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A Guided Inquiry to the Bromination of Alkenes: An Effort to Foster Student Understanding of Thin Layer Chromatography in the Organic Chemistry Laboratory

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An effort to foster student understanding of Thin Layer Chromatography in the Organic Chemistry Laboratory

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Honors Thesis

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I. Introduction

In this introductory section we explore the motivations of our work and the contributions we are making to the field of chemical education. We present the context in which the laboratory design took place and our aims for the chemistry content knowledge we planned for the students to learn by performing the laboratory experiment.

Motivation

The motivation for this overall study was to create an engaging laboratory experiment for the Organic Chemistry I Laboratory course at Western Michigan University. The laboratory experiments in this course are primarily considered to be expository or "cookbook" labs (Dunlap, 2012). The focus of these labs are to echo the content learned in lecture by having students perform the reactions they find in their chemistry textbook. While the reactions performed are useful in the sense that the products can be produced with reasonable yields and their mechanisms relate to the lecture, the predictability of these reactions makes the labs rather boring for students. It is not uncommon to walk into an organic chemistry laboratory class and find students standing around, disengaged, while they wait for their reaction to complete. Unsurprisingly, the literature reflects this disengagement as labs with the expository format involve minimal critical thinking and challenge for students (Dunlap, 2012). We realized that with a different laboratory format we could make the lab more interesting and thought provoking for the students.

A personal motivation of this project comes from my 4 semesters as a teaching assistant for the general and organic chemistry labs. I have witnessed students finding the laboratory as pointless and tedious. Throughout my coursework in earning my degree, I have also found the mindless repetition of a set of instructions that I know students have been doing for the past 10 years to be discouraging and boring. These experiences have motivated me to seek out more discovery based approaches to teaching chemistry.

This project is also part of a greater effort to bring a sustainable approach to laboratory learning at our university. Performing the same reactions from fifty years ago do not lend these reactions to being environmentally conscious. Due to the sheer volume of students who take organic chemistry laboratories and the solvent and reagent demands, organic chemistry laboratories generate the greatest amount of waste out of any of the laboratories at our university. By creating experiments which utilize green solvents, cut down on waste, and use catalytic means, we hope to remedy our previously wasteful ways. We also wanted to understand student conceptions of chemistry by working to find ways in which students engage in chemical inquiry.

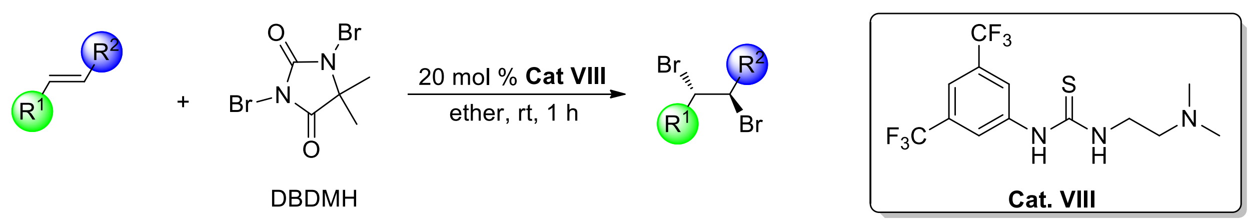
Another motivation of this work was to fill in a gap in the organic chemistry laboratory curriculum. Students perform an expository Thin Layer Chromatography (TLC) experiment at the beginning of the first semester. The technique is not used again until the second semester. The instructors noticed that many students were confused when approaching the technique, the second time and did not know what the results of the analysis meant. The experiment presented here falls toward the end of the first semester of our curriculum and is intended to give students a more in depth experience with Thin Layer Chromatography.

This work presents a new experiment for the organic chemistry laboratory which can be used to engage students in an inquiry experience. The literature in Chapter 2 shows that there are guided inquiry experiments using Thin Layer Chromatography, but that there has been little work done to assess student misconceptions about TLC and how polarity relates to the technique. Our findings contribute to the greater body of work about misconceptions students have and fill a gap in the literature about students' misconceptions as they relate to thin layer chromatography.

Laboratory Design

We designed a guided inquiry experiment for the electrophilic addition of bromine to an alkene forming a vicinal dibromide. This is a reaction that students learn about in the first semester organic chemistry lecture and perform the experiment in lab. Historically, the production of a vicinal dihalide was done by adding the substrate to water and reacting it with Br_2 to form a halohydrin (Hunt, 2012). The reaction was also performed with Br_2 in dichloromethane. While these reactions illustrate the bromination across an alkene well, the Br_2 used is highly toxic and when placed in a chlorinated solvent only increases toxicity. Using HBr and hydrogen peroxide to generate the Br_2 in solution is a less toxic option (Kerr, 2002). However, HBr and peroxide are fairly reactive species and while they are less harmful than Br_2, the use of pyridinium tribromide salt is a safer option (Wigal, n.d.). Currently, our curriculum uses the bromination reaction with the pyridinium tribromide. While this reaction is time efficient and produces a relatively pure product, the reaction and characterization involve minimal cognitive effort by the student.

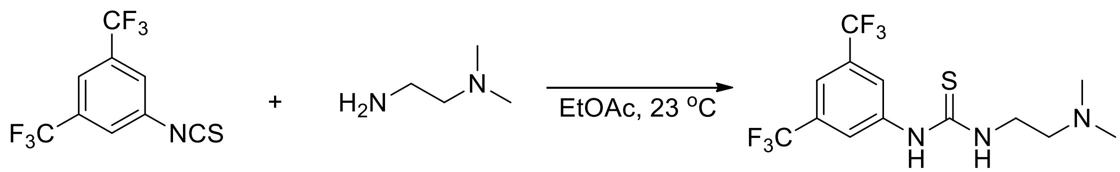
An organocatalytic reaction from the contemporary literature using 1,3-dibromo-5,5-dimethylhydantoin (DBDMH) as a bromine source and a thiourea catalyst gives a great deal of diasteroselectivity for the trans-dibrominated compound (Hernandez-Torres, 2012). This degree of stereoselectivity was lacking in the reaction with the pyridinium tribromide reaction and allows us to expand the reaction to different substrates. The thiourea catalyst can be used at 20 mol % which decreases the reaction waste to less than that produced by the previously used reaction. The reaction conditions for the bromination of an alkene are shown below:



Hernandez-Torres, Tan, & Barbas, 2012.

