problems, students require high order thinking skills and vast knowledge of reactions. As they propose synthetic pathways using elements such as carbon, hydrogen, oxygen, sulfur, halogens, or ready-made starting materials, they must be able to visualize how these reactions lead to the desired product (Nicolaou & Sorensen, 1996; Raker & Towns, 2011; Flynn, 2011). Students solve the problems by combining small molecules using reactions they have learned throughout the course in Organic Chemistry to produce complex molecules. In the process, the students must ensure that their problem-solving strategies account for regiochemistry, stereochemistry, and chemoselectivity (Flynn, 2014). Research has proposed different methods to enable students to conceptually understand synthesis. These methods are highlighted in table 2.5.

Table 2.5: Synthesis approach methods for understanding synthesis

Synthesis Approach Methods.	Authors
Representation systems	Bowen,1990; Bowen & Bodner, 1991.
Retrosynthesis and forward synthesis	Blackburn, 2018.
Scaffold approach	Wood, Bruner, & Ross, 1976; Sloop, Tsoi, & Coppock, 2016.
Roadmap problems.	Schaller, Graham, & Jones, 2014.
Functional group transformational notebook	Teixeira & Holman, 2008.
Computer-assisted program	Stolow & Joncas, 1980.
Videos	Al-Jarf, 2012; He, Swenson, & Lents, 2012; Richards-Babb, Curtis, Smith, & Xu, 2014; Pennington, 2016; Box, Dunnagan, Hirsh, Cherry, Christianson, Gibson, Wolfe, & Gallardo-Williams, 2017; Gillette, Winterrowd, & Gallardo-Williams, 2017; Tierney, Bodek, Fredricks, Dudkin, & Kistler, 2014; Ranga, 2017; Ardisara, & Fung, 2018.
Flipped classrooms	Fautch, 2015; Cormier, & Voisard 2018.
Active and cooperative learning	Dougherty, 1997; Paulson,1999.
Card games	Gogal, Heuett, & Jaber, 2017; Farmer, & Schuman, 2016.

Active learning in large lectures	Paulson, 1999; Bradley et al. 2002; Carpenter & McMillan, 2003
Designing of synthetic compounds	Cannon, & Krow, 1998
Use of case studies	Fleming, 1973; Nicolaou & Sorensen, 1996
Total synthesis	French, 1992
Learning cycles	Libby, 1995

As indicated in table 2.5, videos are widely used as technological tools for teaching Organic synthesis problems. In their study, Rose, Pennington, Behmke, Kerven, Lutz, and Paredes (2019) investigated the use of videos at Georgia Gwinnett College with Organic Chemistry II students solving synthesis problems to demonstrate their thinking process. The Organic Chemistry faculty developed a series of five synthesis problem sets, with each set consisting of at least three to four problems.

The faculty then developed videos of the synthesis problems explaining more than one approach to the problem and the purpose of using each method. The completed videos were posted to a private YouTube channel for the students to watch and complete the Organic problem assignments. For the second part of the semester, the instructor assessed students' synthesis skills using quizzes and a synthesis exam for both midterm and final exams. The final exam consisted of seven problems that required four or more molecular transformation reactions. These problems were designed to utilize the reactions in the Organic Chemistry sequence. The instructor gave the students printed resources for use during the exam but denied them any electronic media access. Since students had access to some information during the exam, the investigators did not assess the memory or recall of reagents in this case.

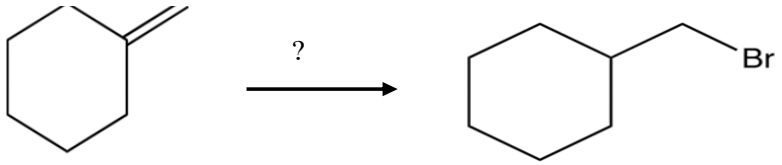
To assess the effectiveness of the videos, the researchers analyzed and compared the synthesis exam scores from 14 sections of Organic Chemistry courses taught between the spring of 2014 and the summer of 2017. Five sections consisted of a pre-synthesis video group who completed the course before the synthesis videos' availability. The second group of nine sections had access to synthesis videos which were designed to show the thought process of synthesis problems as seen in the quiz. The synthesis exam results were analyzed using the Wilcoxon rank test to determine the differences between the two populations. From their findings, the exam scores demonstrated a significant difference between the students who had learned synthesis using the videos and those who did not.

According to Rose et al. (2019), the use of videos outside the classroom with faculty guidance changed the students' learning environment. Students became less apprehensive in providing wrong answers once they understood there could be multiple pathways that would lead to a correct synthesis. This realization increased students engagement with the material and made them more willing to tackle synthesis problems (Rose et al., 2019).

The scaffold learning approach developed by Wood, Bruner, and Ross (1976) involved students mastering skills as the instructor provides feedback that rectifies their mistakes. The instructor frames the reactions as a fundamental synthesis problem while emphasizing the systematic approach that incorporates both structure and reagent to give the students a visual framework that they can use to build their synthetic route from the starting materials to the product. In their investigation, Sloop et al. (2016) discussed the synthesis scaffold approach as a bridging method that helped students build on whatever they already knew and arrive at something they did not know. The following worksheet demonstrates the synthesis scaffold approach that Sloop et al. (2016, p.6-7) upgraded from Sloop's (2010) design. (Figure 2.1)

Synthesis Problem-Solving Scaffold Development.

Given: A starting material from which to produce a target molecule (product).



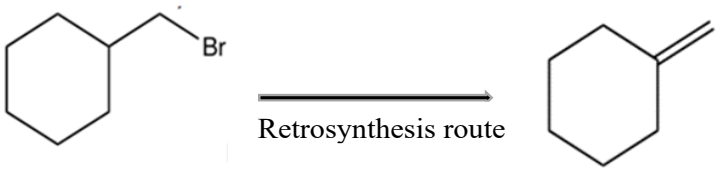
Find: Synthetic route to the desired product.

Plan: 1. Compare the product to reactant and list transformations.

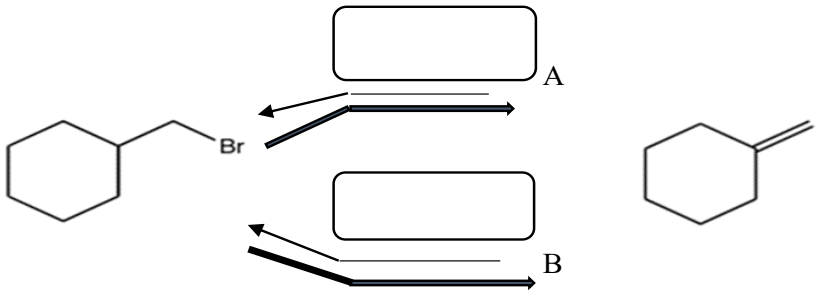
- H-Br installed in an anti-Markovnikov fashion on the C=CH_2 alkene unit

2. Determine if the overall number of transformations requires more than a single reaction step.

Solve: 1. Use a retrosynthetic strategy to "unbuild" the molecule back to the starting material.



2. Propose structure(s) for any viable intermediate product(s).

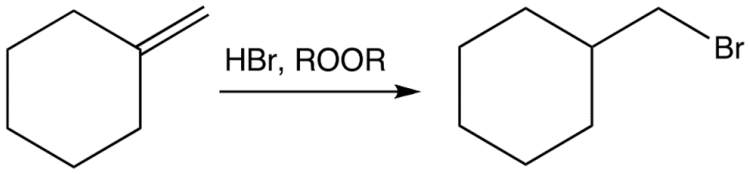


3.Identify and list reagent(s) to be used in the synthetic path that will give the transformations required to prepare the desired product.

a) HBr-adds to the double bond (Markovnikov addition)-NO

b) HBr, ROOR-adds to the double bond (anti-Markovnikov addition)-YES

4. If more than one reagent is chosen for a given transformation, select the best reagent based on the required function.



5. Write the complete synthetic plan.

Check: Ensure that the selected reagents affect the required transformations; intermediate products are correctly drawn, and the overall synthetic plan leads to the product.

The following is the completed diagram (Two possible reagent sets)

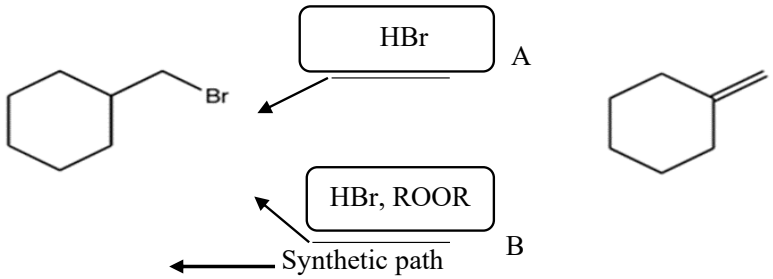


Figure 2.1. Sloop Worksheet

When using a road map strategy, the instructor leads the students through the synthesis one step at a time with blanks of reagents or intermediates left at strategic points for the students to fill in using previous knowledge of reactions (Schaller, Graham, & Jones 2014). According to Schaller et al. (2014), instructors have used road map problems from primary literature for the last 15 years, with periodic changes occurring once the problem is proven to be frustrating for

the students. While doing these problems, the instructors do not expect students to have the right answer but have a reasonable explanation based on what they have learned in class. Road maps provide spatial strategies, a critical skill in learning Organic Chemistry (Schaller et al. 2014).

To utilize fundamental Organic reactions to plan synthesis, the instructors expect the students to recall numerous functional groups from memory (Farmer & Schuman, 2016; O'Halloran, 2017). Teixeira and Holman (2008) gave students in an Organic class an out of a class assignment that enabled them to overcome some of the synthesis challenges. Holman asked the students to keep a functional group transformational notebook (FGT). In this notebook, students wrote the functional groups as the instructor in the class addressed them. According to Teixeira & Holman, the FGT notebook is an excellent resource for the students while doing synthesis activities both in class and at home. Furthermore, using the FGT helps the students think about Organic reactions in both forward and backward synthesis and review mechanisms as they re-copied the notes from the lecture to their notebooks.

The ability to submit responses numerically has led to the development of mechanism-based clicker questions in which students can design a synthesis by selecting any desired starting material or a reagent (Flynn, 2011). This method allowed the instructor to collect and analyze multiple student answers and provide relevant and regular feedback. The investigator did not expect the students to design a full retrosynthesis, but they had to deconstruct a part of the molecules with which they were familiar. The following figure illustrates the first part of the approach involved in recognizing the patterns in targets that suggest a chemical reaction (Flynn, 2011, p. 1497). (Figure 2.2)

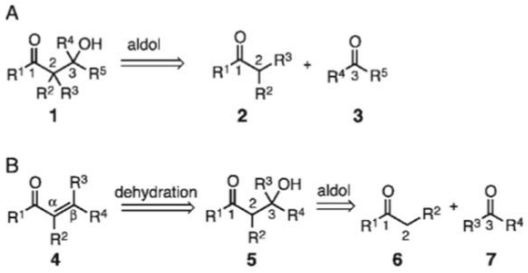


Figure 2.2. Retrosynthetic disconnections for the (A) Aldol and (B) Aldol condensation reaction.

While teaching the Aldol reaction, the instructor highlighted both the 1,3 relationship and the α, β unsaturated carbonyl so that the students could understand and recognize the patterns. Once students conceptually followed the process, they were presented with a more complex molecule, as the following figure depicts. (Figure 2.3)

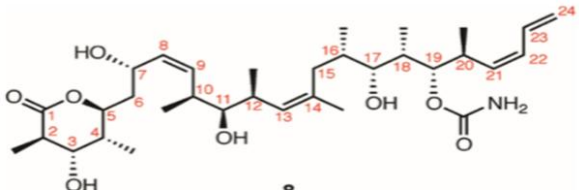


Figure 2.3. Discodermolide molecule

With the complex molecule, the students had to identify any possible sites for an aldol reaction and enter their answer on clickers using a specific format (Flynn, 2011). For example, if they recognized an aldol at carbons 11, 12, 13, they would enter it as 111213. The students' answers were displayed on a histogram, providing an opportunity for the instructor to view the different qualitative understanding of the responses and their errors. Additionally, the approach provided students with an opportunity to think critically and reveal some of the errors and misconceptions they held. According to Flynn, instructors can use mechanism-based clicker questions in small and large classes with hundreds of students. Other methods such as computer programs, ChemDraw, SciFinder Scholar and Web of Science have been used to enhance students learning (Vosburg, 2008, p. 1520).

In addition to the various approaches outlined in table 2.5 above, researchers have proposed problem-solving strategies for synthesis that students can use to achieve success. According to Bowen, instructors should structure an Organic synthesis course around a representation system based on a learning cycle approach (Bowen, (1990, p.365). This was echoed by Bowen and Bodner (1991) who stated that instructors should help students learn the representation system.

Table 2.6: Proposed strategies around representation systems

Proposed Problem-Solving Strategies	Authors
Recognize the functional groups in the target molecule. Disconnect by methods corresponding to known and reliable reactions. Repeat as necessary to reach available starting material	Warren (1982)
Illustrate the applicability of the system. Have students bring in their experiences with the system. Explain the structures and processes used in the system. Discuss the specific strategies used in the system.	Bowen (1990)
Choose a useful representational system for a problem. Select useful tactics within the representational system for solving the problem. Abandon a representation system if it does not provide a solution. Evaluate a solution by using multiple representational systems.	Bowen & Bodner (1991).

In 1990, Bowen described the seven representational systems used in solving Organic synthesis problems: verbal, pictorial, methodological, principals oriented, literary, laboratory oriented, and economical. In his research investigating graduate students' use of representation systems, Bowen found that most students utilized three of the seven representation systems to solve the problems, i.e., verbal, pictorial, and methodological.

Bowen and Bodner's (1991) study of Organic Chemistry graduate students at Purdue University found that the participants had similar preparation tactics, such as examining functional groups before suggesting the reactions to be used to form the target molecule. While evaluating the process, some students highlighted their challenges in forming the molecule based on the functional group's interaction and stereochemistry. From previous studies conducted by Bowen, students considered the methodological approach to be the most useful in solving organic synthesis. "They believe that their job is to find an appropriate process (e.g., reactions) and apply it in the proper order" (Bowen, 1990, p. 359). Students rejected the selected target compounds and opted for others with the assumption that stereochemistry would complicate the process.

The aforementioned strategies provide student engagement while solving Organic synthesis problems. They clearly address the cognitive and strategic dimensions of Fink's taxonomy. However, the aspects of human dimension (self-awareness) and caring (developing new interest and value) are not explicitly highlighted in the proposed strategies.

Organic Chemistry Textbooks

The change in the Organic Chemistry curriculum and increased pervasiveness of mechanistic language (*e.g*. bond-forming, use of arrows, functional groups) in the textbook has been documented in the literature as a solution to alleviate student difficulties in learning Organic Chemistry. However, students still struggle in solving synthesis problems. Most Organic Chemistry textbooks propose some suggestions for solving Organic synthesis such as knowing a lot of reactions or reading and understanding the synthesis chapter, but it is unclear whether they help students develop problem-solving skills (Clayden, Greeves, & Warren, 2012; Klein, 2012; Bruice, 2014).

Wheeler and Wheeler (1982) investigated the state of Organic chemistry textbooks for over 100 years and found that the textbooks had only two revolutions responsible for the advances in the teaching of Organic Chemistry. The first Organic Chemistry textbook revolution, which occurred between 1858-1874, involved the development of fundamental ideas of structure and stereochemistry.

The second revolution that occurred between 1940-1958 was based on theoretical and practical development, which led to gradual textbook changes. These practical developments involved using a spectrophotometer to examine Organic compounds and separation methods using chromatography. Furthermore, today's textbooks are written using a Physical Organic approach format of the 1960s, although it was not regarded as a new development (Wheeler & Wheeler 1982). Despite these efforts, many textbooks do not provide the students with user-friendly systematic methods that would enable them to be proficient in Organic synthesis. Goldish (1998) supported both Wheeler and Wheeler's and Johnston's ideas by arguing that

there had not been any substantial changes in the Organic Chemistry textbooks for more than 30 years apart from the addition of spectroscopy topics, new reactions, and mechanisms.

Symposium organizers at an ACS national meeting in San Diego, CA, 2016 brought together faculty members and Organic Chemistry textbook publishers to discuss the crisis in Organic Chemistry education (Halford, 2016). Although the publishers argued that Organic Chemistry students have more innovative materials than they have ever had, faculty members believed that the textbooks had not changed much over the last 50 years. Despite devoting significant attention to publishing synthesis as a single chapter in textbooks or incorporating the synthesis chapter throughout the textbook, finding the best way to teach the subject to time-strapped students is a challenge to faculty members (Hornback, 2006; Bruice, 2014).

According to the research conducted by Johnson (1990) from 33 institutions on how instructors taught Organic Chemistry, various trends emerged throughout the population: first, most faculty used the functional group organization for their course. Secondly, some faculty presented mechanism as a *fait accompli* without detailed substantiation or spending time on the ionic mechanism, carbocation, and carbanion based, which were more prevalent throughout the course. Lastly, most faculty members were unsure of when or how to incorporate certain topics in Organic Chemistry or real-world Chemistry in their lectures. Further analysis found that all the faculty members gave regular class examinations ranging from one to five tests throughout the semester.

For those faculty members who assigned problem sets for their classes directly from their textbook, most did not grade them; some used them as practice problems in class or instructed teaching assistants to review them during classroom discussion sessions (Johnson, 1990). When questioned about their thoughts on the course's future, most of the instructors had concerns about

the amount of time available for teaching the course, the lack of students' background preparation for Chemistry, and lack of leadership on the part of the writers and publishers of the textbooks. For example, looking at the excerpts in Table 2.7 from some Organic Chemistry textbooks about synthesis, authors are uniform in their advice on what students need to do to be successful in solving synthesis problems.

Table 2.7: Textbook Suggestion for Success in Solving Organic Synthesis Problems.

Textbook Title	**Organic Synthesis Chapter Excerpts**
Organic Chemistry, 7th ed.; Pearson: Upper Saddle River, NJ, 2014.	"The most important factor in designing a synthesis is to have a good command of organic reactions. The more reactions you know, the better your chances of coming up with a useful synthesis" (Bruice, 2014, p. 694).
Organic Chemistry, 2nd ed.; Oxford University Press: New York, NY, 2012.	"The aim of this chapter (retrosynthetic analysis) is to introduce you to the principles of retrosynthetic analysis: Once you have read and understood it, you will be well on the way to designing your own organic syntheses" (Clayden, Greeves, & Warren, 2012, p. 974).
Organic Chemistry, 2nd ed.; John Wiley & Sons: Hoboken, NJ, 2012.	"In this chapter, our modest repertoire of reactions will allow us to develop a methodical, step-by-step process for proposing syntheses. This chapter aims to develop the fundamental skills required for proposing a multistep synthesis" (Klein, 2012, p. 547).
Starkey, L. S. (2012). *Introduction to Strategies for Organic Synthesis* (1st edition). John Wiley & Sons.	*Introduction to Strategies for Organic Synthesis* is designed to fill this void, teaching practical skills for making logical retrosynthetic disconnections, while reviewing basic organic transformations, reactions, and reactivities. It also demonstrates each reaction from a synthetic chemist's point of view, to provide students with a clearer understanding of how retrosynthetic disconnections are made. (Starkey, 2012)

Bruice, P. Y. (2016). Organic chemistry (8th ed.). Pearson.	"The Eighth Edition builds a strong framework for thinking about organic chemistry by unifying principles of reactivity that students will apply throughout the course, discouraging memorization." (Bruice, 2016).
Reinhard, B. (2002). Advanced Organic Chemistry: Reaction Mechanisms. Academic Press.	"Well, the present text contains only about 70% of the knowledge that I would expect from a *really well-trained* undergraduate student; the remaining 30% presents material for graduate students. Whether one seeks to understand nature or to create the new materials and medicines of the future, a key starting point is thus understanding structure and mechanisms." (Reinhard, 2002).
Pine, S. H. (1987). Organic Chemistry (5th ed.). McGraw-Hill Companies.	"The text attempts to teach thinking as well as facts and theories. Like earlier editions, the textbook presents Organic chemistry by a mechanistic approach. The reaction mechanism logic relates to how a chemist thinks, how a science student should think and how chemicals actually react, and how they form compounds." (Pine, 1987).
Norman, R. O. C., & Coxon, J. M. (1993). Principles of organic synthesis (3rd ed.). CRC Press.	"The planning of synthesis is helped considerably by an understanding of the mechanisms by which the reaction occurs. This book is designed for those who have had no more than a brief introduction to organic chemistry and who require a broad understanding of the subject." (Norman & Coxon, 1993).

After randomly selecting various textbooks, I observed that the guidance on what students need to do while studying the textbook is largely consistent across the selections. They all advocate for an integrative skill-based approach to learning Organic synthesis such as use of mechanistic reasoning and retrosynthetic thinking. This approach represents high order thinking skills which aligns with cognitive domains (foundation knowledge, application, integration) in Fink's taxonomy of significant learning. However, it remains unclear whether students or instructors pay attention to this information or utilize the guidance provided to enhance their understanding of Organic synthesis.

SIGNIFICANT LEARNING

Unlike Bloom's taxonomy, which is known for articulating cognitive learning objectives, Fink's taxonomy offers a more holistic model of learning that extends beyond cognition alone. Fink incorporates six dimensions of learning that include not only foundational knowledge and application, but also integration, human dimension, caring, and learning how to learn (discussed later in the chapter). These elements are particularly relevant to the study of Organic synthesis, where success often depends on students' ability to connect prior knowledge across topics in Organic Chemistry I and II, develop a sense of personal relevance, and adopt metacognitive strategies for independent problem-solving while using high order thinking skills. This expanded view of learning helped in analyzing not only the strategies experts and novices use in solving Organic synthesis but also instructional methods and expectations between the two.

Fink defined learning as change. According to Fink, without change learning has not occurred. Therefore, significant learning requires that there be some kind of lasting change that is important in terms of the learner's life (Fink, 2013). Wilson and Lee (1989) argued that for significant learning to occur, the instructor/learner relationship must be one built on trust and

empathy and characterized by an attitude of freedom to learn (p.11). To promote significant learning, Parra (2019) conducted a study in a computational Chemistry course. The goal of the study was for the students to determine the research questions that could be effectively addressed using computational Quantum Chemistry as a tool while designing a project. Each class meeting was divided into two periods, with the first period devoted to knowledge acquisition and the second period to hands-on activities to master those skills.

Parra (2019) found that students who grasped the skills quickly helped their peers in class or after class. According to Para, this social aspect added the human dimension of learning which helped narrow the gap in performance among students with different learning abilities. The research project helped to promote students' ability to become independent self-directed learners. Students have achieved better than satisfactory level of competence (80% or better) for the nine times the course has been offered since 2002. By promoting significant learning, some students were able to apply what they learned in computational Chemistry to other academic aspects of their lives. Some of the students went further to finish the projects on a level acceptable for publication (Parra, 2019).