This afforded us the opportunity to introduce organocatalysis in the introductory laboratory. Additionally, this offered the chance to create greater continuity in the introductory chemistry curriculum by reestablishing the concept of a catalyst. Students are introduced to this concept in the general chemistry courses when they learn about reaction kinetics but frequently do not encounter the concept in the laboratory. An organocatalytic reaction is a way to show students contemporary methods of performing the reactions which they have seen in the lecture. Currently, asymmetric organocatalysis is a synthetic technique that has been gaining traction in total synthesis over the past several decades as new small molecule catalysts are developed (Hernandez-Torres, 2012). Among the most common types

of catalysts are acid-base catalysts, hydrogen bonding catalysts and organometallic catalysts. In this lab we make use of a bifunctional hydrogen bonding catalyst. These catalysts have various applications in total synthesis, particularly in the development of natural products as molecular scaffolds become more and more complex (Marqués-López, Herrera, & Christmann, 2010). The use of a hydrogen bonding catalyst in the sophomore organic lab is appropriate as many are easily synthesized and can be used under standard conditions. The catalyst we proposed for use in the undergraduate organic laboratory is a thiourea catalyst which acts by hydrogen bonding and can be easily synthesized using the reaction scheme below (Opalka, Steinbacher, Lambiris, & McQuade, 2011):



Opalka, Steinbacher, Lambiris, & McQuade, 2011.

Once we had identified a potential reaction and catalyst we thought about what we wanted students to learn from the lab. In designing our lab, we used the process of backwards design. Backwards design is an approach to curriculum design in which the instructor identifies the problems and questions students should be able to answer when they come to the conclusion of the lesson and designs the lesson plan around those questions. Our goals for students are summarized below:

- Students are able to use thin layer chromatography to make conclusions about reaction completion.
- Students can use melting point and thin layer chromatography to identify unknown starting material.
- Students have some understanding of the utility of binary solvent mixtures for Thin Layer Chromatography

Since we wanted students to identify an unknown during the course of the experiment, we had to come up with potential substrates for them to identify which produced solid products with relative purity that students could use thin layer chromatography and melting point determination to identify. Our final substrates were cis-stilbene(*cis*-1,2-Diphenylethylene), trans-methyl cinnamate (Methyl (*E*)-3-phenylprop-2-enoate), or trans-chalcone ((1,3-Diphenyl-2-propen-1-one) students were given one of these substrates with which to perform the reaction.

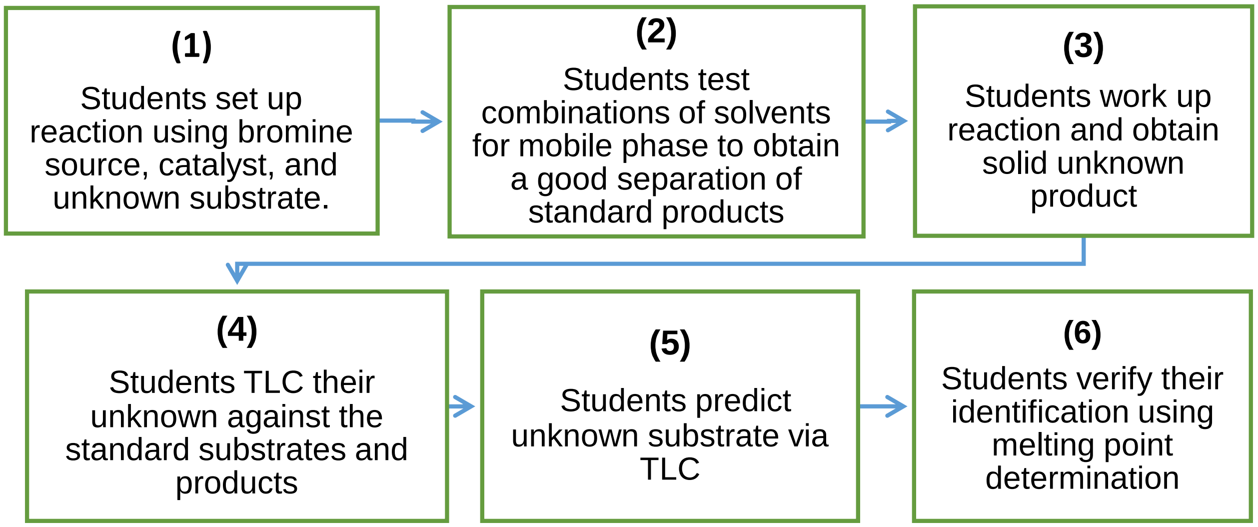


Figure 1: A brief outline of student procedures in the experiment

The above scheme shows a brief outline of the procedural outline students followed when performing the experiment. The handout provided to the students can be found in Appendix I. Students were given their unknown starting material which was dissolved in diethyl ether to add to their reaction mixture. They then added the hydantoin bromine source, solvent, and catalyst and allowed the reaction to run for 40 minutes while stirring at room temperature. While the reaction was running, students were given TLC standards for their starting material as well as the three unknown products. The identities of the products were not revealed to the students so as to have them identify their unknown using their understanding of polarity and thin layer chromatography. Students were tasked with finding the ideal binary solvent mixture of hexane and ether for eluting their unknown starting material and the standard products while the reaction was running. Once the reaction was completed, a simple purification step with silica was performed and the filtrate was evaporated on a rotary evaporator to obtain the solid product. This product was compared to the starting material and standard products for identification. The product was also analyzed by melting point determination. Students then answered guided questions about the laboratory and completed a concept mapping assignment focused on Thin Layer Chromatography which can also be found in Appendix I.