In a similar study, Evans, Heyl, and Liggit (2016) redesigned an undergraduate Biochemistry laboratory course to foster significant learning experiences that would prepare students for academic and professional scientific careers. Students engaged in hands-on research aligned with faculty projects, learned Biochemical techniques, collaborated in teams, and developed independent grant proposals. The results indicated increased student satisfaction, improved critical thinking, and deeper understanding of Biochemical principles. Based on evaluations, students rated the course effectiveness higher compared to similar laboratory

courses as they felt more prepared. Students also reported enhanced confidence, problem-solving abilities, and appreciation of real-world scientific processes (Evans, Heyl, & Liggit, 2016).

In their study, Billiot and Forbes (2021) applied Fink's (2013) taxonomy of significant learning in a retail marketing course to help rural, price-sensitive students develop empathy toward high-end urban customers, particularly those from higher socioeconomic backgrounds. The researchers sought to cultivate not only cognitive learning (foundation knowledge, application and integration) but also affective domains (learning how to learn, caring and human dimension). The study also showed that the integration of gaming and experiential activities, aligned with the six components of significant learning and led to a more meaningful and transformative learning experience (Billiot & Forbes, 2021). Students reported an increase in empathy awareness and expressed intentions to continue developing beyond the course.

The dimension of significant learning is comprised of six kinds of learning as mentioned previously. These kinds of learning are transactive with significant learning occurring at the center of the overlapping dimensions. A significant learning framework when used in course design helps to provide a high impact, dynamic and student-centered learning experience. Damrow (2021) while incorporating learning how to learn in his study mentioned that it is not enough just to mention effective study strategies and make suggestions. Instead, learning how to learn must be built into the course design and made available to the students. The following figure represents the significant learning framework. (Figure 2.4)

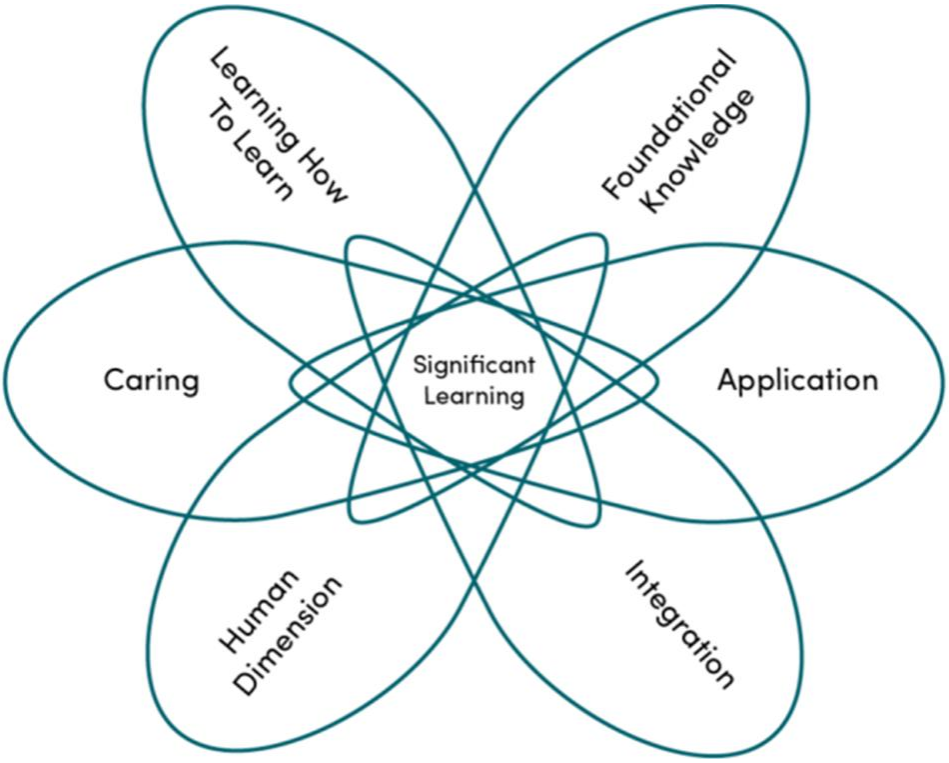


Figure 2.4. Significant Learning Framework (Fink, 2003)

The first three components (foundation knowledge, application and integration) comprise of the cognitive domain while the other three (learning how to learn, caring and human dimension) are the affective domains

Foundational knowledge

Foundational knowledge is the ability of students to understand and remember specific information and ideas. This provides a basic understanding of other kinds of learning. For example, if students can remember what they learned in Organic Chemistry 1 or the early chapters of Organic Chemistry 2, it may be easier for them to do synthesis. They are able to connect the new information with prior knowledge to enable them to solve the task. According to Fink (2013), it is the responsibility of educators to teach students not only factual knowledge but also help them understand the underlying conceptual structure of the subject.

Application

Application involves learning how to engage in various types of thinking (critical and practical). Critical thinking involves analyzing and evaluating something while practical thinking occurs when someone tries to apply knowledge to solve a problem. The application also involves developing certain skills such as communication and learning how to manage complex projects (research etc.). For this study, application will involve the participants' ability to apply the knowledge and skills they have gained through solving the synthesis task while thinking aloud.

Integration

When learners can make connections across disciplines or with the outside world it means that they understand the concept. According to Fink (2013), making new connections gives learners a new form of power (intellectual power). The main purpose is to help the learner connect and integrate different kinds of information, perspectives, and methods of inquiry to gain a more holistic understanding of the problem. Integration of ideas in this research involved the ability of learners to make connections with materials learned in class or personal studies. It also involved learners making connections on how the molecules they are using in these tasks are used in real-life applications such as in drug synthesis.

Human dimension

When students learn about themselves, or others, they can function and interact with others effectively (Fink 2013). What students learn or the way they learn gives them self-image and a self-ideal. It also gives them confidence that they can do something. For this study, the human dimension focused on students' individual challenges in solving Organic synthesis tasks.

Caring

When students care about something, there is a higher possibility that they will put forth energy and effort to make it part of their lives. At the same time, their learning experiences can change the way they care about a specific discipline. Caring is also related to the future goals and future interests the learners have in their careers. New feelings about synthesis are connected to the confidence the students have in tackling the task and how they feel about the course and the instructor. For example, do the students feel that the course or the instructor meets their expectations? Caring will also focus on whether the faculty experts care about their student learning and the expectations they have.

Learning how to learn

Learning how to learn can be related to learning about the learning process but most importantly learning how to be a better student. Helping students to become self-directed learners involves diagnosing one's own needs and then developing a learning plan that will help them be successful. A part of this would entail helping students learn how to answer questions and incorporate the new knowledge into their existing knowledge. For this research, this component will be used to focus on methods used by the students in their personal study time such as the use of note cards, online resources, and practice of synthesis problems.

CONCLUSION

Students taking Organic Chemistry are confused by the different representations which are unlike what they were accustomed to in General Chemistry. Thus, students struggle as they try to make sense of the material. Based on the accounts reviewed in this section, instructors expect the students to apply prior knowledge in solving synthesis problems. However, students remain challenged by the course despite literature suggesting numerous strategies that they can use to solve synthesis problems. Whether these challenges are motivational, instructional, or attitude-based, Organic synthesis remains a barrier for most students.

Additionally, some of the methods used for instruction, such as retrosynthesis, seem to be more suited for experts than novice students. While literature reveals a clear explanation of the differences between expert and novice approaches, there are still no generalizable methods that instructors can use to close this gap. Second, most research has focused on how novices (successful or unsuccessful) solve synthesis problems without a focus on the expert (faculty) perspective. Thirdly, there has been partial usage of the components of significant learning with emphasis on cognitive aspects (foundation knowledge, application, and integration) with little or no emphasis on other domains (learning how to learn, caring, human dimension). This study took a holistic approach focusing on all six components of significant learning.

Guided by this broad framework, the next chapter focuses on the cognitive aspects of significant learning examining how both experts and novices approach Organic synthesis problems. Rather than following the conventional approach highlighted in literature of classifying students as experts, this study draws a clear distinction between the two as discussed in next chapter. This distinction provides a better analysis of how problem solving strategies vary with experience, how foundational knowledge is organized and applied differently. The study features the challenges in Organic synthesis and the role of working memory in problem solving.

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CHAPTER III

A Significant Learning Perspective on How Novices and Experts Approach Organic Synthesis Problems.

ABSTRACT

Organic synthesis problems present a significant challenge to most Chemistry students when first introduced in the Organic course. Students must assimilate the information they learn, build schemas, and recall that information in a novel context. Organic Chemists have proposed various methods for solving Organic synthesis problems: retrosynthesis, disconnection approach, and chiron approach. While these methods highlight the fundamental principles and the foundation for understanding Organic synthesis, it is not clear how they prepare students to solve synthesis problems. This research explored the differences between experts and novices on how they approach solving Organic synthesis problems and how those differences affect student's success while focusing on the following research questions: (1) What strategies do novices and experts use while solving synthesis problems? (2) How do novices and experts differ in how they organize, and prioritize foundational knowledge during Organic synthesis problem-solving? and (3) To what extent do novices and experts connect Organic synthesis with prior learning during synthesis problem solving? Data was collected from undergraduate students (novices) and faculty (experts) in Organic Chemistry II. The data was analyzed using the Fink significant learning framework and an open coding system developed by Flynn (2014) modified for this study. Based on the results, the experts demonstrated use of strategies such as chemoselectivity, regiochemistry and well organized knowledge network.. Some of the novices' work aligned with that of the experts, although many struggled to determine the suitable reagents, formulate strategies required to solve the tasks, and connect prior knowledge to the new information.

INTRODUCTION

Organic synthesis is often described as a crossroads of multiple subdisciplines, integrating different aspects of Physical Chemistry, Analytical Chemistry, Inorganic Chemistry, and Biochemistry depending on the objective, viewpoint, and project focus. It involves the means, such as development of new strategies, conceptual approaches, and methodologies; the end, which includes the access to biologically important compounds and processes; and the beginning, which is marked by discovery of a new breed of man-made molecules and catalysts (Hanessian, Franco, & Larouche 1990, p.1887). Since the discovery of Organic synthesis in the early eighteenth century, scientists have used it to synthesize biological and medically essential molecules. Organic synthesis helps Organic Chemists to (a) discover and develop new reactions, (b) investigate and develop scarce biological and natural products, and (c) develop pharmaceutical drug candidates as clinical agents for use against diseases. (Nicolaou, 2014, p.6).

From the 1950s to the 1970s, instructors taught Organic synthesis as an illustrative representation of actual syntheses approaching each problem in an *ad hoc* way (Corey & Cheng, 1989, p. 4). More recent synthesis activities designed for instruction included scaffolding to develop students' conceptual understanding of synthetic skills based on the author's experience, expertise in synthesis education, and research in problem-solving (Flynn, 2011, 2014). These scaffolding strategies and the incorporation of higher order thinking skills demonstrated the ability to enable students to solve Organic synthesis problems effectively.

Students have described Organic synthesis as one of the most challenging topics to learn in Organic Chemistry (Bhattacharyya & Bodner, 2005; Ferguson & Bodner, 2008; O'Dwyer & Child 2017). Organic synthesis requires students to apply a process-oriented view of how

reactions occur, and to maintain an array of chemical principles in their minds to apply to various steps.

Students must gather all the information they need such as regiochemistry, functional group selectivity, reagents, mechanisms, and stereochemistry to analyze the problem logically. Students also must incorporate knowledge of how transformations of these compounds take place through mechanisms. Once these thoughts and logical analyses are applied to the target molecule, learners can develop concepts and strategies to solve synthetic problems (Bhattacharyya et al., 2003).

Problem-Solving

A problem is defined as not knowing how to bridge the gap between where you are now and where you want to be (Hayes, 1981) or a task that requires analysis and reasoning towards a goal (Smith, 1988). The method of finding the solution, as described by Hayes, requires the learner to comprehend the nature of the problem (representing the gap) and explore ways to bridge that gap. Hence, the ability to solve the problem necessitates the individual to have high order cognitive skills (Tsaparlis, & Angelopoulos, 2000), to use representation systems (Bowen, 1990), to access prior knowledge (Lopez, Shavelson, Nandagopal, Szu, & Penn, 2014), and to be motivated.

An exercise can be distinguished from a problem based on the level of familiarity an individual brings to a given task (Bodner, & Domin, 2000; Lopez et al, 2014; Randles & Overton, 2015). Tsaparlis and Angelopoulos (2000) suggested the difference between a problem and an exercise is that the solution of an exercise requires the application of well-known and practiced procedures (algorithms). Exercises are worked in a linear, forward-chaining, rational

manner from start to finish, while problem-solving is cyclic, reflective, and sometimes an irrational process (Bodner and Domin, 2000).

Consider a question that asks a student to determine the mass of oxygen gas required to burn a pre-determined amount of calcium given the following equation.

$$2Ca(s) + O_2\,(g) \longrightarrow 2CaO(s)$$

This type of equation would be a routine exercise for expert Chemists and perhaps some students who are proficient after they have worked on similar questions multiple times, but it could be a problem for beginning Chemistry students.

In most General Chemistry examinations, problems are primarily algorithmic, as they require the learner to use familiar methods to arrive at their solution (Bennett, 2004). In Organic Chemistry, however, many pathways need to be identified and evaluated so, solving "real" problems in both General and Organic Chemistry take a significant amount of time. If the students can easily apply algorithms to solve a question, it should no longer be considered a challenge since a problem implies that a learner is confronted by something where he/she cannot immediately recognize a path to the solution (Randles & Overton, 2015).

In her research, Graulich (2015) mentioned that Organic Chemistry problems are classified based on their content: mathematical, nonmathematical, and mechanistic problems. In contrast, Raker (2011), identified the problems in Organic Chemistry as follows.

- Project level problems- Problems composed of identification and selection of target molecules for synthesis. Project-level problems deal with the societal application of the target molecule structure or its functionality.

- Day-to-day problems- these include the challenges/obstacles, hurdles, or anything that needs to be fixed during the laboratory routine process. For example, while synthesizing a molecule in the laboratory, a researcher can encounter the formation of an unexpected product or a byproduct. As a result, a standard exercise (routine reaction) becomes a problem as it requires the researcher to purify and characterize the product as well as determine how and why it formed.
- Synthetic planning problems- Two closely linked problems arise in synthetic planning: retrosynthetic analysis of the target molecule and developing several proposed synthetic pathways. These two problems occur and are solved simultaneously while planning synthesis (Raker, 2011).

While a problem cannot be solved by recall, recognition, reproduction, and algorithm alone, an exercise can be solved with an algorithm and still be a problem to the student (novice) since the pathway may not be evident to them unlike to the instructor (expert) (Bunce et al, 1991; Smith,1988).

Expert Novice Dichotomy

There are many definitions for describing novices and experts (Ardac 2002; Galloway et al., 2017). In this study all students in Organic Chemistry II were considered novices and the Organic Chemistry faculty as experts. The decision to classify students as novices was based on the Dreyfus model of skill acquisition, which describes how students develop from novice to expert. Becoming an expert requires more than just doing well on certain tasks in class.

According to Persky and Robison (2017), the development of expertise occurs through various stages, and a learner cannot move directly from a novice to an expert without going through the stages, as the following figure shows.

Figure 3.1. Dreyfus Model of Skill Acquisition.

The students at the novice stage are introduced to the basic foundations of a domain topic. As they move to the advanced beginner stage, they begin to gain experience through practice but need assistance in making meaningful connections. At the competent stage, the learner begins to perfect their skills and apply what they have learned in a problematic setting. Once they reach the proficient stage, they can display confidence and rely on intuition. The last stage consists of an expert who has gained knowledge in the domain and can recognize patterns while solving the problem.

According to Persky and Robinson (2017), accomplishing specific tasks with a degree of automaticity does not qualify one as an expert, but being an expert requires building a substantial knowledge base that affects what they notice, organize, represent, and interpret. They also argued that the accumulation of knowledge or experience is not enough to develop expertise. It requires not just practice but a unique type of practice to become an expert. In other words, a learner cannot move from a novice directly to an expert but will have to undergo several stages as described by the Dreyfus model of skill acquisition. As the learners develop progressively, they engage in increasingly complex problems that are challenging and relevant to their current situation, eventually solving those types of problems faster like experts (Larkin, McDermott, Simon, & Simon, 1980; Lopez, Shavelson, Nandagopal, Szu, & Penn, 2014).

Hambrick, Oswald, Altmann, Meinz, Gobet, Campitelli (2014) described participants who had spent 10,000 hours to become some of the best violinists as experts. Those participants who spent at least 5000 hours, Hambrick et al. (2014) described them as good, while those with 2000 hours were amateurs. Unlike novices, experts have engaged in many hours of practice on a circumscribed set of tasks in their work environment (Feltovich, Prietula, & Ericsson, 2006). This study did not categorize students as either advanced beginners, competent or proficient but considered all of them as novices.

Working Memory

Having success in problem solving depends on a combination of strong domain knowledge, problem solving skills, and attitudinal components (O'Neil, & Schacter, 1999; Johanssen, 2000). For Organic synthesis problems, having a strong domain knowledge and problem-solving skills would include understanding of reaction mechanism, reagent selection, and selecting the best synthetic routes. Students also would need to develop the knowledge of chemoselectivity and steric effects. The attitudinal components towards problem-solving can be grouped into willingness, perseverance, and self-confidence (Sturm & Bohndick, 2021). Students are more task-oriented and easier to motivate when they are willing to work on a variety of tasks until they find a solution. Students who are willing to pursue goal-oriented behavior can persevere and overcome obstacles. Confidence is an individual's belief in their ability to succeed in solving challenging problems. Students who lack confidence in themselves can undermine their ability to solve problems in a productive way (Lester, Garofalo, & Kroll, 1989; Shaughnessy, 2013).

Another thing that can impact an individual's success is the connection between problem solving and working memory. Working memory (WM) can be defined as temporary storage where information is manipulated and transformed or a combination of storage and executive control to support a skill (Morrison & Chein, 2011; Vandierendonck, 2016). Executive control is responsible for allocating attention, remembering instructions, juggling multiple tasks successfully, and coordinating activities between the different components of working memory (Solaz-Portoles & Sanjosé-López, 2009; Diamond, 2013). This allows for the efficient processing and manipulation of information during cognitive tasks (Baddeley,1986,1990; Miyake & Shah,1999).

Memory according to Baddeley (1996) consists of three main kinds, short term, long term and working memory. Short term memory has a smaller capacity whereby a person can hold about seven chunks of information in a short time frame while long term memory has a larger capacity. Working memory involves both the short-term storage and control mechanisms that help swap information between long term and short-term memory (Solaz-Portoles, & Sanjosé-López, 2009). The difference between the experts and novices is not the capacity of their working memory but their ability to create chunks of information.

According to Gobet and Clarkson (2004), chunks are acquired over years of practice and study within a domain. When the chunks are small, only a small amount of information can be represented in short-term memory; when the chunks are large, a large amount of information can be represented in short-term memory (Jones, 2012, p.1). Unlike the novices who learn synthesis for one semester, experts have extensive knowledge of Organic synthesis which they have stored as large chunks after many years of experiences working on the same subject.

This study focused on problem-solving in Organic synthesis by defining problems as a task that required analysis and reasoning toward a goal. The goal of the task was for the participants to solve synthesis problems while thinking aloud. The think-aloud method has been used in literature to study participants' thinking while working on a given task (Bowen, 1990; Kozma, & Russell, 1997; Madden, Jones, & Rahm, 2011; Webber, & Flynn, 2018). Similarly, the study applied Anderson's (2005) and Graulich's (2015) definitions of problem-solving, "using the cognitive operation to judge trends, devise mechanisms and rationalize spatial relationships to predict a chemical product."

Challenges in Organic Synthesis

The challenges in Organic synthesis for students can be explained through five key factors. First, instructors teach students basic reactions but expect them to propose a full synthesis without teaching them how to integrate their knowledge and skills effectively (Flynn 2014; Bode & Flynn, 2016; Farmer & Schuman, 2016). Second, Organic Chemistry requires different skills and knowledge such as spatial reasoning, molecule visualization, and understanding of functional groups than those utilized in the General Chemistry prerequisite course (Lopez et al., 2014). Third, most Organic Chemistry instructors give students predict-the-product problems, which are easier to grade, rather than assigning numerous multi-step synthesis problems. This limits students' opportunities to develop the cognitive, analytical, and practical skills necessary for success in Organic synthesis (Raker & Towns, 2010). Fourth, students face the challenge of selecting the appropriate reaction from seemingly thousands of possibilities each potentially leading to numerous synthetic routes (Rose et al., 2019; Zheng et al., 2019).

The fifth challenge is the structure of Organic Chemistry books. Research has shown that most second-year Organic Chemistry textbooks are organized based on functional groups and this structure has not changed over one hundred years (Wheeler & Wheeler 1982; Goldish 1988; Halford, 2016). Instructors teach these chapters focusing on the reactions that feature specific functional groups (Johnston, 1990; Teixeira, & Holman, 2008). While this teaching approach is orderly and reasonable, it is not ideal for preparing students for the thought process involved in solving Organic synthesis problems which can feature any combination of functional groups (Teixeira, & Holman, 2008).

The textbooks propose reactions in a forward sense A + B $\longrightarrow$ C, where A is the featured functional group. Conversely, the retrosynthesis approach requires the students to think in reverse; C $\rightarrow$ A + B, where C represents the desired functional group. Students are challenged in thinking backwards and finding the transition to a retrosynthetic approach difficult (Teixeira, & Holman, 2008; Cannon, & Krow, 1998). Although the textbooks propose strategies for solving Organic synthesis, it is unclear whether a book organized based on functional groups can help students develop broad synthesis problem-solving skills (Clayden, Greeves, & Warren, 2012; Klein, 2012; Bruice, 2014). Additionally, it is not clear how book organization helps or hinders students in solving Organic synthesis problems.

Organic Chemists have discussed various methods for addressing ways of solving synthesis problems such as the disconnection approach (Warren, 1982), the chiron approach (Hanessian et al., 1990) and retrosynthesis (Corey,1991). These three methods agree that a significant amount of knowledge in Organic Chemistry is required to be able to solve synthesis problems successfully. While these methods highlight the fundamental principles and the foundation for understanding Organic synthesis, they provide little insight into students learning

Organic Chemistry. As a result, these methods seem to be designed for experts who are already knowledgeable in the subject and not as a learning strategy for novices who are just being introduced to it.