Incorporating multiple techniques into one lab allows students to showcase their lab techniques as well as apply them to solve new problems. Students had used melting point determination and Thin Layer Chromatography before in expository formats so we were able to challenge them to use these techniques to identify their unknown.

Conclusion

Our work is motivated by a desire to engage students in the laboratory while promoting sustainable chemical practice. A guided inquiry experiment for the electrophilic addition of alkenes was created by using an organocatalytic reaction from the current chemical literature. The experiment was set up to teach students about thin layer chromatography as a chemist would use it when doing a synthesis. The

experiment presents a way for us to bridge a gap in our organic chemistry curriculum and also presents the opportunity for educational research which is presented in the study detailed in the following pages.

II. Literature Review

This chapter places our work within the context of the relevant literature in chemistry and science education. Our laboratory design was performed through the lens of constructivism, therefore, we had students perform a guided inquiry experiment. We wanted to engage students in meaningful learning as it is cognitive theory in which students must make connections from their previous understanding to make sense of new information being learned. A great deal of our work focuses on the misconceptions which students generate as they are learning about chemical concepts and how those affect subsequent chemical understanding. The nature of chemistry makes it inherently difficult for students to learn and we therefore recognize some of the epistemological challenges students face in learning chemistry. The literature containing information about misconceptions, specifically those pertaining to polarity, are presented here as well.

Constructivism

This study was performed through the lens of constructivism. This cognitive theory comes out of Piaget's research in developmental and educational psychology. In this framework, the learner must experience and connect present information to the reality which they have generated (Piaget, 1967; Bodner, 1986; Von Glasersfeld, 1984). The student must contextualize the information before it can be integrated into their knowledge base. This subjectivist way of viewing learning lends itself to the realization that students are not blank slates when they walk into the classroom. Each student brings their own set of experiences and pre-conceptions about the subject matter when they come into the classroom (Bodner, 1986; Ausubel, 1968). In *Educational* Psychology, David Ausubel wrote, ''If I had to reduce all of educational psychology to just one principle, I would say this: The most important single factor influencing learning is what the learner already knows." To close that gap between what a student knows and what they are trying to learn requires students to create the knowledge for themselves. Cognitive educational research supports this theory: students need to be able to create knowledge for themselves (Ausubel, 1968; Palmer, 2001; Johnson, Johnson, & Smith, 1991). Chemistry courses need to be structured so students create knowledge for themselves, rather than verify the information chemists have learned before them (Palmer, 2001). To help students learn the nature of chemistry, instructors must have a grasp of what students know and don't know when they walk into the classroom.

Guided Inquiry

Traditional laboratory experiments can be described as expository experiments in which students perform a prescribed experiment with a known outcome (Dunlap, 2012). In fact, in a content analysis of laboratory manuals, it was found that many expository experiments fail to go beyond engaging students in lower level cognition (Domin, 1999). There are alternatives to this expository approach which include a problem based, open inquiry, and guided inquiry (Gaddis & Schoffstall, 2007). Each of these inquiry styles has its strengths. In a problem based and open inquiry experiments, students are required to create a procedure to solve a problem or investigate a particular chemical phenomenon (Dunlap, 2012; Mohrig, Hammond, & Colby, 2007; Gaddis & Schoffstall, 2007). While the positive outcomes of these experiments are numerous, these experiments rely heavily on facilitation by the teaching assistant,

support of the faculty, and an extensive amount of time for student planning (Chatterjee, Williamson, McCann, & Peck, 2009; Allen, Barker, & Ramsden, 1986).

Guided inquiry experiments maintain the discovery-based and inductive approaches while being time efficient and easy to implement at larger institutions (Gaddis & Schoffstall, 2007). In a guided inquiry experiment, the procedure is given, but students are tasked with solving a problem such as solving for an unknown or identifying unanticipated products (Dunlap, 2012; Gaddis & Schoffstall, 2007). This approach teaches students how to perform data interpretation to learn directly how the science of organic chemistry is done (Mohrig, Hammond, & Colby, 2007). Inquiry experiments require students to work together in the laboratory which mirrors the way in which science is done in research laboratories and is backed by cognitive research which shows that students learn better through social interaction. (Spencer, 1999)

A study about student perceptions of guided inquiry laboratories showed that the majority of the 700 students surveyed at a large research university have a positive attitude toward guided inquiry labs and believe that they have to do a lot of thinking and analyzing to write their report (Chatterjee, Williamson, McCann, & Peck, 2009). Another study showed that at a large Midwestern research university, students and teaching assistants had positive reactions to the integration of inquiry experiments in the lab (Bodner, Hunter, & Lamba, 1998). A positive attitude towards the lab is important for student engagement (Johnson, Johnson, & Smith, 1991). Students are also aware that conceptual development is occurring in the laboratory in an inquiry experiment instead of only occurring when they answer questions about the experiment in their report (Domin, 2006). If we as instructors want students to engage in higher level cognition than what expository experiments require, guided inquiry is a feasible option for moving our laboratory experiments in the direction of achieving this aim.

There are a variety of guided inquiry experiments in the literature in which students use Thin Layer Chromatography as a tool for inquiry. An experiment investigating the stereoselective reduction of esterone by sodium borohydride required students to use Thin Layer Chromatography, melting point determination, and Infrared Spectroscopy to identify the product, but was focused on showing students how chiral molecules interact with the TLC plate differently (Aditya, Nichols, & Loudon, 2008) Another experiment has students characterize phospholipids extracted from eggs using Thin Layer Chromatography which relies on color comparison to identify the phospholipids in student's extractions (Potteiger & Belange, 2015). An interesting approach to the thin layer chromatography inquiry was described by Hessley to have students do the computational calculations for intermolecular and intramolecular forces which were then used to investigate the polarity of several substances by TLC (Hessley, 2000). A pleasant smelling inquiry had students use Thin Layer Chromatography to differentiate between spearmint and peppermint extracts while elucidating their components (Pelter, et al., 2008). Another experiment focuses students on the aspects of TLC involving hydrogen bonding with the plate, retention factor, and polarity before presenting them with a contrived problem about solving for reaction completion (Dickson, Kittredge, & Sarquis, 2004). While each of these experiments has varying levels of involvement with thin layer chromatography and some focus the technique for measuring reaction completion, they do not require students to figure out a binary solvent mixture for thin layer chromatography analysis. This is one of the steps which an organic chemist does regularly to ascertain reaction completion and figuring out a solvent mixture for purification by column chromatography.