Other research has proposed additional strategies for teaching such as studying existing total synthesis approach (French,1992), designing synthetic routes to compounds by the students (Cannon & Krow, 1998), comparison of published strategies for synthetic targets (Vosburg, 2008), and use of case studies (Fleming, 1973; Nicolaou & Sorensen, 1996). In the total synthesis approach, students reviewed original journal articles in class to prepare for lectures and discussions. The course emphasized all aspects of the synthetic process, including element selectivity, rationales for target molecule selection, and strategic planning and execution of synthetic routes (French,1992).

Students in the upper-level Organic synthesis course at Temple University mirrored the process that Chemists use when designing synthetic routes to complex natural products (Cannon & Krow, 1998). Students employed a collaborative learning approach, in which they researched a target molecule and devised the necessary reagents and synthetic procedures. Approval for the final project required successful identification of key elements such as disconnections, stereochemistry, and functional group complexity. Students presented their findings in class, using a grading rubric developed by their group to facilitate peer evaluation (Cannon & Krow, 1998).

These methods helped the students examine the primary literature in Organic synthesis and develop a grading rubric. They also engaged in both intergroup and intragroup grading, which required them to critically evaluate each other's work. Further, these methods helped students develop communication skills through writing and oral presentations. Despite these

successes, Vosburg (2008) mentioned that these methods are not a treatment for synthetic strategy but a way to engage students and build their confidence to solve synthesis problems independently.

Students can solve Organic synthesis using the forward-thinking approach and backward thinking approach (retrosynthesis). The forward thinking approach begins with the starting material to form a target molecule while retrosynthesis begins with target molecules and ends up with the reactants. (Corey, 1991). Through the retrosynthesis approach, students need to use multiple construction processes that utilize chemical reactions at each step, leading to a specific structure (Corey, 1991; Parson, 2019). This necessitates that the students use problem-solving and higher order thinking skills to solve Organic synthesis problems, but developing these skills is a challenge for them. Without systematic strategies or methods for solving synthesis problems, even the most successful students experience difficulties (Bode & Flynn, 2016).

Theoretical Framework

The literature has shown that students can be skilled in adopting the strategy they need to be successful in their classes but can fail to integrate meaningfully what they learn into their conceptual framework (Edmondson, & Novak, 1993). To be successful, students must utilize prior knowledge and be able to anchor the new knowledge to that prior knowledge, thus leading to learning that is not only meaningful but has a significant change in the learner. Significant learning is not hierarchal but relational and interactive. The interactive nature of Fink's taxonomy shows that each kind of learning is related to other kinds of learning and achieving one aspect enhances the possibility of achieving others (Fink, 2013).

There are two major implications for educators in significant learning taxonomy (Fink 2013). First, learning goals of a course should go beyond content mastery and make the learning experience more worthwhile and interesting. Second, educators should use a combination of

significant learning goals to create interactions and synergy that will enhance significant learning by the students. Fink's taxonomy is made up of six kinds of learning that are related and have a distinctive value to the learner. These categories include foundational knowledge, application, integration, human dimensions (confidence and challenges), caring (attitude, future goals and interests) and learning how to learn. This manuscript focused on the first three components (foundation knowledge, application and integration) of significant learning for analysis.

Although most studies focus on the pedagogical approach to problem-solving, little is known beyond anecdotal evidence of how experts engage in these strategies compared to novices. To address this gap, the present study focused on the following research questions:

1. What strategies do novices and experts use while solving Organic synthesis problems?
2. How do novices and experts differ in how they organize, and prioritize foundational knowledge during Organic synthesis problem-solving?
3. To what extent do novices and experts connect Organic synthesis with prior learning during synthesis problem solving?

The first research question focused on application; the second question on foundation knowledge and the last question on integration as related to Fink's taxonomy of significant learning.

METHODOLOGY

To address the research questions, a qualitative research design was adopted. This section provides a detailed account of the research participants, the data collection strategies and procedures implemented, as well as the analytical methods utilized to interpret the data.

Participants and Setting

The participants for this research were 17 Organic Chemistry students and 4 Organic Chemistry faculty members at a large regional comprehensive state university. Student participation was voluntary and students who did not participate in the study did not have any impact on their grades in the course. Experts in this study had extensive knowledge and experience in teaching different sections of Organic Chemistry I and II each semester. Dr. Irene and Dr. James taught for 26 years each, Dr. Rachel had 30 years of teaching experience, while Dr. David had less than 5 years of teaching experience when this study was conducted.

To maintain the confidentiality of participants, pseudonyms were used in place of actual names for both students and faculty throughout the study. The participants were given 2 synthesis problems (tasks) to solve while thinking aloud about what they were doing and why. They were also expected to show their work through mechanisms. Mechanisms play a vital role in synthesis as it allows one to comprehend the process and the rationale behind the reaction instead of rote memorization. After the participant completed the task, the researcher asked them several questions about Organic synthesis.

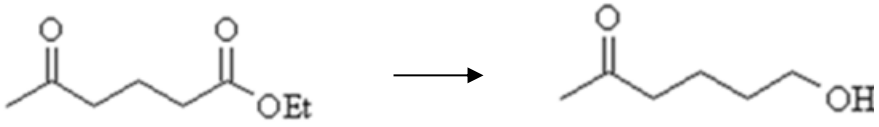
Data Collection and Analysis

Data collection was done through Zoom, and the tasks were provided to the participants through an iPad. Only audio transcripts and completed tasks were used for data analysis. Participants were given instructions outlining the expectations on how to solve the tasks when they scheduled their interviews. After reading the task questions, participants began by explaining their strategies for how they would approach the tasks. If the participants failed to articulate their thought processes, the researcher prompted them with questions. The tasks were selected based on the material that the instructors had already covered during the semester at the

time of the interview. However, the tasks used were not those found in the textbook or completed as classroom examples. The data collected through think-aloud interviews provided a more accurate glimpse of when, how, and why the participants applied alternative strategies (Stieff, 2011).

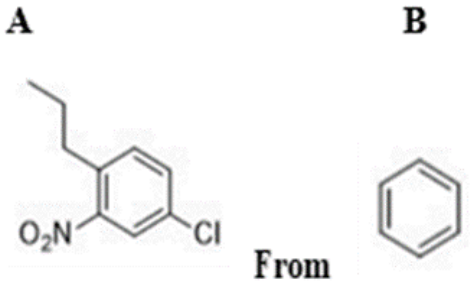
Task I

Which reagents are required to go from the starting material to the product? Write a mechanism for the formation of the target molecule.



Task II

Using retrosynthesis, how would you derive structure A given structure B. Explain each step in detail and show the mechanism.



Coding System

The coding system developed by Bode and Flynn (2016) was modified and used during the analysis of the tasks to help define the appropriate code for each question. For example, if the participants demonstrated the movements of electrons for some or all the steps of a synthetic pathway it was coded as *use of reaction mechanisms* and aligned with Fink's taxonomy as application. If participants labeled, circled, or pointed out functional groups in both the starting

and target molecules, it was coded as "*functional group identified*." This was aligned with Fink's taxonomy as a demonstration of foundational knowledge.

RESULTS

The figures below (artifacts for both Task I and Task II) display the results for two experts and four notices completing these tasks. They serve as representatives of the overall participant group.

RQ1: What strategies do novices and experts use while solving Organic synthesis problems?

Experts

Task I

Dr. David: The first thing I notice is I am reducing the ester only. So, two functional groups can be reduced, but only the ester is reduced.

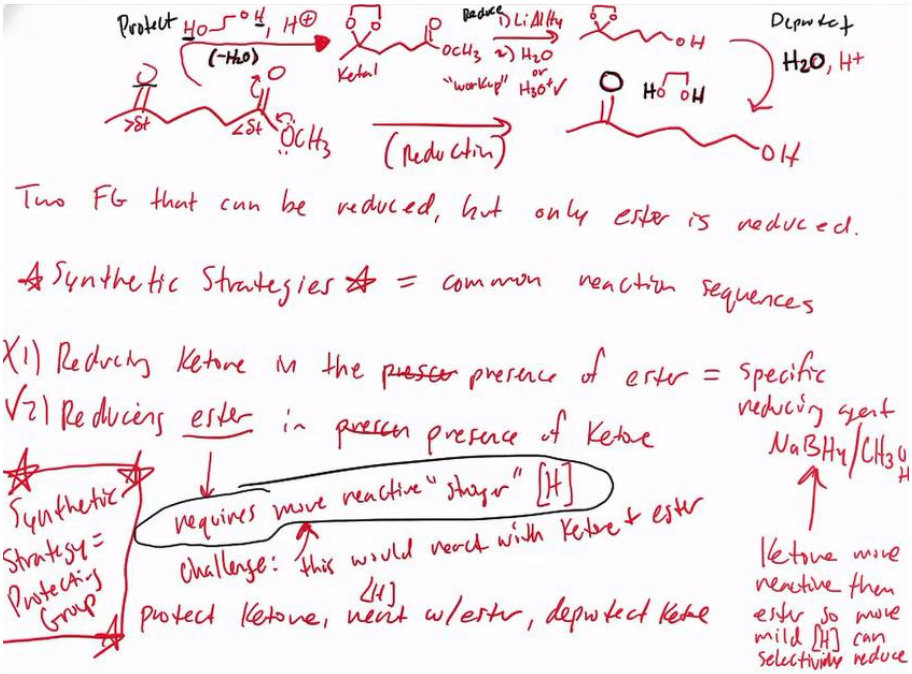


Figure 3.2. Dr. David's response to Task I

The first thing Dr. David noted was the presence of functional groups in both the starting material and the product which helped him to determine that one of the functional groups had to

be reduced. He demonstrated forward and backward analysis strategy by saying that "*So, this is the way I see it. I'm going from a starting material to a product. So retrosynthetically I'm going to work backwards*." Dr. David applied the strategy of chemoselectivity, reactivity and compatibility while choosing the correct reagents.

> **Dr. David**: Ketone is more reactive than an ester. A less reactive reducing agent will react with the more reactive functional group. So, we have to use a more reactive reducing reagent.

In his argument, Dr. David mentioned that using a reagent such as sodium borohydride would react with the ketone, since it's a mild reducing reagent. So, he chose lithium aluminum hydride as the correct reagent for the reduction process. He applied the roadmap strategy by mentioning the sequential steps by which the reactions should occur.

> **Dr. David**: The strategies are to protect the ketone, reduce ester, and then deprotect. So, the standard protection of the ketone would be ethylene glycol.

Dr**.** David reasoned through mechanistic strategy while demonstrating the movement of electrons and breaking and formation of new bonds in the process.

> **Dr. David**: The ketone is more reactive, and the ester is less reactive. It makes the partial positive charge lower. This has a higher partial positive charge. I use greater than and less than, just to what I'm thinking in my head. So, you're able to react with the ketone selectively. So now the ketone is an acetal then you can reduce the Ester. Ester can be reduced down one oxidation state to an aldehyde or can be reduced down two oxidation states to alcohol. You lost water in the process and to reverse, you have to add water, and it has to be acid catalyzed.

Carbon mapping is another strategy Dr. David applied in solving Task I.

> **Dr. David**: So, you have a six-carbon compound. I'm counting the carbons in my head. I teach 'them to count one when they put their pencil down and every time they move it, it's 1, 2, 3, 4, 5, 6.

Mentally counting the carbon atoms, as he drew the structure ensured that he avoided errors such as missing or adding extra atoms. His goal as an instructor is to help novices develop expert-like habits while fostering deeper pattern recognition through carbon mapping. And lastly, he

mentioned that "*there are other ways you could do it, but I think this would be the most efficient way*."

Similar to Dr. David, after determining the functional groups, Dr. Rachel's strategy was on how to reduce the ester in the presence of a ketone as she stated, "*what I would think first is how to reduce the carbonyl since you have a ketone and an ester but only one needs to be reduced*."

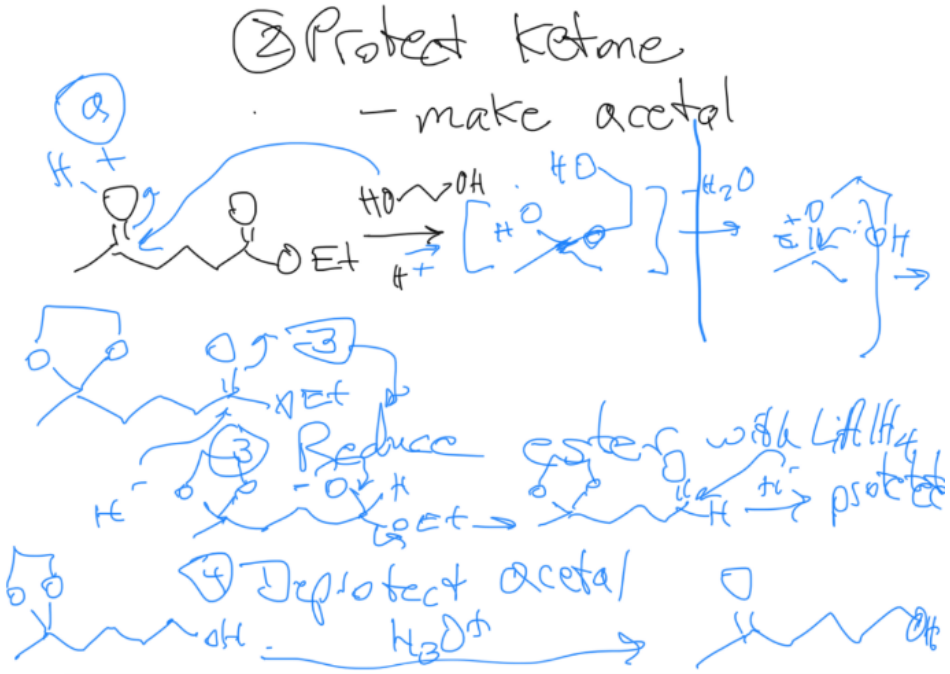


Figure 3.3. Dr. Rachel's response to Task I

Dr. Rachel's awareness and explanation of reactivity, compatibility and chemoselectivity strategies demonstrated her expert level ability to choose reagents that selectively target one functional group. She emphasized the need to protect the ketone due to functional group reactivity.

> **Dr. Rachel**: The ester is less reactive, so they need a stronger reagent. So, they need to protect the ketone because there's no reagent that's going to reduce the ester without reducing the ketone. Sodium borohydride would only reduce the ketone; Lithium aluminum hydride would reduce both. And what they want to reduce is the ester.

For the roadmap strategy, Dr. Rachel emphasized not only the order in which the reactions should occur, but also the reagents that are required in the process.

> **Dr. Rachel**: They're going to have to protect the ketone that's the strategy using Ethylene glycol and to make the acetal. And then the second step is to reduce the ester, $LiAH_4$, to get the alcohol. And then deprotect the ketone.

Dr. Rachel applied mechanistic reasoning while sketching out each mechanistic step on how to protect the ketone and reduce the ester as shown in figure 3.3 demonstrating electron flow and reaction intermediates.

> **Dr. Rachel**: I usually use ethylene glycol and that is going to pronate the ketone. So, they're going to have an intermediate where one of the oxygens has added and they get a Hemiacetal. So, I'll just put a couple of arrows in there and then they're going to lose a molecule of water. And then the second oxygen will add, and they'll get the acetal. So, once they've done that, they've protected the ketone. Now they can reduce the ester with lithium aluminum hydride. So, the hydride is going to add to the Carbonyl. So, you've added a hydrogen, you get tetrahedral intermediate that gives an aldehyde intermediate, you add another hydride equivalent and that gives the acetal on one side and alcohol on the right.

Task II

The first strategy Dr. David used was determination of functional groups and the reactions required to add them. While working on Task II, he stated, "*The first thing I think about is the three reactions that are required to add the three groups attached to benzene*."

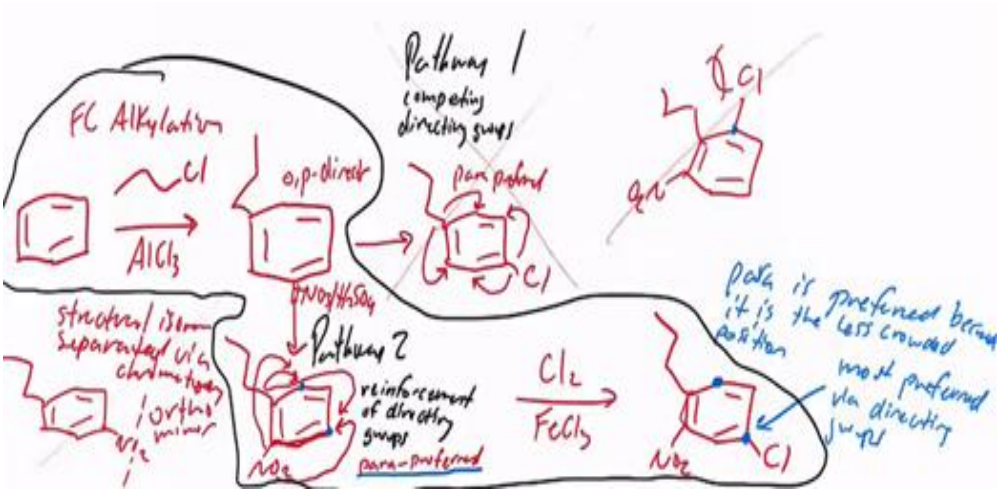


Figure 3.4. Dr. David's response to Task II

Dr. David demonstrated a deep consideration of directing effects in aromatic substitution and used them to justify the order in which the reactions should occur.

> **Dr. David:** You have to think about activating versus deactivating. And then you think about ortho, para versus meta directing. So, this is deactivating and it's an ortho para director (*chloro group*). This is deactivating and it's a meta director (*nitro group*). And then this is activating and it's an ortho para director (*alkyl group*). You usually don't want to add the deactivating meta director first because if you add this first, it can direct the addition of the next substituent, you want to add the activating ortho para director. Next we have to add the nitro group before the chlorine.

According to Dr. David, the reagents and the reactions required to add the three functional groups would be, "*Friedel–Crafts alkylation, nitration to add the nitro group using nitric acid with sulfuric acid and then chlorination using chlorine and iron (III) chloride."* He emphasized the possibility of having multiple pathways for solving Task II while maintaining his awareness of orientation symmetry when he stated that "*The para is preferred because it's the less crowded position*" In his argument, Dr. David suggested that pathway II was better than pathway number I because of competing directing groups as the following excerpt shows.

> **Dr. David**: So, you've got two competing pathways; pathway one and pathway two, And the first pathway, the alkyl group is directing ortho. There's already something at the para position. So, you can't add there. Then the chlorine, even though it's a deactivating group is ortho as well. So, you have competing directing groups in this pathway. In pathway two, you have the alkyl group directing ortho, the meta group. You have the meta director also directing to the same carbon. So, the ortho position of the alkyl group is the meta position of the nitro group. And there are of course two meta positions. The alkyl group is also a para director. So, with pathway two, I call it a reinforcement of directing groups.. And then the pair is the preferred product. So, the alkyl group is an ortho para director. The alkyl group is directed toward the ortho position, which is also reinforced by the nitro group, but it's also directed toward the para position, which is also reinforced by the nitro group. So, if you have to choose which of these is more preferred, the para is preferred.

The first thing Dr. Rachel thought about was the orientation of the substituents while considering the sequence of the reactions and directing effects. "*So, when you're doing a synthesis of an*

aromatic compound, you have to think about strategy and what is an ortho para director and a meta director so that things can go into the right position."

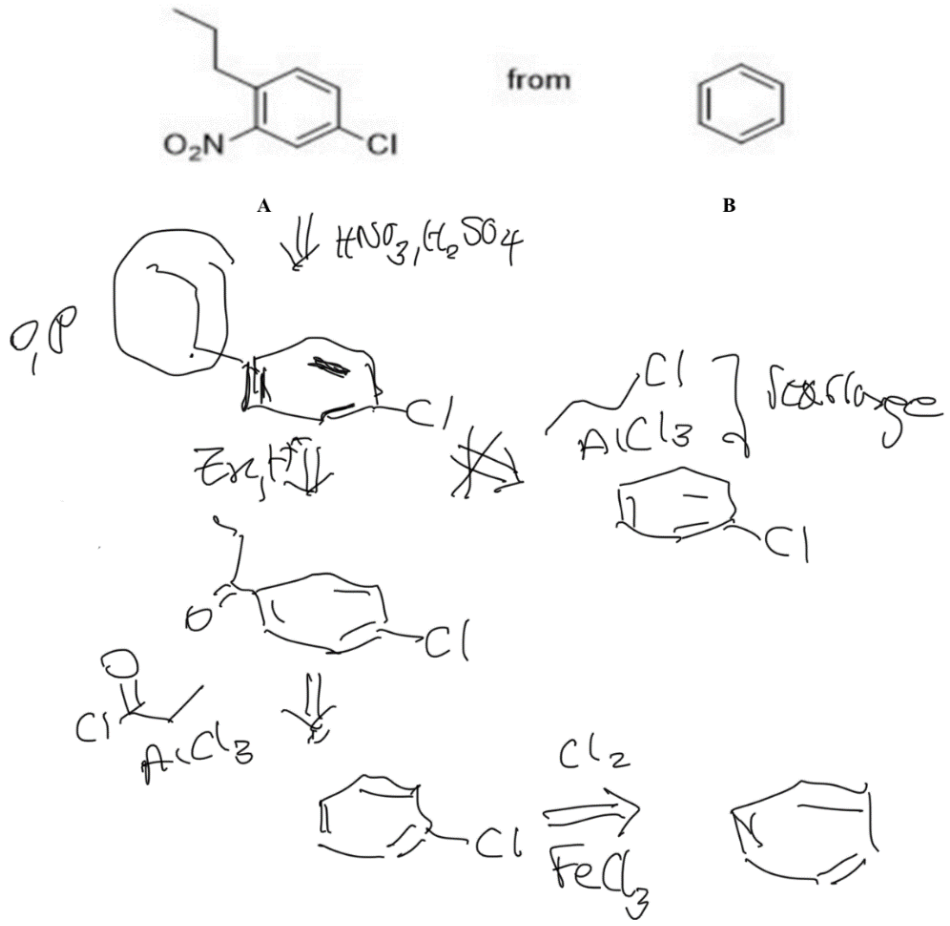


Figure 3.5. Dr. Rachel's response for Task II

She engaged in retrosynthetic thinking stating that "*I'm going to work backward from A*" while emphasizing the reagents and the reactions needed to solve the task.

> **Dr. Rachel**: You need a chloro, so you're going to have to chlorinate, using chlorine and iron (III) chloride, you need a nitro. You're going to nitrate using nitric acid and sulfuric acid. The three-carbon chain you can't put on with Friedel-Crafts alkylation because it will rearrange.

Based on her explanation from the excerpt above, Dr. Rachel used Friedel-Crafts Acylation to add the alkyl group. She also emphasized that she would add the nitro group last.

Dr. Rachel acknowledged that task II can have multiple pathways of solving it as long as regiochemistry is preserved. "*You could change the order; the steps are all going to be the same*." Changing the order of adding the functional groups involved the alkyl and the chlorine groups as she still emphasized adding nitro group last in the second pathway.

There were similar strategies emerging among all the experts (Dr. David, Dr. Rachel, Dr. James and Dr. Irene) involved in the study. The first strategy was recognition of alternative or multiple pathways. For example, Dr. James stated that "*there are all kinds of routes that could be used here…. This is probably the simplest because it involves the least number of steps and also the least amount of oxidation-reduction chemistry*." The same was echoed by Dr. Irene, "*there are many ways you could do this*." Each expert evaluated the possible strategies and chose the most practical and efficient pathway illustrating their adaptive problem solving.

Another unifying strategy among the experts was the consideration of directing effects in aromatic substitution. Dr. James, "*Chlorine is an ortho para director, nitro is a strong deactivating meta director*." Dr. Irene followed the same line of reasoning just like other experts, *"The nitro group is deactivating the ring strongly, So, nitro is ortho* [to the alkyl] *and the chloride is going to go para*." This demonstrated how experts apply the knowledge of electronic effects in determining regiochemistry.

Across the board, all the experts applied mechanistic reasoning to justify their approach in solving the task. Dr. Irene explained the mechanism of acetal formation using arrow pushing formalism: "*so I am going to convert it into acetal by taking a diol in the presence of acid. So, the way to do this is just to activate the carbon by protonating it. And then I'm going to show resonance structures that put the positive charge partially on the carbon.*" The use of

mechanistic reasoning by the experts demonstrated their ability to internalize and apply the correct reagents and reactions to predict the outcome.

Another similarity among the experts was the use of retrosynthetic and roadmap strategies to determine the order in which the reactions would occur. Each step in the reactions involved selection of correct reagents and reactions. Experts demonstrated application of knowledge and chemical principles in planning synthesis. Choosing conditions that targeted certain functional groups was another strategy exemplified by the experts. Each expert highlighted the importance of protecting the more reactive ketone before reducing the ester. For example, Dr. James stated that "*we need to reduce an ester but there's also a ketone, what needs to be done first is to go ahead and protect that ketone*." Dr. Irene echoed the same, "*The only important step is lithium aluminum hydride. It's the strongest reducing agent that we have available and so, I know that it's going to reduce my ester. I've got protected ketone."*

Novices

The results of four novices were used to represent the novice group. Novices were given the same initial question just like the experts. The first strategy George employed was carbon mapping on both the starting material and the target molecule.

> **George**: My first thought is that I would number all my carbon atoms on each side. I see the carbonyl on the left has not been reduced but the one on the right has been reduced, so I need a protector group on the left carbonyl.

By identifying the functional groups on the starting material and the product. George was able to determine that the ester had undergone a reduction process.

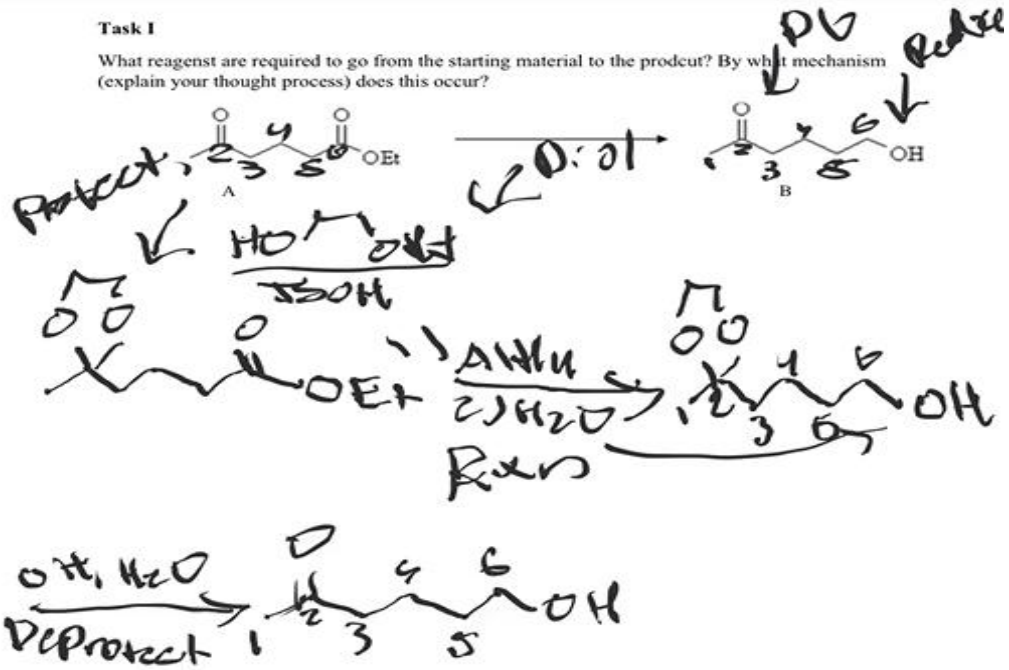


Figure 3.6. George's response to Task I

George demonstrated his understanding of chemoselectivity as he tried to explain how different functional groups respond to reagents. His explanation resembled that of the experts.

> **George**: I have to think about what reduces an ester, and it has to be a strong reducing agent because the mild one $NaBH_4$ will not reduce. And I know it's not a Grignard reagent that's being used because there's no carbons being added. Because for me, it was either between that or $NaBH_4$ over H_2O. And I know that $NaBH_4$ is a mild reducing agent which won't reduce esters. And only, $LiAlH_4$ will reduce esters as far as I know.

Roadmap was another strategy employed by George in determining the order in which the reactions were to take place, "*So, for me you have three steps, protect, reduction, and deprotect*." As can be seen in Figure 3.6 above, in each step he was able to write down correct reagents that were required to protect, reduce and deprotect to form the target molecule. George also applied mechanistic reasoning to justify how he solved the task to form the target molecule.

> **George**: How does this react? So, the LiAH is going to reduce that and make it some oxygen. And then the H_2O will protonate the oxygen. And then water will come in and pronate you'll get, OH. So now what you need to do is to deprotect what we protected so you can get the carbon back.

He articulated a partial reaction mechanism on how the alcohol is formed from the reduction of the ester referencing nucleophilic attack and protonation. In terms of alternative pathways, George did not think there was any other way to solve task I as he stated, "*I just don't think there's enough going on to do multiple things*."

Debbie first thought was to determine the functional groups and with that she could come up with correct reagents for the reaction.

> **Debbie**: My first step is to look at the differences in the starting material and the target molecule. Then I can start thinking about the reagents that would give me the most effective synthesis.

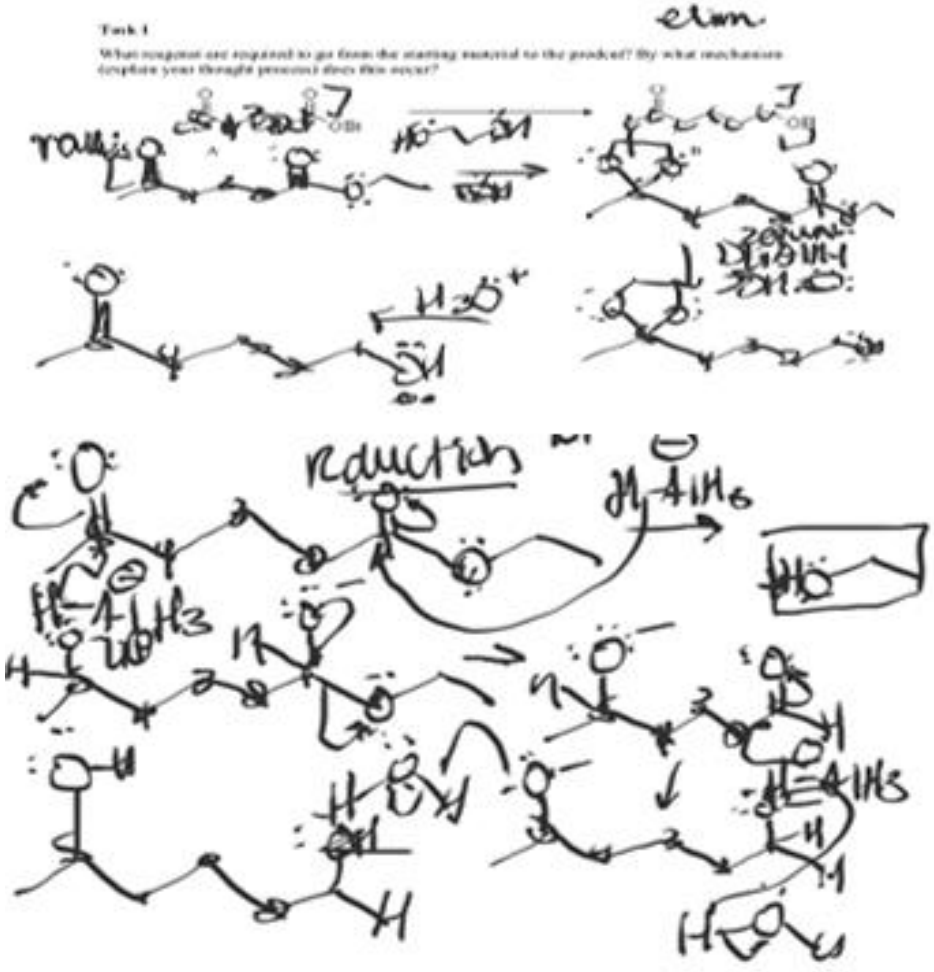


Figure 3.7. Debbie's response to Task I

She counted the carbon atoms to keep track on the structural changes as she stated "*And I like to count. This is where we have change right here*." (pointing to the alcohol on the target molecule). Debbie recognized the need to selectively protect the ketone showing awareness of chemoselectivity, "*I would protect my keto functional group first*." She outline a clear three step sequence based on order of operations while highlighting the reagents needed for the reaction.

> **Debbie**: So, what I do first is I would protect with a diol. I could go ahead and reduce this group (ester) all the way down to that primary alcohol using lithium aluminum hydride. And now you could use H_3O^+ to deprotect.

Debbie applied mechanistic reasoning by drawing a step by step mechanism while using arrow pushing formalism to formulate the movement of electrons.

> **Debbie**: This might be kind of a lot. But I typically like to draw my mechanism completely. It's just going to help me conceptualize what's going on here. So, hydride attacking here. The same things occurring over here to me in my head is what I'm kind of seeing. Now I'm going to draw this hydrogen animated just to help me keep track. And we've still got this alkoxides group here. So, my next step here is a little different and I remember that. So, I'm going to eliminate this group and I'm going to show lithium associating. So, I remember to go back and protonate. So, this arrow looks bad. I'm going to erase it distracting there. So now we got this group, which is ultimately going to become an alcohol. That's one of our byproducts. And so now this is the step where I would go ahead and protonate here with water. I'm just going to show it happening.

Drawing the mechanism helps Debbie to visualize reaction pathways and verify her thinking, "*I use a white board at home, that way I can tell if I'm going wrong*." Unlike Debbie and George who expressed more expert like strategies, Jane struggled in solving the task beyond engaging in basic structural comparison and carbon mapping, "*first, I would probably consider the functional groups and number the carbon atoms*."

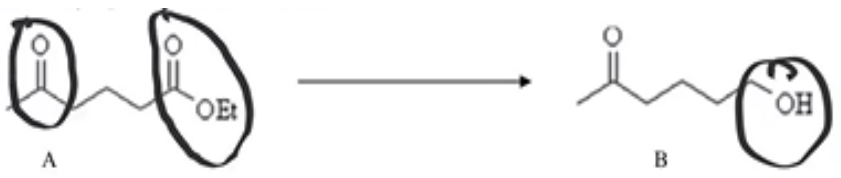


Figure 3.8: Jane's response to Task I

Similar to Jane, Doris employed the strategy of comparing the structural features on both starting material and target molecule as she stated, "*first I look at what is missing in the product and the starting material*." She struggled in determining the correct reagents for protecting the ketone and deprotection strategies.

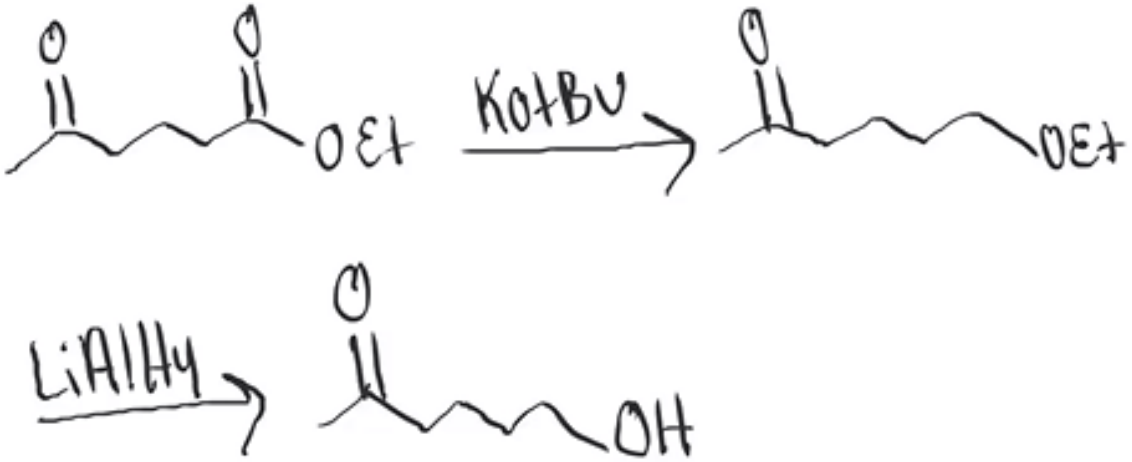


Figure 3.9. Doris' response to Task I

Although she was not sure how a different pathway would look like, she recognized that there is a possibility of solving the task differently, "*I would do task I differently*." Both Jane and Doris withdrew from solving the task once they could not determine the correct reagents and the roadmap strategies as seen in Figure 3.8 and 3.9 respectively.

Task II

George's first thought involved sketching the reactions to help him visualize the orientations in which he would add the functional groups. He proceeded to determine his roadmap strategies which involved the reagents and the reactions involved in each step.

> **George**: I am going to write out which ones are happening first before I do anything else. So first you add chlorine using Cl_2 /$FeBr_3$. Second, you add NO_2 using HNO_3/H_2SO_4. And lastly, you do Friedel-Crafts alkylation since there's no carbonyl.

While explaining his thought process, George emphasized the use of Friedel-Crafts alkylation to add the propyl group, "*I kind of did it all in my head visually, but I could have written it out. I*

thought like, this carbon group doesn't have a carbonyl, so it's not Friedel–Crafts acylation its alkylation."

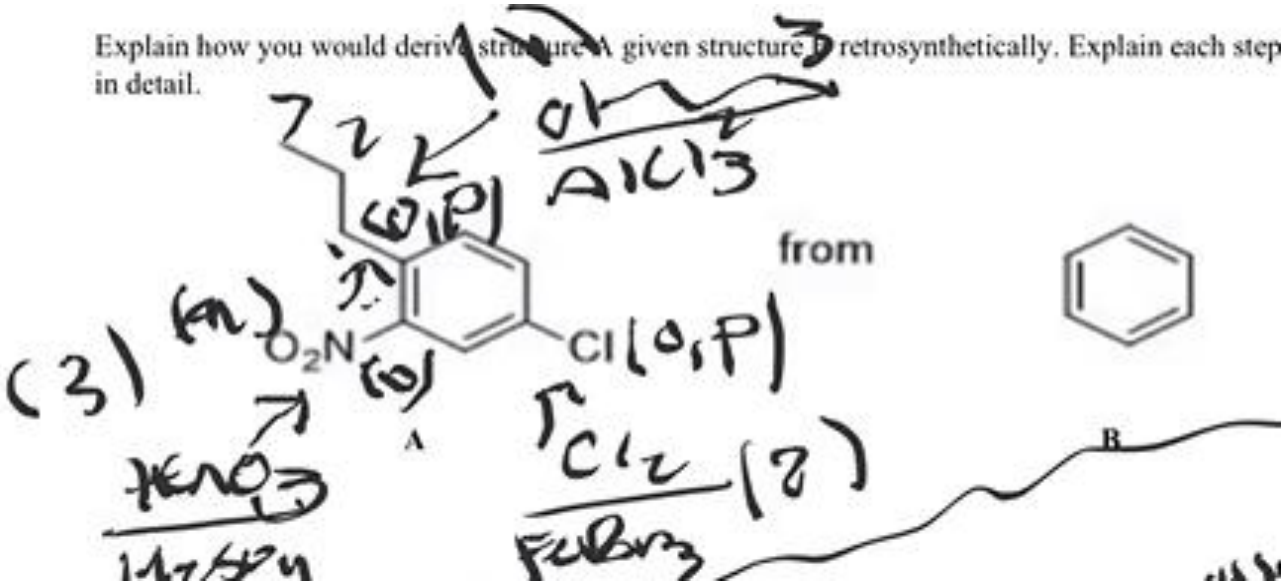


Figure 3.10. George's response to Task II

George applied regiochemistry logic to justify the order in which he would add the functional groups.

> **George**: And now I'm thinking about what order they come in. This adds an ortho para, but it's a deactivator (*Chloro group*). This adds meta and is deactivate as well (*Nitro group*). And then this one is going to add an ortho para as well and it's an activator (*propyl group*).

He demonstrated the understanding of reinforcement and directing effects while showing his awareness of molecular symmetry "*So, nitro will have no choice but to add in this position….. it's like winning the battle*." Throughout the task solving process, George reflected on his own reasoning while constructing a coherent framework of understanding, "I *kind of did it all in my head visually, I guess that's how I think about it*" which demonstrated his metacognitive abilities.

Debbie initial strategy was to focus on the structural features on the molecule "*I'm going to start by looking at functional groups on the benzene ring*." With this in mind, Debbie

highlighted her roadmap strategy in sequential order on how she would add the functional groups.

> **Debbie**: I know I need to do Friedel–Crafts acylation which is the most sensitive. First, I put an alkyl group on the benzene ring. Secondly, I would do chlorination using $Cl_2/FeCl_3$ and third I would do nitration because of different directing effects. That's how I think about it.

Unlike George who used alkylation, Debbie expressed her reason of using Friedel-Craft acylation instead of Friedel-Craft alkylation "*You know, there's conditions in which you can't do Friedel–Crafts alkylation I think with any strong, like meta or deactivating groups*."

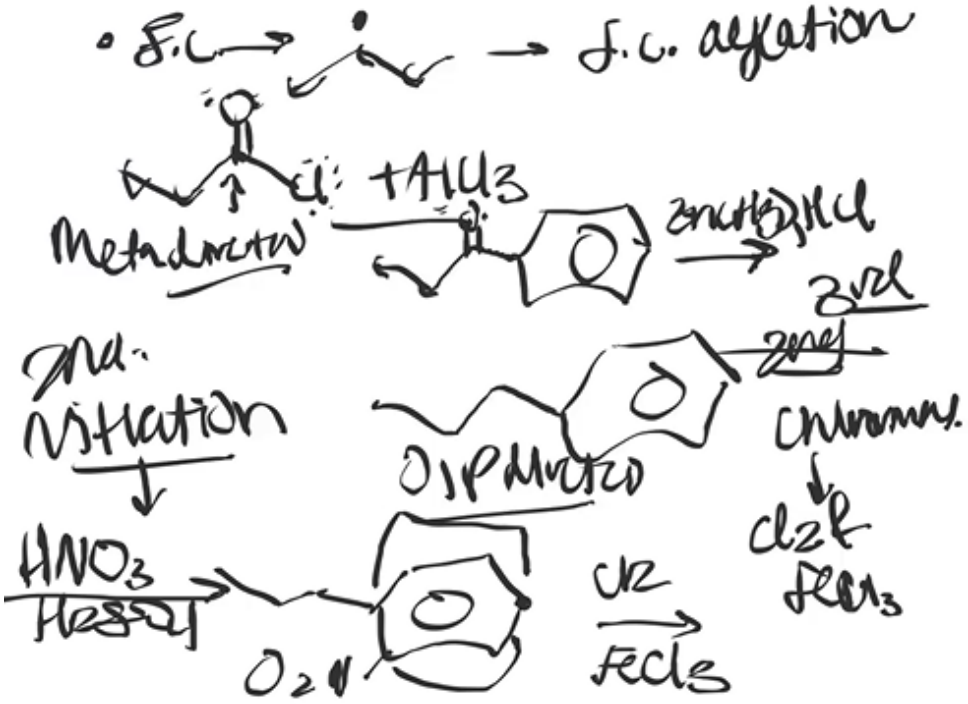


Figure 3.11. Debbie's response to Task II

She considered the directing effects in aromatic substitution which helped her determine the orientation symmetry.

> **Debbie**: I'm realizing that I have an alkyl group, which is an ortho director. I've halogen, which is also an ortho director, but it's deactivating. And then I have a nitro group, which is a meta director and it's strongly deactivating.

Although Debbie felt that there is another pathway in which the reaction could occur, she was not sure if a different order of adding the functional groups would be more effective.

> **Debbie**: So, another thing that I could think about would be to put on the halogen first. Let me think about it. Because if you put the halogen on first then it would direct. I mean, I don't think it's the best route.

While solving the task, Debbie was able to reflect on her thinking, check her mistakes using mechanisms and revise her strategies where necessary. She also emphasized counting the carbon atoms to avoid any errors "*So, you still have your three carbons like this*" (referring to the alkyl group).

Similar to Task I, Jane's struggles were evident in Task II as she only determined the functional groups by circling them "*First, I would look at the functional groups*." She withdrew from solving the task after redrawing the starting material as shown in Figure 3.12 below.

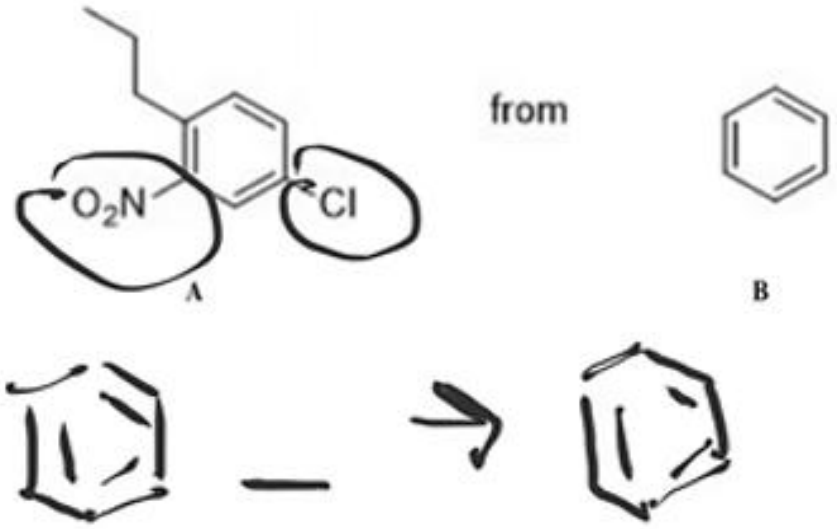


Figure 3.12. Jane's response to Task II

Similar to Jane, Doris' initial step was to recognize the structural features on the molecule while expressing her lack of confidence "*I notice the functional groups, but I'm not sure at all. I'm not sure about any of it, I guess the carbon chain is coming off*." "*I won't know how to do that*."