Transition from Novice to Expert Through Meaningful Learning

As students take subsequent classes in chemistry, ideally, they should move along a continuum from novice to expert in which they learn from instructors who are considered experts in the field. As they do so, it is expected that their previous conceptions about chemical concepts are adjusted to fit to the conceptions that have been discovered through measurement of chemical phenomena (Kozma & Russel, 1997). To learn new information, students must make inferences between prior knowledge and the information being learned (Pyburn et. al, 2013, McNamara and Magliano, 2009). Yet novices do not yet know how to apply their conceptual frameworks about a subject in a flexible manner to make these connections (Wang & Barrow, 2013). To become flexible learners, students must depart from rote learning techniques and approach those of meaningful learning (Grove & Lowery-Bretz, 2012).

Chemistry is an inductive science meaning that a chemist must backtrack from the observed phenomena to find an explanation for the phenomena using the tools we have to measure and characterize the phenomena (Johnstone, 1991). Chemists measure emergent properties when using various analytical techniques. Emergent properties are those properties which arise from the constituents which makeup a whole (Tumay, 2016). In chemistry this means that there are the constituents of an atom that have certain properties which give the atom its specific identity and characteristics. If we then move to the molecular level, those atoms which are the constituents of a molecule will behave in a certain way by themselves and behave in a different way depending on how they are arranged to form the molecule. Going further up the scale, the phenomena observed on the macroscopic level arise from many complex layers of ordered chemical interactions which are then interacting in a dynamic manner which are not as ordered as those on the microscopic level, for students to relate the macroscopic they must be able to reconcile the subatomic, atomic, and molecular phenomena with the macroscopic phenomena which come from randomized interactions of the particulate matter (Tumay, 2016; Johnstone, 1991; Becker, Stanford, Towns, & Cole, 2015).

To reconcile emergent properties with one another requires a systemic perspective which is infrequently supported by the way general chemistry courses are taught (Grove & Lowery-Bretz, 2012). Relativistic thinking is one of the key stills needed for solving problems in chemistry. The need for this skill arises from the characteristic of emergence in chemistry. Students need a precise and coherent conceptual understanding of general chemistry that allows them to apply the most relevant model. (Wang & Barrow, 2013)

A recent qualitative study looking at student expectations of organic chemistry showed that students perceived general chemistry content as being dualistic with a straightforward connection between problems and answers, and expected they could apply this perspective to organic (Grove, Hershberger, & Bretz, 2008). Unsurprisingly, they were sorely mistaken as organic chemistry requires an ability to perform relativistic thinking (Grove & Lowery-Bretz, 2012; Grove, Hershberger, & Bretz, 2008; Akkuzu & Uyulgan, 2016). Students who realize that they must engage in meaningful and conceptual connection to the course material perform well in organic chemistry courses (Grove & Lowery-Bretz, 2012).

One would assume that the laboratory would be the place where students could easily engage in meaningful learning as it presents the opportunity for the student to experience the science which has been presented in lecture, yet somehow, we fail to connect students to meaningful experiences at all. Student methods in the lab are not guided by their conceptual understanding of chemistry, and they often find it to be meaningless (Novak & Gowin, 1984).

Misconceptions

Misconceptions are concepts or beliefs about scientific phenomena that students hold which differ from those held by the scientific community. (Ozmen, 2004) An example of a misconception a student might have about chemical phenomena is the belief that when a substance melts, or undergoes a phase change from solid to liquid, the bonds which make up the molecules themselves have been broken or dissociated. From a naïve standpoint it stands to reason that the compound being observed is breaking down in some way, chemists know from observed phenomena that the forces *between* molecules are what are disrupted in the process of undergoing this phase change. The generation of misconceptions makes sense from a constructivist standpoint as all learners are bound to make mistakes when incorporating new conceptions and relating them to their previous experiences. Unsurprisingly, students bring misconceptions with them from their everyday experiences as well as those generated in previous courses (Ozmen, 2004). Obviously it is against the aims of instructors for students to be gaining misconceptions when taking courses, or even from the textbooks they use in those courses. But it's not surprising to find that students are generating misconceptions due in part to the nature of chemistry itself. (Tumay, 2016). Misconceptions can be problematic, as misconceptions formed about prior material may negatively affect subsequent learning (Palmer, 2001).

Two identified sources of misconceptions in chemistry are from language and symbolic representations. Misconceptions arising from semantical confusion can occur when trying to translate words from everyday life into a chemical context or in learning scientific language in general (Song & Carheden, 2014). When chemists appropriate language for describing chemical relationships and phenomena, students must relearn those words in the chemical context which is often very different from the meaning of those works in everyday life. Another source of language confusion comes from students being expected to learn and understand chemical vocabulary. Much of the language that students must learn in organic chemistry is domain specific, meaning that students need to learn words which do not have any application outside of that subject (Song & Carheden, 2014; Ausubel, 1963). This creates a retention issue for that vocabulary if students do not use the vocabulary regularly (Ausubel, 1963). There is a wealth of research about student misconceptions as they relate to symbolic representations of chemistry (Johnstone, 1991; Becker, Stanford, Towns, & Cole, 2015; Graulich, 2015; Kozma & Russel, 1997). We will address these further in the next section.

Polarity and Understanding Functional Groups

It is well known that students struggle to understand chemical bonding and functional groups (Akkuzu & Uyulgan, 2016; Hoe & Subramaniam, 2016). One of the emergent properties which students grapple to think about is polarity, especially as it pertains to molecular representations. Students find it difficult to interpret and translate between chemical information such as Lewis structures, stereochemical information, Fischer and Newman projections, and different 2D and 3D representations which chemists use on a regular basis (Kozma & Russel, 1997). From this we see that there is a cognitive gap between structural representations and their chemical meaning; students can recognize bonds and atoms, but not the physical consequence of functional groups (Graulich, 2015).

Undergraduate students in an organic chemistry course had difficulties with applying the hydrogen bonding concept to boiling point differences, effects on NMR and IR spectroscopy, and its impact on reactions (Henderleiter, Smart, Anderson, & Elian, 2001). General chemistry students struggle to make meaningful relationships between the intramolecular forces of electronegativity and polar covalent

bonding (Burrows & Mooring, 2015). Turkish undergraduate organic chemistry students generally had low levels of understanding of concepts relating to functional groups (Akkuzu & Uyulgan, 2016). This issue is prevalent with American undergraduate students as well. McClary and Bretz found that students hold misconceptions about functional groups which pertain to acidity, saying things like: ''Functional group determines acid strength and "Stability determines acid strength." (McClary & Bretz, 2012) .This is an unfortunate consequence of low levels of general chemistry content knowledge when taking organic chemistry. Students don't seem to connect basic principles learned in general chemistry to phenomena in the organic chemistry class and basic chemistry topics are often not discussed again in the organic chemistry classroom and students are further impeded by the overwhelming amount of additional content they are expected to absorb (Graulich, 2015)

A commonly held misconception about polarity is that it has to do with the weight of the two atoms which share a covalent bond, rather than the electronegativity of those atoms and the subatomic particles from which the electronegativity arises (Wang & Barrow, 2013). The literature clearly shows that students don't understand basic bonding interactions. We found good evidence that there is a gap in student's knowledge about intermolecular and intramolecular forces when approaching the organic chemistry curriculum. However, there is little evidence of how students apply or fail to apply these basic chemical concepts to Thin Layer Chromatography which directly requires them to use concepts about polarity, functional groups, acidity, and noncovalent interactions.

<u>Proposed Gap in The Literature</u>

While the literature provides a wealth of experiments for students to perform in the lab which focus on thin layer chromatography, few require students to use the technique as a chemist would. None of the experiments we found required students to solve the problem of creating a binary solvent mixture. In addition to these gaps, the literature contains many studies focused on first year chemistry courses, but we don't have a complete perspective on what knowledge is relevant as students continue through the chemistry curriculum. Our study proposes to learn more about student conceptions when taking the organic chemistry sequence.

Thin Layer Chromatography offers an applied technique which requires an understanding of polarity and intermolecular forces to use effectively. This technique gives us a way to look at how students approach solving a problem using the tools given to them in the laboratory and how they apply chemical knowledge to understand new concepts. We wanted to see if our guided inquiry was effective as the laboratory literature reports that guided inquiry has higher impact on student learning. We were unable to find evidence in the literature that there has been investigation into student misconceptions with Thin Layer Chromatography.

III. Methodology

This chapter provides the context of our research and details how the work was carried out. Therein our research questions are presented to give focus to the study. We used constructivism as the context for our guided inquiry experiment and data analysis. Student laboratory reports and concept mapping assignments were collected as classroom artifacts for analysis. Detailed within is our concept mapping analysis in addition to our phenomenographic approach to the laboratory report data. Also recognized are the influence of the researcher and the limitations to the study.

Research Questions

1) Does student understanding of the chemistry behind Thin Layer Chromatography change after a guided inquiry experience?

2) Do students persist in having misconceptions about polarity as they learn about TLC?

Theoretical Frameworks

Constructivism

Our work is grounded in constructivism which is a framework that comes out of developmental and cognitive psychology. This theory holds that knowledge is constructed in the mind of the knower as new experiences are had. Knowledge cannot be gained by a learner without having an experience in which the knowledge is discovered and can therefore be incorporated into the knowledge base (Bodner, 1986). This goes against the traditional knowledge concept in which there is a real world which exists without our interaction with it. In constructivism, there is only the reality which we construct for ourselves (Bodner, 1986; Campbell, 1998). If we can only construct knowledge in the context of our own realities, we must actively construct the knowledge that fits with the reality we have come to know. From this theory of knowledge, we realize that students need to be engaged in some sort of scientific inquiry to connect the information that scientists have learned about our common concept of reality to their individual concepts of reality in a meaningful way. A well-researched method of doing this is through engaging students in discovery based learning.

The discovery based learning approach we decided to use was guided inquiry. This type of pedagogy has been shown to allow students the space to construct knowledge in science (Bodner, Hunter, & Lamba, 1998). In the guided inquiry format, students are given a set of guidelines with which to perform the experiment and presented with a problem to solve using the tools provided to them in the lab (Allen, Barker, & Ramsden, 1986). Our goal was to ease students into an inquiry experience as our organic chemistry laboratory curriculum consists almost entirely of expository experiments. We wanted to construct an hour or so in the lab where students would be able to use tools that organic chemists use on a regular basis to assess reaction completion when performing a synthesis. Therefore, we had students perform a synthesis as they would in an expository experiment and tasked them with identifying an unknown starting material using Thin Layer Chromatography and melting point determination. Once students had set up their reaction, students were encouraged to collaborate with one another to solve the problem of finding a solvent mixture which would allow them to identify their unknown.

We also recognized that in addition to the lack of student experience with inquiry-based labs, the teaching assistants who instructed the students in the lab did not have a basis in scientific education other than the experiences they had with their own instructors. Previous work in our group shows that the laboratory instructors have a significant influence on student learning outcomes (Current & Kowalske, 2016). To alleviate this problem, we had an extensive meeting in which we briefed the teaching assistants on the lab they would be teaching and effective ways of asking students questions to help them identify their unknown. The teaching assistants were also not informed of the identity of the unknown starting materials when they were teaching the lab to encourage them to engage in helping students solving the problem of what their unknown was based on the laboratory data the students collected.