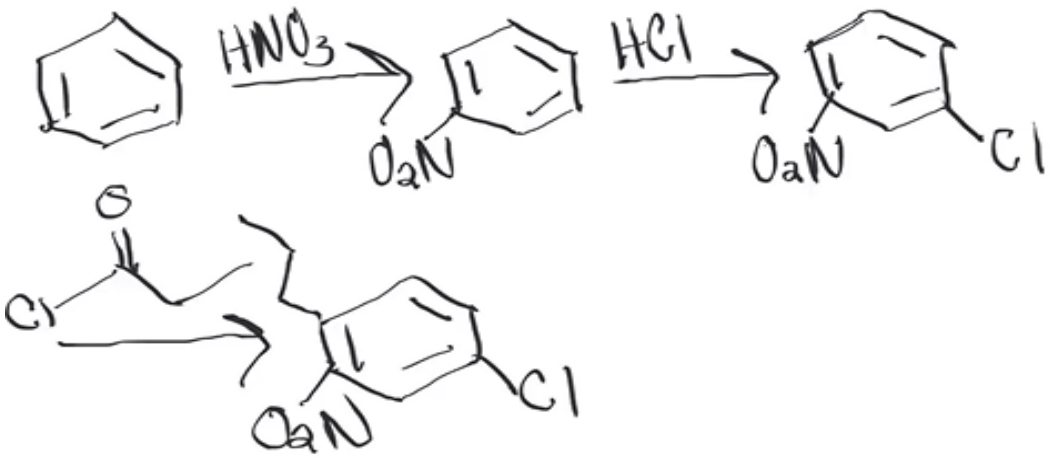


Figure 3.13. Doris' response for Task II

While she was unsure of the functional groups, she partially identified the correct reagents. Her roadmap strategy involved adding nitro group, then chloro and lastly the alkyl group. She demonstrated her ability to recognize directing effects in aromatic substitution, "*I know, with certain molecules the ortho position can make it sterically hindered and then like in the para position it's better since it's favored in the reaction*." However, she was unclear on the orientation of the functional groups. Doris engaged with the concepts while solving the task but lacked structured application of the skills.

There were some similarities among the novices on the strategies they employed especially between George and Debbie, who exhibited expert-like strategies. Some of these strategies includes chemoselectivity, regiochemistry, roadmap strategy, carbon mapping and mechanistic reasoning. Both Jane's and Doris' strategies represented the majority of the novices who struggled in solving the tasks. Jane had minimal engagement with problem solving strategies as she focused on recognition rather than application. Doris demonstrated a lot of gaps in her application which could be reflective of memorization patterns rather than conceptual understanding.

RQ2. How do novices and experts differ in how they organize, and prioritize foundational knowledge during Organic synthesis problem-solving?

The analysis of the faculty responses while solving the tasks revealed expert-level reasoning especially in how they employed mechanistic reasoning. Their knowledge structure was deeply grounded on functional group reactivity, electron flow and regiochemical outcomes which guided their decision on how to solve the tasks. Experts exhibited their knowledge on prioritization of the problem goal rather than isolated outcomes which could be as a result of memorization. This was reflected in their roadmap strategies in Task I or regiochemical considerations and structure orientations in Task II.

The application of retrosynthetic strategies and selection of efficient pathway from other alternatives pathways demonstrated their vast knowledge of reactions and reagents. They prioritized the most feasible synthetic path. In contrast, rote recall and content reliance were absent among the experts. However, they mentioned them in relation to students difficulties.

Unlike the experts, novices, particularly Jane and Doris, showed more fragmentated and surface knowledge organizations. They seemed to rely on memorization or recent exposure to the content rather than integrated strategies; for example, Jane frequently said that "I don't remember the reagents. Doris portrayed confusion between reagents in task I "*I know PDC can reduce, but I am not a hundred percent sure if it can reduce that*" highlighting her challenge in knowledge of reagents/reactions. However, Debbie and George exhibited more expert-like knowledge organization and prioritization in how they solved and explained their reasoning.

RQ3. To what extent do novices and experts connect Organic synthesis with prior learning during synthesis problem solving?

The experts did not reference any previous lectures or chapters in the textbook when solving the tasks. They explained it based on how they would teach it in class or how they would expect the students to solve it. However, novices explicitly relied on prior learning in class and from the textbooks. For example, George stated "*I was taught that this semester by my professor and it helps*." (In reference to carbon mapping). Debbie echoed the same, "*because we were taught that it would not protonate the alcohol. I don't know if that's correct. But at least in high or good yield according to the textbook*."

Both George and Debbie represented a high level of integration not only in recalling the strategies but also in applying them while solving the tasks. Doris also tried to recall materials she had learned in class even though the reagents she had suggested were incorrect.

> **Doris**: I can't remember, but the professor had used this reagent, and it had something to do with the double bond to the oxygen, and I felt like it had removed it. But I know that it's a bulky base. I'm not sure if that's correct. I think he said the first oxidation state like with the Grignard reagents.

Her reasoning seemed to be more based on recall from classroom examples but not fully integrated in her understanding. She continued to state that "*I am not sure at all…..I just know I have seen reagents that he has put that have been like this*." While she recalled isolated features of synthesis problems, she could not make coherent connections that would enable her to solve the task. Jane on the other hand, seemed to be completely disconnected from the prior knowledge or she was not drawing on it while solving the task. Once she stated, "*I am not sure*" she withdrew from solving the task.

DISCUSSION

The preliminary stages in the problem-solving process not only determine the success and failure but also involve extracting relevant information from the problem and restructuring it into one that the individual understands (Pribyl and Bodner, 1987). In this study, participants were required to solve the tasks while thinking aloud, explaining each step of their process. The results of study were categorized based on the three components of Fink's significant learning framework (2013) (application, foundational knowledge and integration) as discussed below.

Foundational Knowledge.

Experts possess a large domain of knowledge that is well organized into elaborate, integral structures and this organization allows optimal access to long-term memory (Ardac 2002; Galloway et al., 2017; Stains & Talanquer, 2008). The borders between long term memory and working memory among experts become so fluent that the capacity of working memory is considerably expanded (Ericsson & Kintsch, 1995).

The fluency of the experts while thinking aloud demonstrated that they have been able to develop big chunks of information throughout the years which allowed them to have access to substantial amounts of content. Experts demonstrated a vast knowledge of Organic synthesis while solving the task by determining the correct reagents and reactions. As indicated in the results, experts were able to use electron-pushing formalism to show the movement of electrons while doing the mechanism. This was not the same for most novices.

The first strategy used by experts when given the task was to determine the functional groups and the synthetic process they needed. For example, in task I, they were able to point out which functional group to reduce and that reducing the correct carbonyl required protecting the ketone. By just looking at the starting material and the target molecule, experts knew that they

needed to reduce the ester in the presence of a ketone. The experts' strategies for solving tasks were clearly explained through thinking aloud and demonstrated using a mechanism.

In Task II, foundational knowledge was critical in understanding regiochemistry in electrophilic aromatic substitution. Experts clearly explained how directing effects guided their choice of roadmap strategies while adding the functional groups. Only a few novices such as George and Debbie demonstrated expert like knowledge such as chemoselectivity, strategic sequence, retrosynthesis, orientation symmetry. Most of the novices like Doris and Jane failed to account for regiochemistry or showed partial reasoning of the concept. This led to incorrect sequences of functional groups or incomplete syntheses.

Application.

Application was demonstrated through participants ability to use critical, practical skills and foundation knowledge to solve multistep synthesis tasks. In task I, experts applied their mechanistic reasoning/understanding and knowledge of reactions and reagents to device a clear strategic plan (roadmap strategy) of protection, reduction and deprotection. Novices such as George and Debbie, mirrored experts strategies even though they lacked mechanistic details. Jane and Doris, who represented the majority of the novices in this study, demonstrated limited problem-solving ability.

In Task II, there were some differences in application of the synthetic strategies among the experts. The addition of propyl group to benzene required Friedel-Craft acylation and not alkylation. Three of the experts used acylation while Dr. David applied alkylation justifying his decision through reinforcement of directing effects. Other experts considered the use of alkylation as theoretically possible but not practical because of a rapid hydride shift. Among the novices, Debbie successfully followed routes similar to the experts and explained the reason

behind using acylation instead of alkylation. While George understood regiochemistry and the correct reagents for Task II, he explained his purpose of using alkylation instead of acylation while adding the propyl group. Other novices struggled to proceed beyond the initial steps of identifying functional groups demonstrating their gaps in foundation knowledge, which limited their ability to use the knowledge they did possess.

Integration.

Although the experts did not explicitly demonstrate connections of prior knowledge from prior learning, their thinking aloud sessions reveled deeply interconnected knowledge which they applied with ease while solving the tasks. Debbie and George showed active transfer of knowledge from classroom learning and textbooks into problem solving contexts while Doris showed a week conceptual linkage by employing surface level strategies which lacked a structured logic of retrosynthesis. Jane struggled to activate and apply any prior knowledge. Integration was challenging among novices in Task II where understanding of directing effects was crucial.

CONCLUSION

This study highlighted the key distinction between experts and novices in organic synthesis problem solving as interpreted through Fink's taxonomy of significant learning. Experts demonstrated strong foundation knowledge when identifying functional groups and selecting the correct reagents and reactions. In contrast, some novices struggled with reagents selection and displayed gaps in conceptual understanding particularly in regiochemistry. Experts effectively mapped their strategic sequence (roadmap strategies) and mechanistic reasoning in application of knowledge while some novices exhibited limited ability to solve and justify their approach. Although some novices like Debbie and George coherently integrated knowledge from

prior learning experiences, the majority struggled in connecting the fragmented knowledge to cohesive strategies.

Some of these challenges can be explained by understanding how working memory affects learning and comprehension. Working memory capacity limits the amount of information to be processed which can affect the performance on problem solving tasks when the information load exceeds a student's working memory capacity (Johnstone & El-Banna, 1986). With Organic synthesis presenting a vast amount of information that novices needed to grasp, most novices seemed overwhelmed as they tried to conceptualize the knowledge they needed to solve the task.

These findings suggest that targeted instructional methods that emphasize deep understanding, pattern recognition, and/or thinking aloud processes may help reduce students cognitive restriction and promote significant learning in Organic synthesis. By guiding students on how to recognize underlying reaction patterns, articulate their reasoning and connect new information to prior knowledge, instructors can create an environment that supports retention and flexible use of concepts. As novices strengthen their foundation knowledge and actively engage in applying those concepts, across varied synthesis problems, they can begin to internalize expert like strategies which includes, ability to prioritize relevant information, anticipate possible pathways and evaluate alternative solutions.

While this chapter has examined the cognitive domains of Fink's significant learning framework, the next chapter shifts focus to the affective and metacognitive domains (human dimensions, caring and learning how to learn). These components, though weakly emphasized in the literature review are essential for fostering student motivation, self-awareness and the ability to take ownership of their learning beyond the classroom. The study focuses on the expectations

both experts and novices hold in relation to learning Organic synthesis. In addition, the study will examine what student value as important to their success for learning Organic synthesis.

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CHAPTER IV.

Understanding Novice and Expert Values and Expectations in Learning Organic Synthesis: A Significant Learning Approach.

ABSTRACT

Faculty hold expectations about students' learning approaches, while students have expectations for how faculty will provide effective instruction and support for their success. Differences between the two groups can create an expectation gap as faculty members and students try to communicate the material meaningfully. The aim of this study was to investigate the differences in expectations between faculty and students regarding strategies for learning Organic synthesis while focusing on the following research questions. (1) What instructional methods do experts employ in teaching Organic synthesis, and how do novices use these and other strategies to support their learning? (2) What values and expectations do novices hold toward success in Organic synthesis? (3) In what ways do the expectations of novices and experts align regarding Organic synthesis? To address these questions, this research gathered data from 17 novices and 4 experts in Organic Chemistry. The study used semi-structured interviews and a student survey tool to gather data on students' expectations and perceptions. The data was analyzed and categorized within the three components (Learning how to learn, Caring, and Human dimension) of Fink's significant learning model. Based on the results, the components of Learning how to learn were evident from the strategies the experts employed in their instructions such as learning activities and assessments. Novices valued and expected the experts to use examples and classroom discussions in their instructions which aligned with human dimensions. There was an alignment on foundation knowledge expectations between the experts and the novices.

INTRODUCTION

Cognitive expectation plays a vital role in students' success, regardless of the course, as it helps them shape the attitudes they bring into the classroom (Grove & Bretz, 2007). In Organic Chemistry students come with apprehension based on the rumors of former students who have struggled to find ways to navigate through the course. Many students encounter challenges and perceive Organic Chemistry as "bone dry" (Schaller, Graham, & Jones, 2014, p. 2142) due to limited understanding of the significance of synthetic Chemistry. To develop a deeper understanding, students need to integrate new material into their existing mental frameworks to enable meaningful learning.

The cognitive structure of an individual is the principal factor in determining meaningful learning and retention of new material (Ausubel, 1963). To foster and assess meaningful learning, instructors must emphasize cognitive processes that go beyond remembering since learning is not merely presenting information to learners in books and lectures and assessing them to see how much they remember (Mayer, 2002). Learners should not only acquire knowledge but should also be able to apply that knowledge to other contextual situations.

The cognitive processes involved in meaningful learning can be categorized into two groups: the first cognitive process is related to retention (*remember*), while the others focus on knowledge transfer (*understanding, applying, analyzing, evaluating, and creating*) (Mayer, 2002). When the instructional goal is to help students retain information, the cognitive process of remembering is most important. If the goal is to promote information transfer, then the focus shifts to the other five cognitive processes.

Students do not come to the Organic Chemistry classroom as blank slates but with a myriad of experiences, ideas, understandings, and conceptual constructions about what it takes to be successful in in the course (Woodin, Carter, & Fletcher, 2010; Grove, & Bretz, 2012). Faculty also come with preconceived notions and expectations about how students should conduct themselves in the learning process, both inside and outside the classroom. Students think they know what they need, and faculty think they know what students need as well, but these perceived needs often do not align. This misalignment can create tension between the students and the faculty as they all strive for successful meaningful learning.

Expert and Novice Expectations

An expert is someone who has acquired knowledge in a domain through experience, and has a highly structured, consistent, and organized knowledge base (Ardac, 2002; Galloway et al., 2017; Stains & Talanquer, 2008). In addition, they have extensive knowledge (a network of information) that affects how they notice and interpret information in their environment (Gulacar et al., 2019). This information network consists of collections of isolated facts created from previously learned knowledge and stored as schemas. A novice is defined as someone who has minimal exposure to a domain (Galloway et al., 2018) and possesses a fragmented and incoherent knowledge base with several inconsistencies (Ardac, 2002).

A clear example of expectation misalignment between experts and novices is evident in the use of arrow-pushing formalism. For instance, some Organic Chemists, who view electron-pushing as essential for mastering Organic synthesis, may assume that students fundamentally understand its role in representing physical and chemical concepts such as the movement of electrons required to proceed from starting materials to products. However, students may struggle to connect the structures and arrows drawn on paper to the underlying concepts (Caspari et al., 2018). As a result of the disconnect in the conceptual understanding of the relationship

between the structures and arrows, most students focus on remembering a specific mechanism representation rather than focusing on the broader fundamental chemical principles they represent. Consequently, they resort to rote memorization of complicated mechanisms. (Kraft et al., 2010; Strickland et al., 2010).

When instructors are presenting the principles of Organic Chemistry, such as reactions and mechanisms, they expect students to use higher cognitive levels of application and analysis in Bloom's taxonomy, while students are still functioning at a lower cognitive level of knowledge and comprehension, thus focusing on memorization of unrelated facts (Pungente & Badger 2003). This discrepancy between the instructor's expectations and the student's performance becomes particularly evident during exams. Unintentionally, the instructor can teach at a lower cognitive level but examine the students at a higher cognitive level (synthesis and analysis), while students expect the exam to remain at a lower cognitive level. After the exam, students complain that the exam was difficult while the instructor concludes that students do not understand the basic concepts (Pungente & Badger 2003, p.780).

Redish, Saul & Steinberg (1998) found similar results on expectations while investigating faculty and student expectations using the Maryland Physics Expectations Survey (MPEX) to examine learning Physics at six different institutions. An expert consensus survey was administered to Physics instructors who were highly concerned about educational issues and were sensitive to students. The responses provided by most experts were defined as favorable. Responses from the survey that disagreed with the experts' responses were defined as unfavorable.

For example, “stresses the understanding of ideas and concepts” was categorized as favorable, while “focuses on memorizing and using formulas” was categorized as unfavorable. Novice responses were compared with those of experts to identify gap expectations. Experts agreed with each other on favorable responses 87% of the time, whereas novice students agreed only 40-60% of the time. Additionally, student expectations of the cognitive, coherence, and independence dimensions tended to decline after one semester of instruction, with all institutions reporting a drop in favorable responses and a rise in unfavorable responses.

Similar studies by Anderson (2009) comparing first-year and third-year graduate students in Organic Chemistry revealed that first-year students primarily focused on achieving goals related to the product, such as earning good grades or producing tangible results in their research. Literature-based assessments helped these students transition beyond their undergraduate mindsets. Third-year students demonstrated continued development, greater utilization of resources within the Chemistry community of practice and enhanced mechanistic problem-solving skills. They were also able to distinguish between passive and active mechanistic analysis.

Previous studies examined graduate students’ expectations regarding the process of solving and developing problem-solving skills in Organic synthesis problems. Bhattacharyya (2004) compared first-year students with third-year graduate students in Organic Chemistry and found that graduate students demonstrated greater proficiency in using heuristics. Their synthetic routes on paper were deeply connected to laboratory processes, and they viewed reactions from a mechanistic standpoint, suggesting that they conceptualized reactions at the molecular level.

Other studies have presented synthesis problems with blank spaces for students to determine the reagents and molecules required to complete reactions. For example, Flynn and Featherstone (2017) investigated student success strategies and common errors in their answers to questions that involved electron- pushing formalism (curved arrows). The study found that students scored significantly higher on the arrow questions (where they had to draw the electron pushing arrows) compared to the product questions (those they had to draw the products given the arrows). The average and median scores were 72% and 86%, respectively, compared to 55% and 50%, respectively, for the product questions.

The use of technology has been shown to increase student learning and interactivity. However, some experts believe that technology has affected students' imagination and reduced their thinking abilities (Raja & Nagasubramani, 2018, p.35). The role of technology in education is fourfold; it is included as a part of the curriculum, as an instructional delivery system, as a means of aiding instruction, and as a tool to enhance the entire learning process. (Raja & Nagasubramani, 2018, p. 34). Research indicates that many students expect to be taught using PowerPoint (Rickman & Grudzinski, 2000; Penciner, 2013). Other studies have found that students prefer PowerPoint because of its organization and attention to sustainability (Butler & Mautz, 1996; Daniels, 1999; Savoy, Proctor, & Salvendy, 2009; Seth, Upadhyaya, Ahmad, & Kumar, 2010).

While it seems clear that there is a connection between students' lack of success in Organic synthesis problems and the differences in expectations between students (novices) and faculty (experts), the literature on this topic remains limited. This study investigated the alignment between faculty and student expectations, the instructional methods instructors used to

teach synthesis, and the methods students employed in their studies to succeed in Organic synthesis by addressing three key questions.

1: What instructional methods do experts employ in teaching Organic synthesis, and how do novices use these and other strategies to support their learning?

2: What values and expectations do novices hold toward success in Organic synthesis?

3: In what ways do the expectations of novices and experts align regarding Organic synthesis?

METHODOLOGY

Participants and Setting

The research was conducted at a large research university (R2) in the southeastern United States. The participants for this research were 17 Organic Chemistry students (novices) and 4 Organic Chemistry faculty members (experts) with extensive classroom teaching experience.

Data Collection

Data collection in this study involved a student survey, questions from a semi-structured interview, and a post-survey question administered at the end of the semester. While students participated in both surveys and interviews, experts were not involved in the survey. Instead, experts' expectations were explored exclusively through semi-structured interviews.

The Student Survey Tool

The survey tool used to assess students' expectations focused on five pedagogical and learning components: technology, learning assessment, learning activities, faculty-student interaction, and instructor timeliness. The survey tool was developed and refined so that it could be customized to suit any instructor's needs (Schmitt et al. 2013).

The survey was administered a few weeks after the semester began. The students were asked to check the items they expected in their Organic Chemistry II course from the categories of technology, learning assessment, and learning activity components. Students also indicated their expectations from the instructor, such as holding office hours or engaging with them during class. In the timeline of action, students specified how quickly they expected their instructor to respond to them, whether through email, posting grades, or returning assignments. They also had to provide the grade they expected from the class at the end of the semester. Finally, students were required to rank the three aspects of instruction that they valued the most in their learning experiences.

The experts were asked about the type of technology they used in teaching Organic synthesis, classroom learning activities they employed, and assessments they used to determine if their students had understood the concepts. The experts were also asked about the prior knowledge they expected the students to have from Organic Chemistry I and II to be successful in solving synthesis problems.

The post-survey consisted of one question that the researcher emailed to the students asking whether their instructor or course met their expectations. Students were instructed to email their responses after their final grades were posted. To assist in analyzing the results, the components of Fink's significant learning framework were used. This framework consists of six components that contribute to significant learning: foundational knowledge, application, integration, the human dimension, caring, and learning how to learn (Fink 2013).

Significant learning occurs when students are engaged in class and invest their efforts in learning. This engagement leads to a significant and lasting change in learning, as well as creating long-term effects such as critical thinking, problem-solving skills, and dynamic learning

experiences (Virtue, Maddox, & Pfaff, 2019). Unlike Bloom's taxonomy of cognitive processes that consists of hierarchical structures from low-to high-order thinking skills, Fink's significant learning taxonomy is not only relational but also interactive. Each component of the framework overlaps with the other to show that each is related to other kinds of learning and achieving one enhances the possibility of achieving the other (Fink, 2013).

This study focused on three components of Finks taxonomy: Learning how to learn, Caring, and Human dimensions. Fink describes "learning how to learn" as a way a student becomes more proficient at exploring a subject and developing skills to be self-directed learners; caring as the ability to develop feelings, values, and interests within a significant learning framework; and human dimensions as learning about oneself and others (self-efficacy, effective interaction with others- collaboration) (Fink, 2013).