Participants

Participants were students enrolled in the Organic Chemistry I Laboratory during the Fall 2015 semester. The majority of students were also enrolled in the Organic Chemistry I lecture while taking the laboratory course. Students taking the course were majoring in Biomedical Sciences (Pre-med), Biochemistry, Chemistry, Chemical and Paper Engineering, and Biology with a small representation in the Health and Human Services major. The majority of students are beginning the second year of their degree curriculum when they take the course.

We collected concept maps and laboratory reports from each student who completed them. Overall, we were able to sample 29 students from the original sample size of 133 students. Some of the attrition rate can be attributed to students withdrawing from the course, not turning in laboratory reports, and the fact that the concept map for the thin layer chromatography assignment was offered as an extra credit assignment.

Student Participation	
Total number students enrolled	133
Students who completed the expository TLC Report	133
Students who completed the Guided Inquiry Report	96
Students who completed Map 1	62
Students who completed Map 2	72
Completed both labs and Map 1 & 2	37
Maps Used	29
Percentage of students sampled overall	22%

Table 1: Student participation for the Fall 2015 semester

Data Collection

Data collection was done during the Fall 2015 semester. Students completed a concept mapping assignment answering the focus question: “How does Thin Layer Chromatography work?” after completing the expository Thin Layer Chromatography laboratory experiment. Copies of that assignment were then collected and de-identified. Students then completed a second concept map answering the same focus question after they performed the guided inquiry experiment detailed in this

paper. In addition to the concept map assignment, students answered guided questions about the laboratory experiment which can be found in Appendix I. Copies of the concept maps and laboratory reports completed by the students were collected and de-identified for analysis.

We chose concept mapping as one of our methods for learning about student understanding of thin layer chromatography because it gives us a window into how students construct their conceptions of the world. Concept mapping comes from Ausubel's cognitive learning theory which focuses on meaningful learning and this is reflected in the point values given for hierarchical and synthesis of knowledge. (Ausubel, 1968; Ausubel, 1963; Novak & Gowin, 1984). The brain naturally maps concepts in this webbed and hierarchical fashion (Novak & Gowin, 1984). The maps show connectivity between concepts and allow us to see how students connect new information to their preexisting knowledge.

Early learning of concepts occurs through discovery learning and then reception learning which is reinforced by concrete experiences (Novak & Gowin, 1984). Concept maps are tools for meaningful learning as they require students to make meaning connections between concepts using propositions to complete the map (Novak & Gowin, 1984). Concept maps can be used as a pre-assessment and formative assessment tool to analyze students' knowledge structures regarding a group of related concepts. (Burrows & Mooring, 2015; Yaman & Ayas, 2015). Concept maps have been reported to successfully assess student understanding of chemical bonding concepts, specifically those about covalent bonding and electronegativity (Burrows & Mooring, 2015). This fits with our desire to understand student perceptions of polarity as polarity arises due to electronegativity and covalent bonds.

In each of the concept mapping assignments, students were provided with 5 concepts including the concept "Thin Layer Chromatography" with which to generate their maps. Students were challenged to have at least 10 concepts and 15 connections in the assignment. The concept mapping assignments for the expository and guided inquiry experiments can be found in Appendix I.

Data analysis

Concept Map Analysis

In analyzing the concept maps collected, we used the criterion outlined by Novak and Gowin in *Learning How to Learn* (Novak & Gowin, 1984). From the relevant literature, a critical analysis of the efficacy of analyzing concept maps, showed that the methodology of Novak and Gowin was reported as having high reliability (Ruiz-Primo & Shavelson, 1996). The concept mapping framework is outlined in **Table 2.**

Criteria for the Evaluation of Concept Maps		
Code	*Criteria*	*Point Value*
Propositions	Is the meaning relationship between two concepts indicated by the connecting line and linking words?	**1pt** for each meaningful, valid proposition shown
Hierarchy	Does the map show hierarchy? Is each subordinate concept more specific and less general than the concept drawn above it?	**5pts** for each valid level of hierarchy
Cross links	Meaningful connection between one segment of a concept hierarchy and another segment	**10pts** if the cross link is significant and valid, showing synthesis of knowledge
		2pts if cross link is valid but does not show a synthesis of knowledge between sets of related concepts or propositions
Examples	Events or objects that are valid instances of those designated by the concept label	**1pt** for each example

Table 2: Criteria for Evaluation of Concept Maps

In the coding procedure, the number of valid propositions were first counted and the student was given a point for each valid and meaningful connection made from one concept to the next. Then each map was coded for hierarchy in which student maps were analyzed to look for the propositions going from general to specific.

Cross links were coded in which the student was able to connect one part of the map to the other to show a synthesis of new knowledge. A significant and valid connection was one that would show that a student understood a concept well enough to connect it to something on the map which it is not directly connect to, for instance, a node of the map in which the concept "red" occurs being the node which is generated by the concept "color". To make a significant and valid connection would be to connect the concept of "red" to another part of the map in which the student is talking about the electromagnetic spectrum and sites the concepts of visual and infrared wavelengths which are described as having a red coloring. This would be showing that the student is synthesizing a connection between the information they know about colors and connecting it to the concept of wavelength. To make a valid but not significant crosslink would be to connect the concept of "red" to paint colors, while this is a valid connection, it does not show that the student is understanding something new and significant, but merely that they know that they have bought paint before.

Finally, examples were coded when the student provided some sort of specific connection with the concept to how they had used it or understood it.

We also added qualitative "misconception" codes which were not given a point value like the codes generated by the Novak and Gowin criteria. With these codes we were able to see what students were connecting on their maps that would not be considered correct by chemists. These codes were used to understand what alternative concepts students bring with them when entering the lab and what misconcepts they generate when doing the lab.