RESULTS

In this study, Caring was examined based on students' values (perceptions and expectations of the course and the instructor), and their future career goals (interests). Instructors' expectations of their students were also categorized under the Caring dimension. In this study, expectations were defined as the assumptions students held about their instructor's teaching methods, including assessments, learning activities, use of technology, final grades, classroom collaboration, and the instructor's availability. Data from the survey instrument and semi-structured interviews were analyzed to explore whether the values and expectations of the students (novices) aligned with the expectations of the faculty (experts).

RQ1. What instructional methods do experts employ in teaching Organic synthesis, and how do novices use these and other strategies to support their learning?

Experts

Experts employed diverse methods of instructions to facilitate student learning in Organic synthesis which included learning assessments, learning activities and technology. These methods aligned with Fink's taxonomy of significant learning components which included learning how to learn and human dimensions. For instance, if faculty guided students to recognize which learning strategies were effective, or they mentioned their instructional methods, that was classified as Learning how to learn. For example, "*I tell them flashcard, but with bond-forming reactions, flashcards don't work. You have to think about it. You have to think about the synthetic strategy*." When instructors reflected efforts to encourage student's self-awareness and development, that was categorized as Human dimension. For example, "*I try to make them realize what they're able to do. And I try to tell them, they're powerful. I use this word a lot to them*."

Learning Assessment

Learning assessment ranged from quizzes, exams, in class problem solving and homework. For example, both Dr. Rachel and Dr. David employed quizzes and exams as their main parts of assessment.

> **Dr. Rachel**: I use in-class quizzes and exams. I also use the textbook Connect quizzes (a learning system from McGraw-Hill), and online quizzes. I also ask questions during class discussions, but the only way I can gauge what everyone in the class knows is through a test or quiz.

> **Dr. David**: Apart from exams, I also conduct quizzes or have students solve problems in class at the end of each chapter before starting a new chapter. I provide these problems to them in advance.

Dr. David emphasized on how he grades the exams differently to ensure the students receive credit for partial progress.

> **Dr. David**: I look at their answer to see if they use a series of reactions that would produce the desired product. Then, I determine whether it is an A-level, B-level, or C-level answer. An A-level answer is either correct or closely matches what I have written. The B-level answer has the correct series of intermediates or something close but may use the wrong reaction.

While both Dr. David and Dr. Rachel use tests to assess students' understanding, Dr. David goes a step further by cross-referencing his answers with students' responses when assigning grades. Dr. James tries to design his exams that assess both the foundational knowledge but also high order thinking skills, "*When I create exam, I never want to create an exam where to do well, and by well, I mean getting an A or B on the exam, you have to be able to do synthesis problems perfectly*." Dr. Irene provides homework whereby students can use the points earned on a test as she stated, "*I provide weekly homework worth 10 points, which students later can use to review for exams*." To complete the homework, Dr. Irene expected them to watch videos that she provided as a guide. The strategies employed by the experts combined both assessment of knowledge and process thinking developed through practice using homework which reinforced learning how to learn.

Learning Activities

Learning activities integrated group discussions and practice problems which aligned with human dimension in Finks taxonomy of significant learning. When students learn about themselves or others, they can function and interact with others effectively (Fink, 2013, p.36). Most experts attempted to implement this in their classrooms. For example, Dr. David provided students with numerous synthesis questions to practice after each topic. Additionally, he fostered a sense of community by encouraging group discussion, peer support, and active participation, "*I*

try to tell them things like if you answer a question, someone else will answer the next one. I work to create an environment in which no one is afraid to speak."

Like Dr. David, Dr. James fostered collaboration in his classroom by inviting students to talk to their neighbors and work together within a set timeframe. This created an opportunity for peer-to-peer learning as each student had the opportunity to share their insights and strategies. After the finished their discussions Dr. James then brought the entire class together for them to share their thoughts.

> **Dr. James**: I put up the problem on the board and tell the students; I want you to think about it. If you want to talk to your neighbors, that is fine. You can work on it collaboratively, but everybody works on it. We then come together as a group to share our approach.

Dr. James encourages the students to focus on end-of-chapter questions from the textbook and reach out to him whenever they experience any challenge. Similarly, Dr. Rachel incorporated synthesis examples and demonstrations into class to help students connect materials to real-world applications. However, she experienced frustration when it came to class participation, as only the same group of students engaged consistently.

> **Dr. Rachel**: I usually go through a few simple drug examples of a complex synthesis that use reactions they are covering and say, 'This reaction you are learning was used to make this drug.' I also go through examples in class and ask questions, but it is usually the same three or four students who answer me.

While the experts interviewed in this study implemented similar learning activities in the classroom, the interviews did not explore whether these methods effectively translated into student success.

Technology

Technology was another instructional domain employed by the experts. This study focused on technology as an instructional delivery tool, such as learning management systems (Desire2Learn), the use of PowerPoint, and the use of online resources such as videos and websites. When the researcher asked the experts about their use of technology and their perceived usefulness to students, their responses varied. Dr. Rachel expressed skepticism about the effectiveness of videos in teaching synthesis. She believed that students should prioritize working on problems over watching videos, "*I do not use much technology. They like to watch videos, but there is no substitute for physically working on problems or practicing. I do not think they are helpful and tend to rely heavily on them*."

Dr. Rachel emphasized that while students enjoy watching videos, it should not replace active problem-solving. Dr. James also noted the limitations of videos, arguing that they fail to engage students in active problem solving and are often viewed as mere entertainment despite the abundance of synthesis videos available online.

> **Dr. James**: I haven't found any technology that I think is useful. I know that there are all kinds of videos out there, most of which I do not think are particularly helpful in part because I find in talking to students, especially the better students, they tend to agree with me that watching videos is very passive and they treat it almost as if it is watching their favorite TV show, which means they are watching it for the entertainment value. They're not engaged in the activity.

In contrast, Dr. Irene incorporated technology into her teaching using her iPad to write and record content, which she shared with her students. She posts PowerPoints online for students to print and use notes during class discussions, "*I use the iPad, which I connect to Zoom, and use it for recording. This is much better than when using a board. I also posted PowerPoints online for students to print and bring to class*."

Dr. Irene records an overview of the chapter on her iPad, where she discusses the major concepts and solves some problems. She encourages the students to watch those videos and do further readings. While she is unsure if these videos are helpful, she believes that they provide valuable resources for review and collaborative learning during weekly group sessions.

Dr. David also uses an iPad to work out problems and sends videos to the students, which he believes helps them to understand the tasks conceptually. He emphasized that the importance of visualizing reactions in real time helps students overcome challenges when drawing mechanisms. When students attend office hours seeking help, he advises them to watch specific videos that relate to the challenge they are having as he stated, "*I use an iPad. I erase things and redraw them, so that they can see them. I send videos to them sometimes. This helps them to see reactions occurring in real time*."

Novices

The novices (students) in this study entered the class with preconceived expectations about the teaching methods they expected faculty would implement. Novices adopted some of the strategies employed by experts in their personal learning processes demonstrating learning how to learn. While many students relied heavily on rote memorization to pass Organic synthesis, the findings indicated that some students had adopted alternative study methods to better understand synthesis conceptually as Anaya stated, "*I think what I have found helpful is collaborating with a friend. She does Organic synthesis well, and I was bad at first, but studying with a friend has been helpful*." The figure below reflects the methods novices valued as effective in learning Organic synthesis.

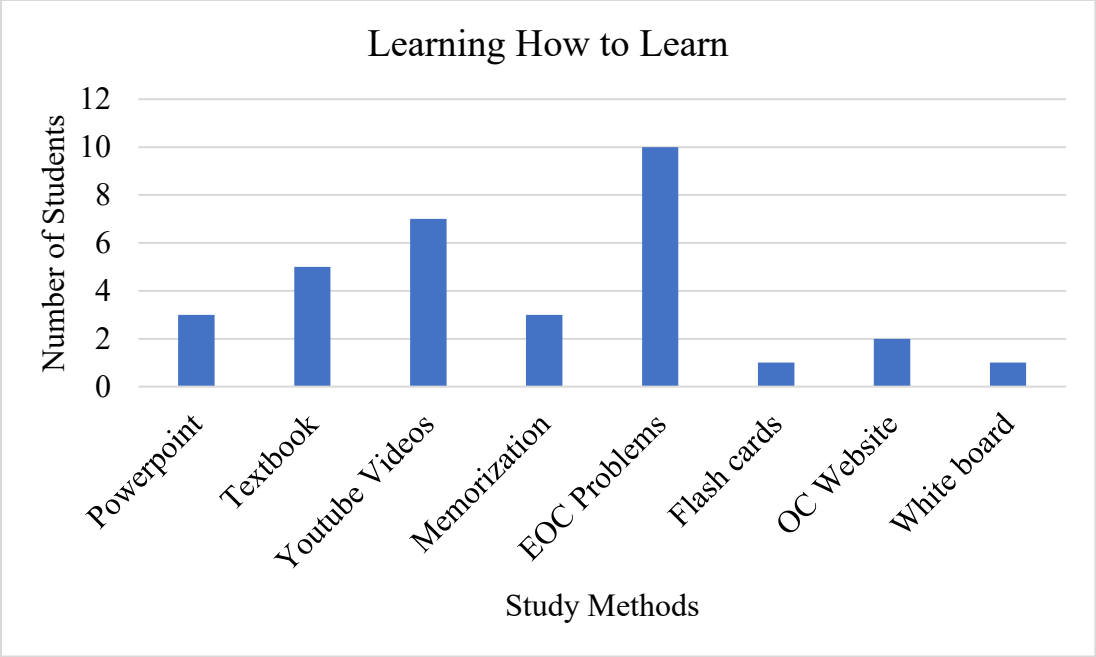

Figure 4.1. Study method used by novices for learning Organic synthesis.

Most students reported using end-of-chapter (EOC) problems as a primary resource for reviewing materials. As previously mentioned, instructors often assigned EOC problems as additional practice. YouTube videos emerged as the second most popular resource among students. These videos featured physical models of molecules in motion, which helped students visualize molecular interactions, as well as Organic Chemistry tutors demonstrating synthesis problem-solving techniques that students could later apply in their practice. Resources such as flashcards, whiteboards, PowerPoints, textbooks and Organic Chemistry (OC) websites were the least used by most students.

RQ2. What values and expectations do novices hold toward success in Organic synthesis?

The question corresponded to caring and part of the human dimension of Fink's taxonomy of significant learning revealing novices values and self-perceptions. To address the question, the study focused on technology, learning assessment and learning activities.

Technology

The results of this study aligned with previous research as students not only thought their instructors would use PowerPoint presentations (expectation) but also, they identified it as the method they wanted their instructors to use (value) for instructional delivery as demonstrated in Figure 4.2 below.

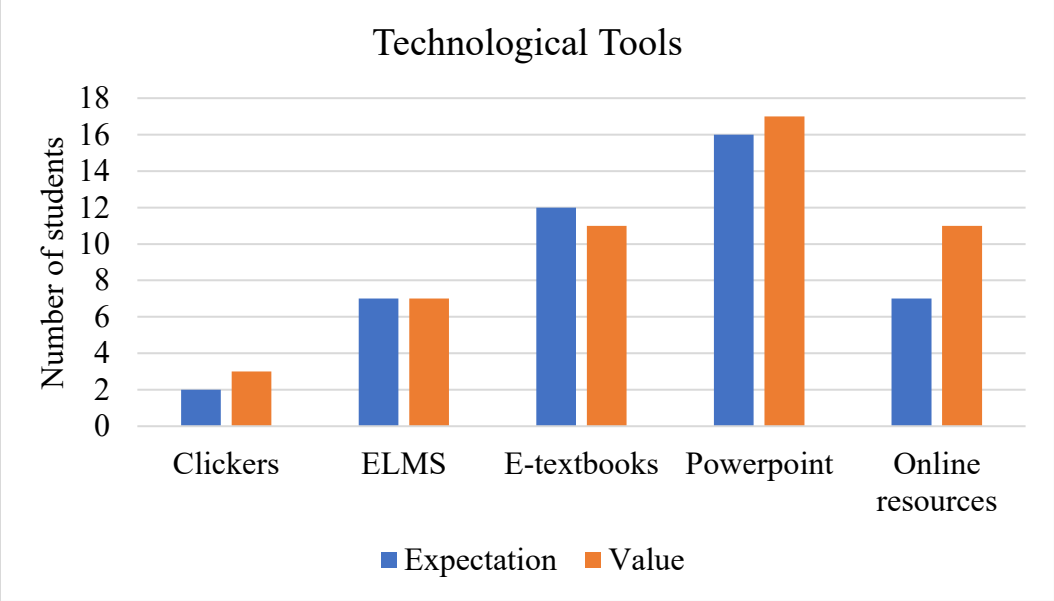

Figure 4.2. Novice value and expectations in the use of technology in the classroom.

For example, Doris expressed that the use of PowerPoint in her class was beneficial to her learning. She acknowledged the instructor's method as valuable but noted that there were limitations on how synthesis was taught. "*the methods used by the instructor are helpful, although some classroom examples are not useful. He will do them on his iPad on the board, but that is all as far as teaching synthesis*."

Some novices felt that the PowerPoint slides prepared by the instructor required more clarity to help them understand. For example, Liz stated that, "*I feel like his PowerPoint could be clearer and easier to understand. I feel like they are a little bit messy for my taste personally*."

Although novices selected the use of PowerPoint as the main method of instruction, they articulated a desire for an instructional method that guided their understanding of problem-solving process as stated by Doris.

> **Doris**: Sometimes one thing that he goes over in class is different from what you see on the exam. I do not know the process to follow because I learned it in a certain way. That is how I feel. I am not looking for simple problems. I just want to understand the process.

Similarly, Anaya valued clarity, "*I think the expectation for me is an instructor who engages the students and explains the material in a way that is easier to understand*."

In addition to the use of PowerPoint, novices believed that other technological tools such as online resources (videos, websites) and e-textbooks could serve as valuable resources for understanding synthesis. However, most novices expressed low expectations of using clickers as a technological tool to enhance their learning. An equal number of novices valued and expected their instructors to use an Enterprise Learning Management System (ELMS) such as Canvas, Blackboard, or Desire2Learn (D2L) to support their learning.

Learning Assessments

Nearly all the students surveyed in this study expected the instructor to assign homework in class. Although novices were not specific on the type of homework, experts assigned the end of chapter questions as described earlier by some experts and demonstrated by the figure 4.3.

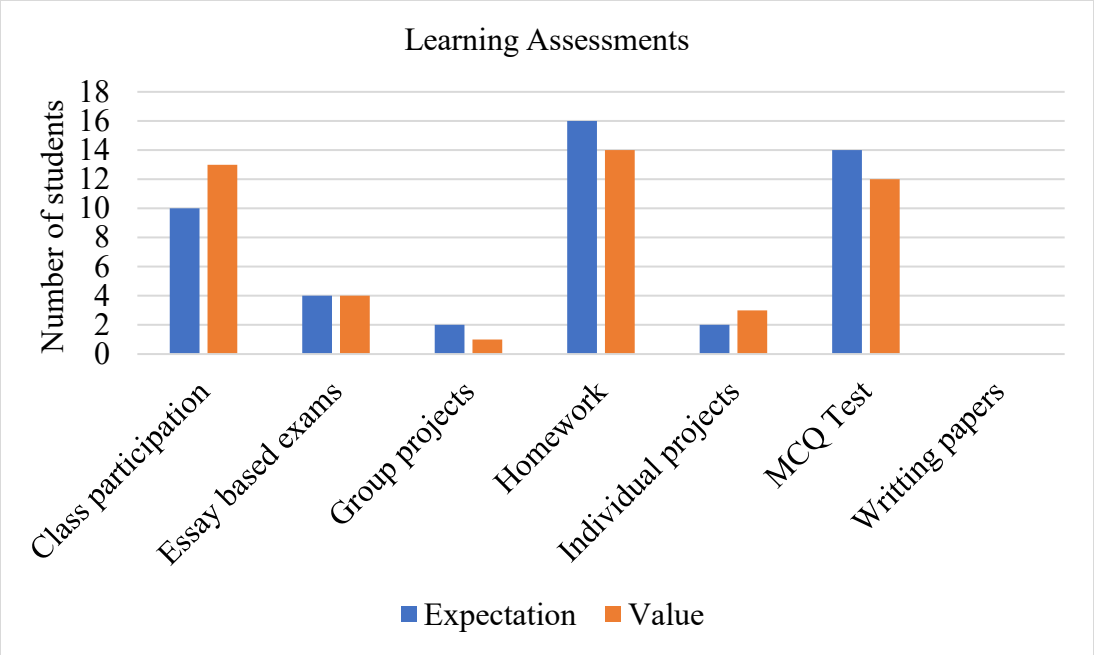

Figure 4.3. Novices value and expectations on the use of diverse types of assessment.

Most students expected the instructor to use multiple-choice question (MCQ) tests, and the difference between those who expected and those who valued this format was insignificant, as shown in Figure 4.3. Multiple-choice questions are rarely used in Organic synthesis, as instructors require students to design a sequence of reactions in which they combine molecules to produce a specific complex molecule (Flynn, 2014). The difference between students who valued and those who expected their instructor to offer class participation points was insignificant. Few students expected or valued essay-based exams, group projects, or individual projects to improve their grades. Interestingly, no students selected writing research papers as either a preferred or expected method of assessment as shown in Figure 4.3 above.

Learning Activities

Novices valued classroom participations, collaborative problem solving and review sessions as Sophie pointed out.

> **Sophie**: I believe weekly reviews of common reactions and synthesis problems will be really helpful. And just in general, slowing down in Organic Chemistry, because it's really not beneficial to the student and the department if half of this class is failing.

The figure below illustrates other preferences valued and expected by the novices.

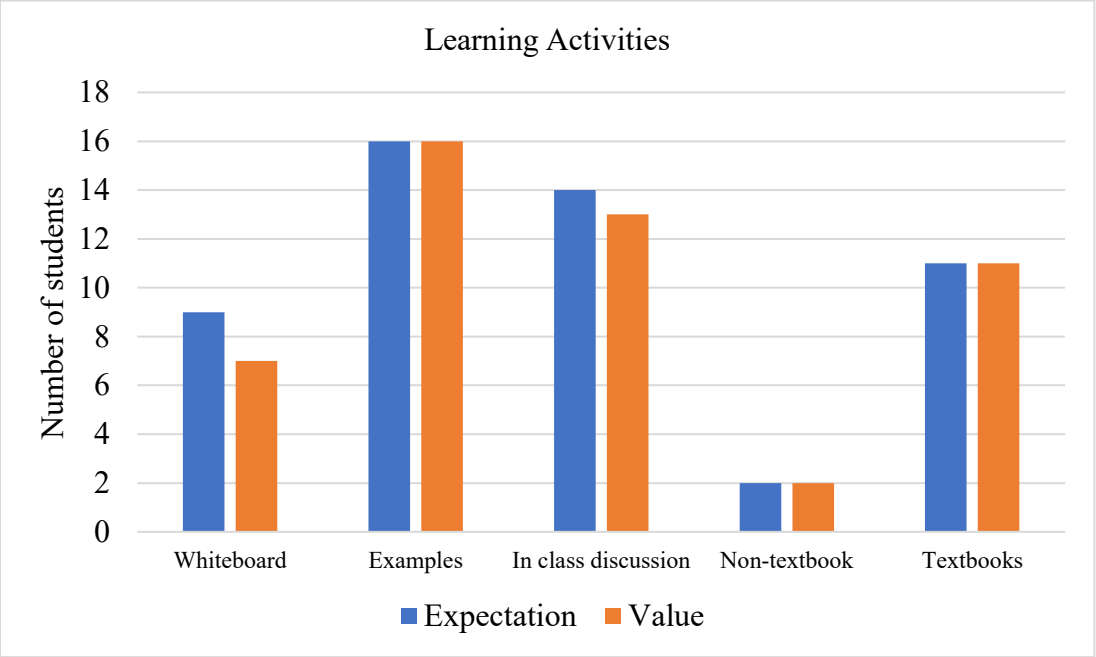

Figure 4.4. Novice's expectations and values of different learning activities in the classroom.

The figure above (figure 4.4) shows that novices placed strong value on examples, class discussions and textbook usage during instructions as stated by Doris, "*our instructor usually provides examples that he pulls from the book or some he has created on his own*." While some novices valued the use of examples to demonstrate concepts in Organic synthesis, others, such as Amelia, found them less helpful, "*I like the examples, and I like that he walks through them. However, I do wish that there were more of them*."

Few novices anticipated and valued the use of non-text readings such as journal articles as well as the use of whiteboards. Despite this, their caring in the subject may have depended on how closely they connected Organic synthesis into their future careers as seen below.

Future Interests

All the novices interviewed in this study explained why they were taking what they perceived as an incredibly challenging course. For most novices, Organic Chemistry II was a prerequisite for their majors. Figure 4.5 illustrates future career interests.

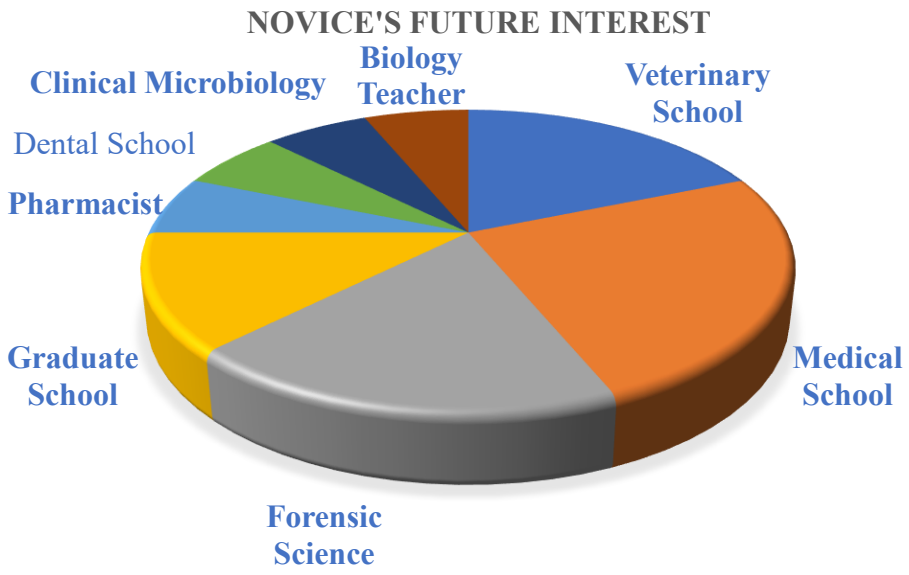

Figure 4.5. Future Interest among Novices.

Most novices were interested in pursuing fields, such as forensic science, medical schools, or veterinary schools. Despite the course being a requirement, many novices expressed doubts about the relevance of Organic synthesis to their future careers. Doris narrated this sentiment, "*I am planning to go to med school to become an orthopedic doctor and so Organic is required for like 90% of the med schools I want to go to. However, I am not going to use this at all, and here I am taking it*."

Seven out of 17 novices shared common perspectives, questioning the practical values of synthesis for their intended careers. Two novices indicated that they were undecided whether to attend graduate school or explore other fields, as illustrated in Figure 4.5. Although this study did not specifically investigate the correlation between the perceived relevance of Organic synthesis and the effort students were willing to invest in understanding the material, one participant's response stood out. Sophie described her frustration with the course and how advice from relatives in medical school influenced her perspective. She felt reassured that Organic synthesis knowledge would not be critical to her success in medical school.

> **Sophie**: I just need to try and obtain a grade of C. The MCAT has only 3-5% Organic Chemistry, so I will be fine. I should not stress about anyone in the medical school asking me to synthesize something. That will not happen.

These sentiments reflect a common perspective among novices, who often viewed the course as a necessary hurdle for their career aspirations rather than a subject with relevance to their future disciplines. They did not see any skills that would be transferable from Organic synthesis to their future career. Furthermore, grade expectations revealed a dissonance between what novices anticipated and what they achieved at the end of the semester as indicated below.

Grades

Most novices anticipated receiving a C grade or higher with only one student selecting a D as their expected final grade as seen in Figure 4.6. Two novices did not select their expected grade, so Figure 4.6 presents the grades of 15 out of 17 novices.

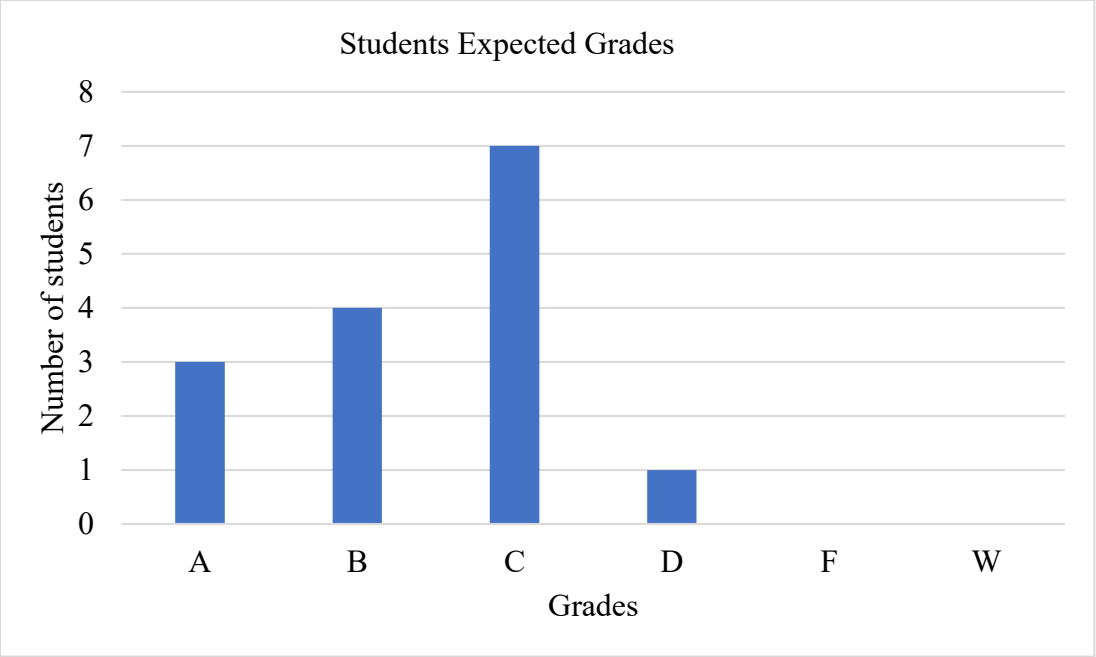

Figure 4.6. The novice expected grades at the end of the semester.

At the end of the semester, the expected grades were compared with the actual grades that the students achieved in the class. The actual grades of two students (who received D and C) were excluded from the analysis in Figure 4.7 below because they did not provide their expected grades at the beginning of the semester.

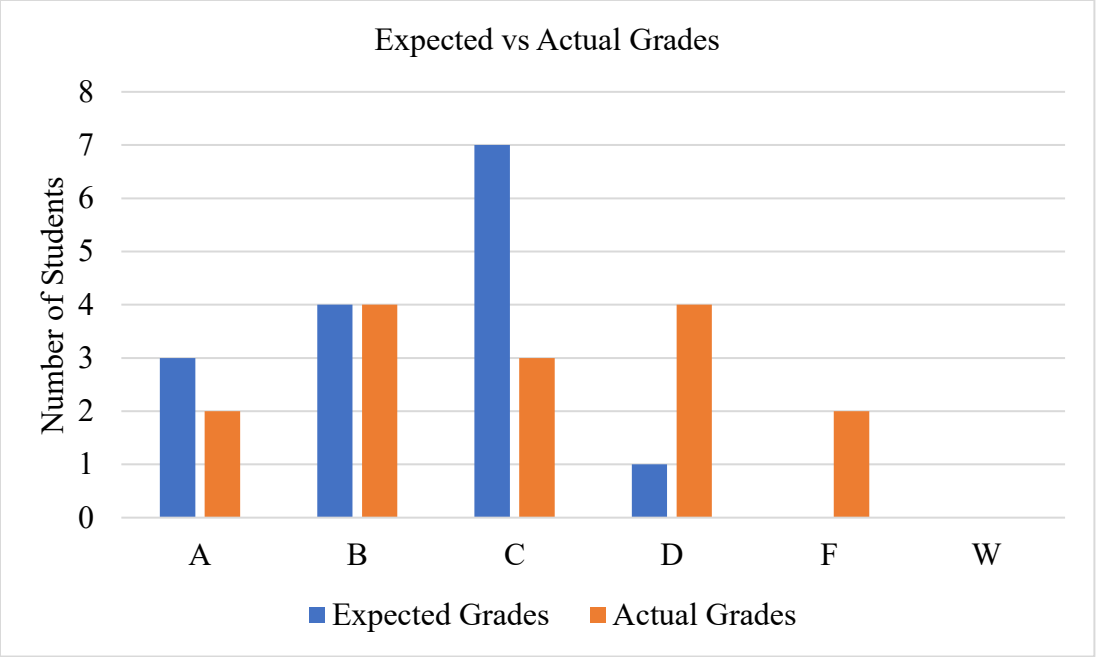

Figure 4.7. Novices' expected grades and actual final grades at the end of the semester.

As shown in Figure 4.7, there was a decline in the number of actual grades for all categories except for grade B. Notably, one of the students who expected a grade of B received a D and another student who anticipated an A received a B at the end of the semester. This explains why the number of students in Category B remains unchanged in Figure 4.7. Most students who expected to earn a grade of C either maintained that grade or dropped to D or F by the end of the semester. Furthermore, the students who received actual grades ranging from D and F frequently expressed having major challenges with Organic synthesis during their interviews. None of the students who participated in the interviews expected to withdraw from the course.

RQ 3. In what ways do the expectations of novices and experts align regarding Organic synthesis?

This question addressed Learning how to learn, Caring, and Human dimensions while interconnecting with other components of Fink's taxonomy such as Foundation knowledge, Integration and Application. Experts expected novices to have a mastery of foundational knowledge and be able to apply it in their learning process as can be seen in the Figure 4.8 below.

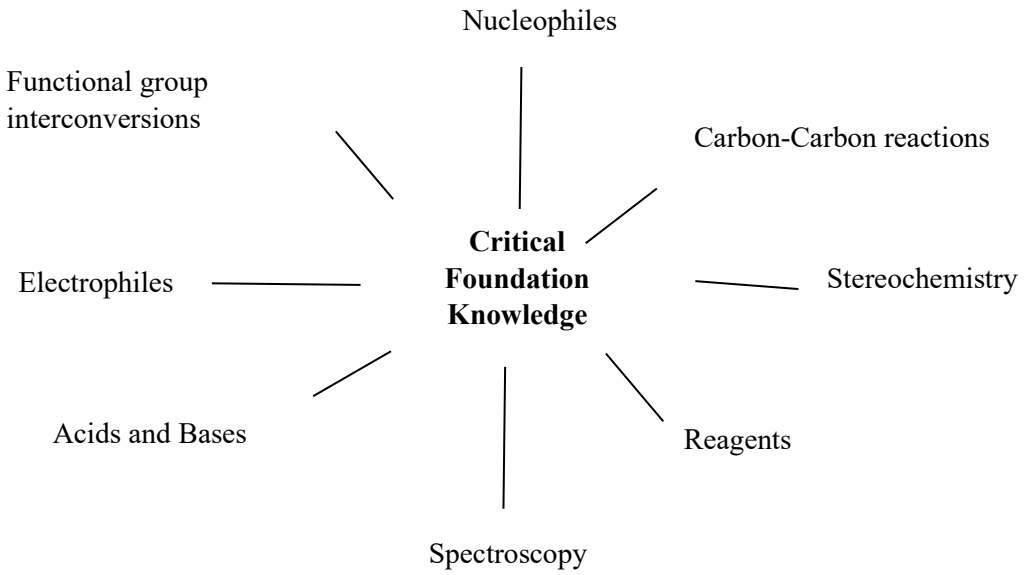

Figure 4.8: Experts knowledge expectations among novices.

Dr. David emphasized the necessity of retaining and applying foundational knowledge from Organic Chemistry I.

> **Dr. David**: Organic I talks about alcohols and alkenes, so I expect them to be able to do this. It is tough; they need to remember everything. Coming into Organic II, they should know functional group interconversions, reagents, and the basic carbon-carbon bond-forming reactions.

Dr. Rachel shared similar expectations highlighting the fundamental concepts and techniques the students need to be successful in Organic synthesis," *I always tell them; they must know*

everything from Organic I. They need to know the fundamentals, stereochemistry, spectroscopy, and all that."

Dr. Irene emphasized the significance of the mechanisms involved in understanding the synthesis. She noted that success involves a balance between memorization and conceptual understanding. She underscored the importance of practicing problems and thinking critically about reactions to reduce reliance on rote memorization.

> **Dr. Irene**: I would expect them to learn reactions. Part of this is memorization, but a lot of it is just practice and figuring out how to do it. They need to think deeply about reactions so that they do not have to memorize as much. That is why I spend more time on mechanism.

Similarly, novices shared their views on the knowledge the expected to have attained in Organic Chemistry I and II before approaching Organic synthesis as shown in the Figure 4.9 below.

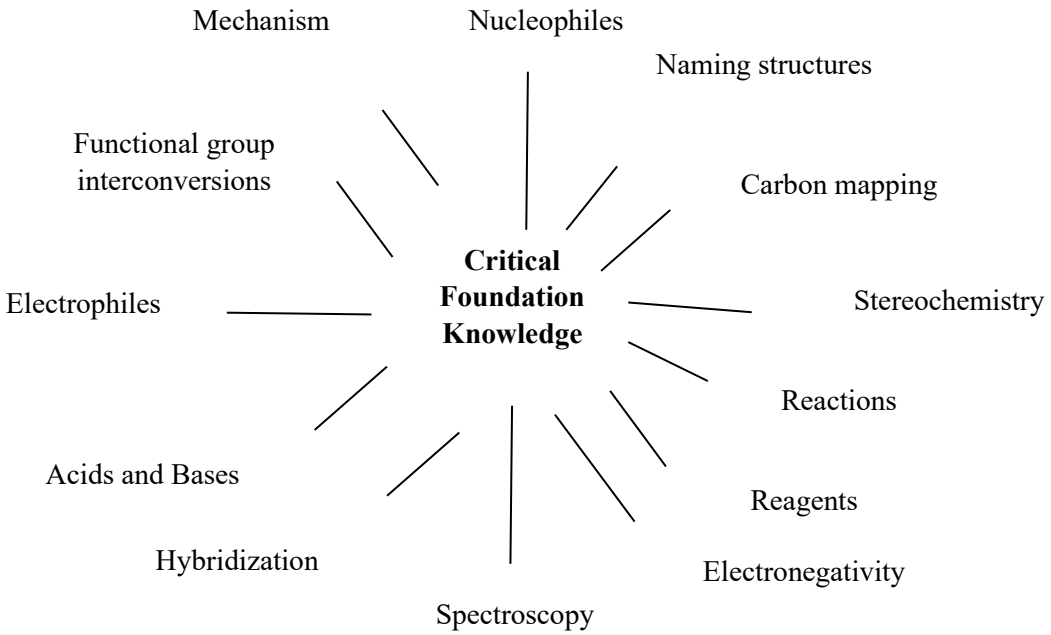

Figure 4.9. Novices prior knowledge expectations for success in Organic synthesis.

There were some similarities between the experts and novices on the type of foundation knowledge that was required to be successful in Organic synthesis as seen in Figure 4.8 And 4. 9 above.

Post Survey

At the end of the semester, all novices received a survey via email asking whether the course or the instructor met their expectations. The novices were asked to explain which expectations were met or unmet. Out of the 17 novices, only 4 novices responded to the post survey question (3 out of 4 novices gave a positive response). Debbi and George were optimistic about earning A's at the beginning of the semester, and their final grades matched their expectations.

> **Debbi**: The course met my expectations. Having access to PowerPoint used in the lecture was extremely helpful, and my instructor also left his notes on the slides to highlight key details. Additionally, the emails that I sent to my instructor were mostly responded to within two days, which helped me to stay on track.
>
> **George**: The instructor met every single one of my expectations. He provided lectures, and in-class worked out problems with time for students to solve the problems themselves. He gave beneficial homework that mimicked the exam questions from the textbook. He had a very expansive amount of office hours, and this was the most helpful thing he provided for us as students.

Both George and Debbi expressed that their class expectations were met. Liz also shared that her learning experience in Organic synthesis met her expectations, even though her final grade did not change, "*My expectations were met. I received a general understanding of Organic Chemistry. The homework was helpful, and he posted extra videos at the end that were also helpful*." Although Megan's grade expectations were met, she valued a more collaborative and interactive classroom experience, "*I expected more from the class itself, like discussions with groups and other types of work, apart from exams and homework*." Megan's value for more collaborative work and interactive learning opportunities in the classroom aligned with most

novices. This revealed a gap in caring and human dimensions in Fink's taxonomy of significant learning.

Based on the results of experts and novices, it is clear that there is a need to integrate multiple dimensions of learning to create a transformative education experience. Based on the results of experts and novices, it is clear that there is a need to integrate multiple dimensions of learning to create a transformative education experience. Instructors can begin their lessons with authentic real world synthesis problems that connect directly to students' societal needs and career goals promoting both integration and human dimension. Expert reasoning can also be scaffolded through think-aloud demonstrations and strategy comparisons, helping students learn how to learn. Additionally, use of structured peer collaboration can help build relationships and diverse perspectives, while reflective activities can encourage metacognitive growth.

DISCUSSION

The findings from the study suggest that experts tried to employ diverse instructional strategies which aligned with significant learning dimensions. However, the translation of these methods to the novice's learning behaviors were partial. Experts emphasized novices' mastery of foundation knowledge in Organic I and II, integration and application of that in Organic synthesis while most of the novices gravitated towards surface learning strategies such as watching YouTube videos and rote memorization. This demonstrated a misalignment from the novices since they already knew the knowledge they were expected to have to be successful.

The human dimension gap was evident from the results as novices did not see themselves as problem solvers but rather as students navigating through a difficult requirement. Novices focused more on grades and immediate requirements rather than long-term learning. This would indicate the absence of significant learning, since significant learning requires there to be some

kind of lasting change that is important to learners' life (Fink 2013). The perception from novices on the irrelevancy of Organic synthesis to their future interest could also have undermined their motivation and caring influencing their engagement in mastering the subject.

Although the survey results showed that most students expected and valued the use of PowerPoint/lecture as the primary instructional delivery method, Figure 4.1 shows that PowerPoint and lectures were among the least used resources for individual studies. Several novices emphasized their preference and expectation for increased classroom participation and collaborative problem solving aligned with learning how to learn and human dimensions. Novices wanted to play an active role in the learning process rather than remain passive as Jackie pointed out, "*I expect more in-class problems and more in-class participation. I mean it is hard when it is just like a straight lecture rather than just focusing on certain synthesis problems together*."

CONCLUSIONS

The study explored the differences between the experts (faculty) and the novices (students) in teaching and learning strategies, values and expectations related to Organic synthesis. Experts used various instructional methods such as quizzes, exams, in-class problem solving, lecture/PowerPoint and discussion to aid in building students problem solving skills reflecting on human dimensions and learning how to learn. Some of the novices adopted the strategies highlighted by experts such as practicing EOC (end of chapter) question or peer collaboration while others relied heavily on online resources such as videos.

It is clear from the study that novices valued clarity in instructions, more classroom collaborations and use of examples even though they expected use of PowerPoint/lecture as the main mode of instruction. Additionally, most of the novices expected a moderate grade of C.

Unfortunately, most of them ended up performing lower than they expected indicating a gap in human dimension. Additionally, most of the novices expected a moderate grade of C; however, many ultimately performed lower than they had anticipated. In relation to human dimension, this gap between expectation and outcome can challenge the novices self-perception as capable learners, potentially leading to feelings of diminished confidence. It can also influence how students see themselves in relation to the subject matter, shaping their future engagement with Organic Chemistry.

Although the study did not establish a clear correlation between novices' future interests and their performance or grades, there was a disconnect in caring as many novices questioned the relevancy of Organic synthesis. These perceptions likely influenced their engagement and priorities in the course, as some viewed it as a requirement rather than a discipline that was directly applicable to their future goals. While experts emphasized the mastery of foundational knowledge, conceptual understanding and practice, novices expressed frustrations with lack of enough interactive and engagement learning experiences.

The misalignment between experts expectations and novices experiences in this study reflects a need for instructional approaches that foster deep learning, that goes beyond cognitive components (foundation knowledge, application and integration). Moreover, there must be a clear connection between Organic synthesis and students future goals. Instructors can achieve this by intentionally incorporating elements of the Human Dimension and Learning How to Learn into their teaching. This includes linking Organic synthesis skills to students’ personal and professional goals, fostering collaborative problem-solving that builds relationships and mutual support, and guiding students to reflect on their strategies in order to develop metacognitive awareness.

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CHAPTER V

CONCLUSION

In summary, this study extends beyond the traditional focus on novices' cognitive skills by integrating expert perspectives and applying all six components of Fink's significant learning framework. By examining both cognitive (foundational knowledge, application, integration) and non-cognitive (human dimension, caring, learning how to learn) domains, the research provides a more comprehensive understanding of the factors that shapes success in Organic synthesis. This holistic approach not only identifies gaps between student and instructor perspectives but also provides a targeted insights for instructional improvement.

As previously noted, students enter the learning environment with prior knowledge embedded in their cognitive schemata. The classroom context plays a vital role in determining which of these existing cognitive structures are activated and how they are used to interpret new experiences, and which memories are drawn to construct meaning from those constructive experiences (Osborne & Wittrock 1983).

In the assimilation process, the learner can determine whether the schemata can provide adequate information to explain the experience or not. This occurs in working memory (WM) which acts as a space where the new and recalled information interacts and is sequenced for response either for learning, solving problems, or storage (Johnstone, 1993; Kempa, 1991). Since WM capacity is limited, most people can hold 7+/- 2 chunks. These chunks of information are controlled by prior knowledge, experiences, and acquired skills (Johnstone and EL-Banna, 1986).

The storage process is more efficient when new information is linked to something (prior knowledge) already in long term memory (LTM). Although LTM has an infinite capacity to hold information, the retrieval system is not always efficient. This could be seen from many novices who mentioned that they could not remember the reagents nor the strategies they needed to successfully solve the task. This can be attributed to a lack of conceptual knowledge in Organic synthesis. The static knowledge or conceptual knowledge in LTM is characterized by what people can report. According to research, there is a direct connection between cognitive structure (LTM structure) and problem-solving difficulties (Kempa, 1991; Kempa and Nicholls, 1983). These difficulties can be attributed to:

Absence of knowledge from students' memory structure.

Novices who lacked static/ conceptual knowledge (facts, principles) struggled heavily while solving the tasks. For example, in task I, novices were required to know beforehand that protecting the ketone before reducing the ester was essential. Ketone is more reactive than ester. A stronger reducing agent lithium aluminum hydride is required to reduce the ester while protecting the ketone. If the ester was reduced without protecting the ketone, then both the ester and the ketone would be reduced, and the target molecule would not be formed. Novices who lacked strategic knowledge struggled to determine the strategies they needed to form the target molecule.

In task II, quite a few novices struggled with the concept of Regiochemistry. They did not understand why the nitro group should not be added first before other functional groups. Out of 17 novices interviewed in this research, 12 of them demonstrated a lack of conceptual knowledge in Regiochemistry. Some of the novices once prompted by the interviewer mentioned that the

order in which functional groups should be added was important, but they could not figure out how or why it should be considered.

Jane demonstrated a lack of knowledge in memory structure to solve both tasks I and II. Even though she was able to determine the functional groups and circle them, she could not recall their names, "*I don't remember the reagent, and I don't think it's necessary to think about the reactions, but I would probably consider the functional groups*."

Like Jane (figure 11 and 15, Appendix C), there were at least 7 other novices who could not solve tasks beyond determining the functional groups. Based on the results, most novices were able to determine correct reagents, and reactions which demonstrated that they had an idea on how to solve the task. However, they found themselves in a state of disequilibrium as they could not adequately explain the strategies needed to form the target molecule.

Incoherent concepts integration.

According to Appleton (1989) some learners develop a strategy of waiting for correct information to be provided either by a book, instructor, or any other authority and then try to learn the information through rote memorization. Since the information is recalled similarly in the context it was provided, it may not be accessible in other contexts. This can lead the learner to quit the learning processor and memorize information just enough to pass the test. Most of the novices who were unsuccessful in solving the task mentioned that they could not recall the reagents involved and thus they stopped putting in the effort.

The inappropriate linkage of knowledge was observed when some novices mentioned that they knew the reagents from certain chapters in the book or had seen it in classroom instructions. However, when they wrote down the reagents, they were incorrect. For example, in task I, Doris (figure 12) did not protect the ketone while performing the task. She used potassium

t-butoxide (KOt-Bu) to remove the oxygen double bond from the ester group. When asked by the researcher her purpose of using the bulky base, her reason was that she could not remember but she had seen it used in class by her instructor, "*I can't remember, but the professor had used this reagent, and it had something to do with the double bond to the oxygen, and I felt like it had removed it*."