Student Report Analysis

Phenomenography is a research method which was generated by Ference Marton in the early 1980's in educational psychology. Phenomenography presents us with a framework which has a deceptively simple basis: everyone experiences the world and phenomena in a different way. (Orgill & Bodner, 2008). This approach involves taking pieces of data from common, shared experiences of others and arranging them according to their similarities and differences (Marton, 1981). Phenomenography fits with our constructivist framework as the phenomenographic approach focuses on the experiences of students in the context of their understanding of the world and in relation to one another. We chose this method because it allowed us to arrange the data in such a way so as to unearth unseen commonalities between students. It should be recognized that this research method is subjective as it involves the researcher imposing categories on the data, the patterns unearthed in the data were found from the categories. This sequence of investigation allows us to minimize bias in our conclusions from the research.

We used this approach to categorize the student answers to Post laboratory questions 1 and 2, which can be found in Appendix II. We took each of their answers and grouped the information based on answers which pertained to thin layer chromatography, melting point determination, and unknown. First we grouped the students by the unknown substrate they were given to identify through the guided inquiry process: *trans*-methyl cinnamate, *cis*-stilbene, and *trans*-chalcone. We then grouped the students based on their ability to identify their unknown and explain why they had come to that conclusion. In that case our categories were as follows: correctly identify unknown and well explained, correctly identify unknown and not well explained, incorrectly identify unknown and well explained, and incorrectly identify unknown and not well explained. A graphical representation of the categorization can be seen in **Figure 2.**

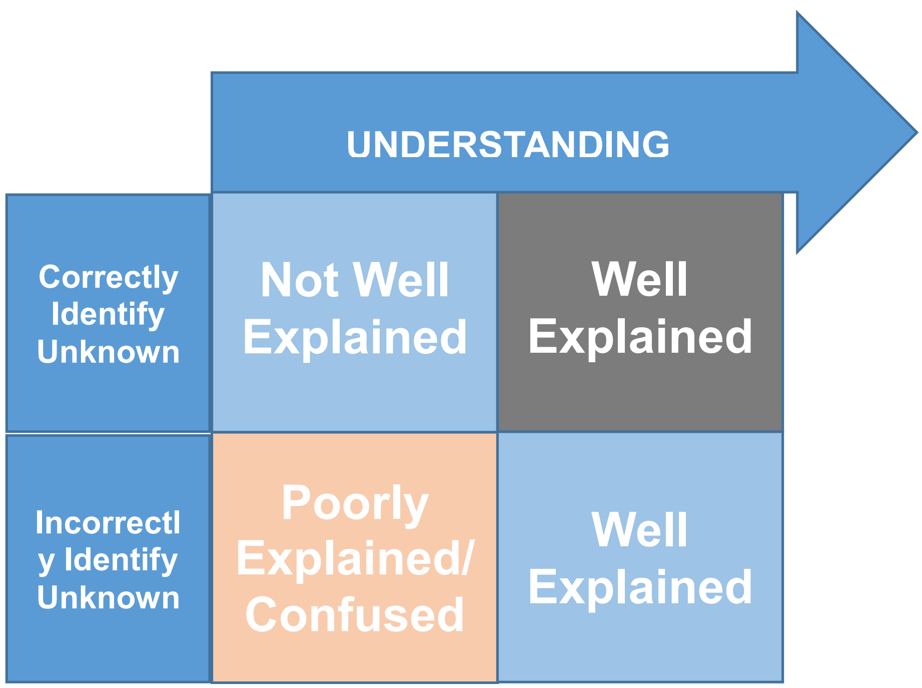


Figure 2: Categorization of student post-lab responses for questions 1 and 2.

Once we had categorized the data, we coded each of the student answers for student misconceptions and language confusion to learn about how students use laboratory data to make chemical inferences.

Role of the researcher

As the researcher in this study, I had an investment in the outcome of the guided inquiry experiment as I designed the laboratory. I recognize that I would want the inquiry experiment to work. However, our methods were exploratory, and therefore were designed to understand aspects of the student's experience in the lab, rather than an attempt to prove that our experiment had a significant impact on student learning. As can be seen in the literature review, there is a great deal of research which indicates that inquiry based experiences have a positive effect on students and learning outcomes.

In addition to my investment in the experiment, I was a teaching assistant in the Spring of 2016 for the Organic Chemistry I Laboratory in which we performed data collection to continue this study. My knowledge of the laboratory experiment could have had the unintended effect of decreasing the inquiry in the experiment, or it may have made it easier for the students to identify their unknown substrates.

Limitations to the study

One of the limitations of our study was that during the Fall 2015 laboratory, the concept map assigned to students after the expository Thin Layer Chromatography experiment was offered as an extra credit assignment. Students needed to have completed both concept maps and the laboratory report for the guided inquiry experiment to be included in the analysis. In conjunction with this issue, students who did not follow the instructions created maps which were not analyzable using our methods. Due to these limitations, we may have sampled only the students who were in need of extra credit in the lab and the high achieving students who would have done the assignment just to ensure that they had the highest grade possible in the lab. We cannot be sure of the student participation in these results for that reason, however, we collected more data during the Spring 2016 semester and will be collecting more data in the Summer I semester to increase our sample size and minimize this sort of biasing of the data. In the Spring 2016 semester, the concept maps were a part of the laboratory report grade for both the Thin Layer Chromatography experiment and the guided inquiry experiment.

Considering that students were the subjects of study, we did not have any control over whether students had been previously exposed to concept mapping in their other courses. The exposure was likely minimal over the students surveyed as we know chemistry instructors at our university do not use this educational technique.

Methodology Summary

The student laboratory experiment was designed as a guided inquiry because it fits within the context of constructivism. We were able to collect data from student's concept maps as well as their laboratory reports using concept mapping analysis from the relevant literature, and phenomenography. Some limitations due to the researcher as well as the method of classroom artifact collection are recognized. Steps have been taken in subsequent data collection to minimize these limitations.