Similarly, in task II, Doris tried to make connections with what she had seen the instructor do in class despite using the wrong reagents and not understanding the order in which the functional groups should be added, "*I'm not sure about any of it, I guess the carbon chain is coming off. I know I've seen reagents that he has put that have been like this. But as far as how to get that I would not know*."

Like Doris, other novices tried to connect the information on the task with what they had seen in chapters 17 and 20 of their organic chemistry textbooks. The reagents and reactions they proposed were inappropriate and could not help them solve the tasks.

Expert-Novice Expectations

Technology (online resources)

Despite technology being used as a tool widely to drive the learning process, most of the experts did not invest heavily in it to teach synthesis. One of the tools that some of the experts used was an iPad which they would write on and project it on the board for students to see. However, there seemed to be no difference with the experts who wrote directly on the board. The use of outside resources such as videos and websites was not something most of the experts recommended the novices to do. Additionally, it was not something they mostly implemented in their classroom. One of the experts mentioned that during the pandemic, she usually recorded videos on the chapters she was teaching so that novices would watch them and solve some

synthesis problems. Unfortunately, she didn't think the videos were helpful to the students after the pandemic was over but still encouraged them to watch.

> **Dr. Irene**: I have recorded all the videos of what I've been doing. I don't know if it's helpful or not, but I recorded what I call an overview for every chapter. Now that they are back in class, I find the videos not as effective as they used to be before and during the pandemic.

Dr. David, on the other hand, ensured that the students watched videos that he shared with them. If they came to the office to ask a question, he would request them to watch a video that pertained to the problem they had a challenge with before showing them how to solve it. Although other experts did not discourage the students from watching videos, they did not think they helped the students to be engaged, nor did they offer a substitution for solving the problem themselves.

As already mentioned in Figure 4.1, chapter 4, novices expected instructors to incorporate online resources such as videos, websites or electronic textbooks while teaching organic synthesis. In addition, they felt that online resources were beneficial as they helped them understand synthesis. At least 9 novices mentioned that they used videos from YouTube or master Organic chemistry website as a study tool to help them understand the concept of organic synthesis. Novices who used videos as a study method mentioned that watching the models in the videos helped them to see the shifting of the molecules and why they were moving in certain orientations instead of just demonstrating them through drawing. However, it was unclear if these videos made them better at solving organic synthesis problems.

Instructional Methods and Collaboration

Based on the results of expectations among experts and novices, experts are more focused on what the novices need to learn. Novices on the other hand were focused on how the experts taught the concepts. Novices who were successful in solving the task used similar methods to

those of the experts. However, those who could not solve the tasks struggled heavily on how and where to begin. Additionally, some novices understood the prior knowledge they needed from organic chemistry I and II to be successful, but application of that knowledge was a challenge.

The results indicated that all the experts interviewed in this research had been using similar methods of instruction "PowerPoint/lecturing" whether writing on iPad or directly on the board. Although most novices felt that this mode of instruction was helpful to them, some of the novices felt that experts should go extra further to provide more examples, or reagents lists.

> **Jane**: Maybe if they could provide like most common reagent lists.
>
> **Shona**: I expect examples for sure. Maybe him explaining them in different steps or maybe let us like tell him what we want him to go over other than what he does in PowerPoint.
>
> **Amelia**: I would expect him to maybe like explain a concept of something and then give an example of whatever it is he's wanting us to understand.

In addition to lecturing/PowerPoint, some novices mentioned that they would like more collaboration in class and clear explanations that would help them understand the concepts. For example, Jackie stated that, "*I like to participate. It's kind of hard when it's just like a straight lecture than just us focusing on certain synthesis problems together as a whole*." Anaya expected more classroom engagement, "*I think the expectation for me is an instructor that is engaging the students and explains the material in a way that's easier to understand*." George felt that the classroom environment was very conducive for learning.

> **George**: I can ask questions, and I don't feel like the professor is annoyed, because he really wants people to ask questions. And it's kind of difficult whenever it's just a class where the professor's talking the whole time and like no one talks at all.

Although there is no shortcut for solving the problems, probably incorporating different instructional methods may be beneficial for the students since they are all diverse learners.

Although this was not part of the study, it was interesting to note that most of the students interviewed had no plans to study Organic Chemistry as a field. Some of the novices didn't think it was necessary to learn Organic synthesis as a part of the course since they would not require it in their future studies. However, there were other novices who felt that synthesis would be useful for example Doris stated that, "*I am going to Med school so organic is required like 90% of the med school I want to go to although I just want to be orthopedic*." Although Michael didn't see a deep connection between Organic synthesis and his future goals, he still thought it was essential to learn the material.

> **Michael**: I am in a pre-vet program so I must take all the sciences that a pre-med student would. I don't know how much of the Organic synthesis I am going to need because the career I am going into won't heavily rely on this. But it would still be useful to know this stuff.

To close the gap between low and high performing students, Teichert et al. (2019) proposed that instructors should analyze what students do correctly in terms of algorithmic and conceptual understanding before applying any intervention. For large classes, instructors can use free-response questions or clicker questions and listen to students' use of chemical language while solving the problems. Lastly, Teichert et al (2019) recommended that instructors' focus should be on *why* solving problems is necessary rather than *how* or *what* students' solutions are.

Although instructors often base students' success in chemistry on their ability to solve numerical problems, the challenges become evident when they face problems in which algorithmic procedures are insufficient to solve the problem. They are faced with heavy cognitive demands on their working memory as they try to retrieve the information and make connections for solving problems that require conceptual understanding rather than algorithmic procedures (Niaz, 1995; Persky & Robinson, 2017). They struggle in developing both critical thinking and problem-solving skills, which are essential in organic synthesis (Flynn, 2011).

When teaching, Gulacar et al (2014) suggested that instructors should emphasize to the students that the solutions found in textbooks are not easily acquired as there are various challenges and false starts to hold to account.

Another thing that came out of this research but was not used for analysis was novices' confidence level. 13 out 17 novices mentioned that they were not confident in Organic Chemistry II, especially problem solving in Organic synthesis. However, some of them mentioned that they were confident when they took Organic Chemistry I. Lastly, the number of hours novices spent per week studying Organic synthesis. There was a variation in the number of hours from 2-10 hours per week. However, there was no correlation between their study time and the grades they received. But one thing that was intriguing was among the novices who scored A/B grades. They spent on average 3- 6 hours a week while some of them practiced Organic synthesis on a daily basis. A few days before the test, they spent many hours revising the concepts.

How effectively are students acquiring the knowledge and skills they are expected to learn?

One of the basic problems is that faculty talks about their students achieving a higher kind of learning but continue to use teaching practices that are not effective in promoting that kind of learning (Fink 2013). For example, one of the learning goals most of the faculty mentioned was that they wanted their students to have critical thinking but relied heavily on lecturing. Based on this research, lecturing was one the techniques highly used by the experts interviewed and what the novices expected and valued. However, Fink (2013) mentioned that even a good lecture is limited in its effectives in helping students,

- Retain information after the course is over.
- Develop ability to transfer knowledge.
- Develop skills in thinking or problem solving

- Achieve affective outcomes such as motivation for additional learning.

The results of this study align with Fink's ideology, as many novices, despite having learned the material, struggled to recall the reagents needed for synthetic pathways and apply them to solve the task. Additionally, they were unable to demonstrate the problem-solving skills they had supposedly developed. As a result, most novices relied on rote memorization simply to pass the class, with many indicating that they did not anticipate using Organic synthesis in their future careers.

Given the challenges students face in learning synthesis and the difficulties faculty encounter in teaching it effectively, there is a need to establish a common ground on what truly works. It is essential to identify and create meaningful learning experiences that all stakeholders—students, educators, researchers, and textbook publishers—can recognize as significant in the teaching and learning process.

Implications of the Study

Throughout this research, on the literature review, various findings suggested that for students to be successful in Organic synthesis, they need high order thinking skills. However, it is unclear whether instructors play any role in ensuring that students have these skills. High order thinking skills go beyond basic understanding and memorization, it involves application, analysis, synthesis and evaluation.

Most novices demonstrated foundational knowledge and application by identifying functional groups, recognizing key details, and labeling carbon atoms and hydrogen additions or removals in the target molecule. They also exhibited knowledge integration by connecting concepts learned in class or referencing textbook reactions. However, while many novices effectively applied foundational knowledge to determine functional groups and reagents, they

struggled with higher-order skills such as analysis, synthesis, and evaluation. They also faced difficulties with reaction mechanisms, electron-pushing formalism, and analytical thinking, particularly in identifying bond formation.

Mastering these skills as highlighted was essential for students' success in solving organic synthesis problems. One of the skills students could develop that could help in minimizing overload is cognitive efficiency. Students can develop cognitive efficiency by strengthening their foundational knowledge of reagents, understanding directing effects, reaction pathways, and electron flow to aid in predicting reaction outcomes. Additionally, they can enhance their skills by identifying key patterns in various synthesis reactions and practicing problem solving under time constraints to improve efficiency instead of memorizing the steps.

For example, when students solve synthesis problems, they can simplify the molecules by representing them with an R-group while omitting the complex parts. This approach may help them free working memory allowing them to focus on essential features rather than spending time on unnecessary details. However, this would require them to have a clear understanding of molecules and reactions in Organic synthesis.

According to Strike and Posner (1992), for conceptual change to occur in the mind of the learner, they must first perceive that their existing knowledge is inadequate. In other words, they lack the skills needed to determine the correct reagents or reactions required to solve the synthesis problems. If the learner fails to make the connection between prior knowledge and new knowledge a disequilibrium may occur leading to an exit from the learning process. The instructor will need to re-examine these disequilibrating events among the students and provide accommodation that will enable the learners to cognitively restructure their existing ideas.

Restructuring these cognitive concepts will also help minimize false accommodations, where students depend on rote learning to prepare for exams. Rote learning often results in knowledge that is confined to specific contexts and cannot be readily applied in different scenarios. For example, during interviews, some novices mentioned that the exam questions differed from the examples practiced in class. They expressed a preference for exam questions that closely mirrored those examples. Instructors may need to encourage students and teach them in a way that helps them understand the process and how to apply the knowledge they acquire in different contextual boundaries.

Based on the results of this study, novices highlighted three areas they believed would be essential for anyone planning to learn Organic synthesis. These areas include an understanding of reaction mechanisms, reagents, and functional groups. The first two, mechanism and reagents, were the main challenges for novices while solving these tasks. Most novices did not show mechanisms on how they arrived at their target molecule.

Despite research mentioning different instructional methods to alleviate challenges in Organic synthesis, the challenges are still significant. However, Damon and Phelps' (1989) view on collaborative learning provides an insight into how this method can be useful in Organic synthesis. Collaborative learning is beneficial for tasks requiring "new insights, conceptual shifts, and the development of deep knowledge structure" (Damon & Phelps 1989, p. 40). To encourage conceptual changes in understanding, both instructors and students must go beyond merely participating in group activities and classroom discussions. Instead, they should actively engage with each other to foster deep collaboration and meaningful interaction, ensuring a more effective and impactful learning experience. This will create an opportunity for students to

verbalize their ideas (think aloud) and errors which provide an opportunity for them to modify their concept through accommodations.

For example, most of the skills demonstrated by novices fell under the three components of Fink significant learning: foundational knowledge, application, and integration. As novices refine these skills and continue to develop schemas like experts, they can transition from memorizing facts to recognizing patterns making meaningful connections. This cognitive shift would help them to approach challenges with confidence. Furthermore, questions that appeared difficult or unfamiliar to them may no longer be a problem but an exercise.

One of the implications to change Organic Chemistry course could be for instructors to select a reasonable number of reactions and include them based on their fundamental importance in the biosynthetic mechanism or primary manufacturing methods relevant to the students. If instructors cannot find reactions repeatedly in literature, they should not include them in the course, and the same criterion should apply while teaching mechanisms in class. Goldish argued that instructors should be mindful of whether the mechanisms help students comprehend the reactions and avoid teaching "mechanisms for the sake of mechanism" (Goldish, 1998, p. 603) but use them to help students understand, predict and modify reactions.

By addressing the interconnection of both cognitive and affective/metacognitive dimensions of Fink's significant learning, this research emphasizes the importance of designing instructional strategies that engages the whole learner. This design would involve strengthening conceptual understanding while fostering intrinsic motivation, self-awareness and ability to take ownership of learning.

Study Limitations and Strengths

The study was conducted within a single academic institution. Although students were enrolled from varied demographic backgrounds, they may not fully represent the diversity of students experiences across other institutions. Students in this institution may share a common academic, cultural or socio-economic context that may influence their learning compared to other settings. Each institution has different characteristics such as academic rigor, grading policies, curriculum structure and admission criteria that shapes both students performances and institution practices. Although throughout literature Organic synthesis is a challenge for many students, the findings should be interpreted within the context in which the research was conducted while been cautious in applying them to different environments.

A second limitation was instructional styles. The participating experts used similar mode of instruction which included lecture-based delivery supported by PowerPoint slides, use of iPads, or writing on the board. These methods restricted the study's ability to explore how alternative pedagogical strategies such as active learning, flipped classroom, inquiry-based instruction may influence students success in Organic synthesis. Based on the findings, students expected and valued the use of lecture/PowerPoint as the method of instruction. However, it would be interesting to determine if these preferences would change in an environment where other pedagogical strategies are consistently applied.

Finally, the study sample size was relatively small consisting of 4 Organic Chemistry experts and 17 novices participating in the study. Although the data provided some meaningful insights, the limited number of participants reduces statistical robustness and increases the susceptibility to anomalies.

Despite these limitations, the study portrayed several strengths that enhances its contribution to the field. The use of semi-structured interviews with both faculty and students, alongside survey tool for the students provided a rich qualitative insight on perceptions, challenges and problem solving strategies in Organic synthesis which can be overlooked when using quantitative research. These insights revealed the weaknesses in human dimensions and learning how to learn components of Finks significant learning framework.

As noted earlier, most research focused on comparing and classifying students as successful or unsuccessful based on their ability. However, the inclusion of both experts and novices perspective in this study enabled a direct comparison between the instructor and students experiences offering a clear picture of the misalignment and how instruction approached might be adjusted. Instructional adjustments would foster deeper learning while integrating all the components of Fink's taxonomy, enhance conceptual understanding and align course content with student aspirations. Lastly, the study lays groundwork for future multi-institution research to examine the effects of diverse teaching styles, institution contexts and students demographics on learning outcomes in Organic synthesis.

Future Research

1. Evaluating Online Organic Synthesis Videos: A Comparative Study of Novice and Expert Criteria Using Mayer's Cognitive Theory of Multimedia Learning (CTML).

Throughout the literature review, use of videos was one of the main proposed strategies for learning. In chapter 4, the results indicated that novices valued using online videos during their personal studies while some of the experts felt that the online videos were unhelpful. According to cognitive theory of multimedia learning (CTML), people learn more deeply from words and pictures than from words alone (Mayer 2003, p.55). For meaningful learning to occur in a multimedia learning environment, the learner must engage in these cognitive processes, selecting words and images, organizing words and images and integrating the information with prior knowledge (Mayer 2003). To explore the criteria experts and novices use to assess the effectiveness of Organic synthesis videos, this study will focus on the following research questions.

1. What features do novices and experts identify as helpful or unhelpful in online Organic synthesis videos?
2. How does the evaluation criteria of novices differ from the experts?
3. To what extent do these evaluation criteria between experts and novices align with cognitive theory of multimedia learning principles?

Methodology

Participants and setting

Undergraduate students enrolled in Organic Chemistry II.

Organic Chemistry faculty (experts) with variations in experiences teaching Organic synthesis.

Data Collection and Analysis

Semi-structured interviews.

Two Organic multistep synthesis problems and 4 online videos (2 videos with different design and variation for each task). Additionally, participants will analyze the video using the 12 principles of CTML. Transcription of the semi-structured interviews and deductive coding based on CTML principles.

2. Exploring Faculty- Student Expectation Alignment in Organic Synthesis Across Institutional Contexts and Teaching Styles.

Faculty- student expectations, instructional methods and proposed learning strategies in literature review were based on a particular institution. There were no comparison on how the expectations of faculty, and the students would vary when compared to different institutions. My research focused on one institution and same instructional method. Future research would focus on how faculty student alignment would vary based on different teaching styles, institutional structure and student demographics. Examples of teaching styles would be lecture-based, inquiry based, flipped classroom. Institutional structure would be research-based institutions vs teaching focused, public vs private institutions. While students demographics would relate to first generation, ethnicity and major. The study would be framed using Finks taxonomy of significant learning while focusing on the following research questions.

1. How does faculty-student expectations align or fail to align across different teaching styles.
2. How does institutional structure influence student faculty alignment?
3. What role does student demographics play in faculty student expectations alignment.

Methodology

Mixed method research consisting of both qualitative interviews and quantitative surveys across multiple institutions.

Participants and settings

Students across different institutions and Organic Chemistry faculty with experiences in teaching Organic synthesis.

Data Collection and Analysis.

Faculty student semi-structured interviews and surveys. The interviews will be coded using Finks taxonomy categories for qualitative analysis while for quantitative, descriptive analysis will be used to compare teaching styles or institutions.

3. Understanding How Confidence Level and Science Identity Affect Student Success in Organic Synthesis.

Various criteria were used to classify students as successful or unsuccessful in literature as discussed in chapter 2. However, there was no focus on students confidence level or how it played role in their science development identity. The results of the study demonstrated that majority of students stated they were not confident at all in Organic synthesis. The novices who stated that they were not confident or had a low confidence level struggled in solving the tasks. Future study will focus on student confidence level influence science identity development and success in Organic synthesis problem solving. The study will use Carlone & Johnson's science identity framework (2007) to understand how students see themselves as science people while focusing on the following research questions.

1. What is the relationship between students confidence level and their performance in Organic synthesis.

2. How does student confidence level influence their development of science identity within the context of Organic synthesis.

Methodology

Quantitative study design

Participants and Setting

Undergraduate students enrolled in Organic Chemistry course.

Data Collection and Analysis

The data will be collected using science identity scale and confidence level survey. The students would be given Organic synthesis problems to solve. Correlation and regression analysis would be used to explore the relationship between students identity, confidence level and performance.

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APPENDIX A

Coding system developed by Flynn (2014) and modified for this research.

Code	Description
Identified relevant regiochemical considerations.	Participants describe regiochemical features of the target molecule and synthetic strategies.
Use of reaction mechanism.	Participants show the movement of electrons for some or all their synthetic pathways.
Carbon atoms mapped	Participants label (number, letters) carbon atoms in both the SM and TM
Functional groups identified	Participants label, circle, or point out functional groups in both SM and TM.
Multiple pathways attempted	Participants consider more than one synthetic pathway to solve the task
Identifies H atoms removed or added	Participants point out H atoms present in the SM and not in the TM and vice versa.
Rewrote SM	Starting material redrawn in an orientation different from how it is presented in the task.
Rewrote TM	Target molecule redrawn in an orientation different from how it is presented in the task.
Retrosynthesis analysis	Participants make retrosynthetic disconnects between 2 or more synthesis intermediates or identify key synthetic intermediates.
Pathway rejected	Participants said the pathway wouldn't work.
Simplification of the molecule	Participants use simplifications such as R groups when drawing the molecules.

APPENDIX B

Coding system in Alignment with Finks Dimensions.

Description	Code	Fink Component
Participants point out, label or circle functional group in both SM and TM	Functional group identification	Foundation knowledge
Participants identify the correct/incorrect reagent and explain why they chose that reagent	Reagents identification	Foundation knowledge
Participants make connections with materials in class or other sources	Content recall	Integration
Participant describes regiochemical features of the target molecule and synthetic strategies	Regiochemical consideration	Foundation knowledge
Participants consider more than one synthetic pathway to solve the task	Multiple pathways identified	Application
Participants state, write down or use synthetic strategies for solving the task	Synthetic strategies	Application
Participants show movement of electrons for some or all their synthetic pathways.	Use of reaction mechanism	Application
Participants label (number, letters) carbon atoms in SM or TM	Carbon mapping	Application
Participants make suggestions of general reactions	General reaction specified	Foundation knowledge
Participants solve the task partially	Partial task attempt	Application

APPENDIX C

A Survey Instrument for Assessing Student Expectation.

Component	Questions	Selections
Technology	Which of the following do you expect in this course? (**Put a check mark**) Rank the **three most important** components in this course for your learning.	Clickers Electronic Learning Management Systems E-textbooks Power point/Lecturing Social media (Videos, other websites)
Learning Activities	Which of the following do you expect in this course? (**Put a check mark**). Rank the **three most important** components in this course for your learning.	Chalkboard/whiteboard Demonstrations/Examples In-class discussions Non-textbook readings Small discussion groups Textbooks
Learning Assessments	Which of the following do you expect in this course? (**Put a check mark**) Rank the **three most important** components in this course for your Learning.	Class participation points Essay-based exams Group projects Homework Individual projects Multiple-choice exams Written papers

Faculty student interactions	Which of the following do you expect from the instructor of this course? (**Put a check mark**)	Hold office hours Interact with students in class Be accessible outside office hours Know students' names Others None of the above
Timeless of Action	How soon do you expect your instructor to: (respond to email, post grades, return assignments, be available to meet with you, respond to phone calls)?	Immediately Within 24 hours Within 2 days Within a week Never NA
Grade	Which grade are you expecting to receive in this class (**Put a check mark**)	A B C D F W

APPENDIX D

Interview Protocol

Student Semi structured Interview Questions

The following guiding questions were used for the semi-structured student interviews.

1. How confident do you feel in Organic Chemistry? How do you perceive your abilities in the subject?
2. On average, how much time per week do you spend studying Organic Chemistry outside of class?
3. What study methods have you found most effective for success in organic synthesis?
4. What instructional methods does your instructor use to teach organic synthesis? Briefly explain. Has this method helped you succeed? If not, what instructional method would you prefer, and why?
5. What prior knowledge from Organic Chemistry I and II do you believe is essential for solving organic synthesis problems successfully?
6. How do you anticipate using Organic Chemistry in your future studies or career?
7. Has the course or instructor met your expectations? (Post-Interview)
    a. If so, which expectations were met?
    b. If not, which expectations were not met?

Faculty Interview Questions.

1. What skills do you believe are necessary or expect your students to have to succeed in solving synthesis problems?
2. What is the primary purpose of teaching organic synthesis?
3. What instructional strategies do you use when teaching organic synthesis, and why?
4. Do you incorporate any technology in teaching organic synthesis? If so, which tools do you find helpful?
5. How do you evaluate students' success in organic synthesis?
6. What do you think makes solving organic synthesis problems particularly challenging for students?
7. Is there anything you would like to change or see improved in the way Organic Chemistry is structured, such as in textbooks?

APPENDIX E

Fink Significant Learning Framework