IV. Results

This chapter presents the results from our analysis of the classroom artifacts collected during the Fall 2015 semester. Findings from the concept mapping analysis and the laboratory report analysis are presented.

Concept Mapping Analysis

We analyzed the concept mapping data using Novak & Gowin's criteria, and found that maps from students 5, 8, 12 19, 21, 23, and 31 were not analyzable using the criterion due to students not providing propositional phrases for the concepts they were connecting or not drawing a map that was coherent. In addition to this issue we found that students did not provide maps that were different enough from one another to provide a total which differed significantly from their first experience with thin layer chromatography. For that reason, we decided that analysis using the point based criterion on all of the maps would not produce significant results. We were able to track students' misconceptions using the concept maps. Presented in **Table 3** are the scores for the maps that we did analyze using Novak & Gowin's criterion as well as the misconceptions including the code and quote which was extracted from the map to represent the student's misconceptions relating to Thin Layer Chromatography.

Concept Map Data				
ID	**Map 1 Score**	**Map 1 Misconceptions**	**Map 2 Score**	**Map 2- Misconceptions**
0	**16**	**Reaction Progress**- "Polarity causes different reaction progress"	**14**	**Reaction Progress**- "Polarity causes different reaction progress based on purity"
1	**15**	**Reaction progress**- "TLC determines solubility through the reaction progress" **Stationary phase is chromatogram** "Stationary phase is called the chromatogram"	**41**	**Stationary phase is chromatogram** "Stationary phase is called the absorbant or the chromatogram"-
3	**5**	Reaction progress is process of running a TLC	**0**	Compound spot sizes shows purity of compound "Size of spot deals with purity"
4	**21**		**5**	**TLC and melting Point**- "TLC can be accurately measured by melting point" **TLC and Electrophilic addition confusion**-"The middle point of TLC is the stationary phase where the bromonium ion is formed"
5		**Speed**-"Polarity increase, components of mixture move faster"		

		Speed- "Polarity decrease components of mixture moves slowly"		
6	**29**	**What can be seen with the UV lamp**-"UV lamp allows for the visualization of molecules distance"	**18**	**What can be seen with the UV lamp**-"UV lamp allows for the visualization of molecules distance"
7	**10**	**Proton number confusion**-"Thin Layer Chromatography determines proton number compounds"	**10**	
8		**Reaction Progress is running TLC**-"Reaction Progress Determined by Polarity and solubility"		**Reaction Progress is running TLC**-"Reaction progress, retention factor, chromatogram"
9	**22**		**17**	
10	**22**		**44**	
11	**14**	**Student confused solvent extraction with TLC** -"Plate separates compounds useful for separation of phases"	**18**	**Student confused solvent extraction with TLC** -"Plate separates compounds useful for separation of phases"
12		**Speed/Absorbent moves along plate** "Polar absorbent moves slower" **Speed/Absorbent moves along plate** -"Nonpolar absorbent moves quickly"		**Speed/Absorbent moves along plate** "Polar absorbent moves slower" **Speed/Absorbent moves along plate** -"Nonpolar absorbent moves quickly" **Compounds are eluents**-"Eluent has multiple spots or stretched"
13	**12**	**Reaction Progress-"**Eluents distance from origin is reaction progress"	**19**	**"Compounds are eluents"**
14	**0**		**33**	
15	**15**	**Speed**- "Eluent moves fastest if high polarity"	**21**	
16	**15**	**Reaction progress-** "Reaction progress also referred to as to strength of absorption to the absorbent"	**34**	
17	**46**		**45**	
18	**10**	**"Absorbent moves along plate"**		**Compound spot sizes shows purity of compound** - "Size of spot deals with purity"
19				
20	**15**	**Reaction Progress is process of TLC**- "Thin layer chromatography can be monitored by reaction progress"		

21		**Reaction Progress is process of TLC-“**Reaction Progress results in eluent front”		**Could not read**
22	11	**“Eluent is stationary phase” “Absorbent is mobile phase”**		
23		**Speed-** “Polarity Solvent polar, faster system”		
24				
25				**Reaction confusion**-“Solubility depends on intermolecular reactions”
26		**Reaction Progress**- “Plate, Reaction progress, retention factor		
27		**Compounds are eluents-** “Separation of eluents is based on polarity”		
28		**Speed-** “Polarity effects how fast compound is moved” **Reaction Progress is process of running TLC**- “Absorbent creates strong absorbent, slow reaction progress”		**Speed**- “Less attraction compound has for absorbent the more rapid movement w/eluent” **Speed**-“ Electrophilic addition is favorable for rapid mobile phase”
29				
30		**Reaction occurs in TLC-** “Polar solvent reacts with compound mix”		**Solvents react with compound** “Polar solvent reacts with compound mix”
31		**Absorbant moves along plate/Speed**-“Polar more polar absorbent move slowly” **Speed**-“Non-polar less polar absorbent moves quick”		**Absorbant moves along plate/Speed-“**Polar more polar absorbent move slowly” **Speed**-“Non-polar less polar absorbent moves quick”
32				
33		**Rf**- “Increase in Polarity increases Rf” **Reaction Progress is process of running TLC-** “‘Polar’, more polar, absorbent moves slowly” Absorbent is mobile phase; Speed- “Absorbent moves slowly/quickly”		**Speed**- “Polar more polar absorbent moves slowly” **Speed**-“ Nonpolar less polar absorbent moves quick
34		**Polarity and Rf**- “The more polar, the further up it (compound mixture) moves away from the TLC plate”		**STUDENT PROVIDED AN IDENTICAL CONCEPT MAP TO THE FIRST ONE**
35				

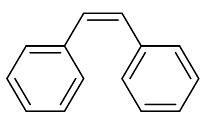
36				
37				
38		**Speed**- "Polar solvents have higher attraction between compound and absorbent and move slower along the plate" **Speed**- "Non-polar solvents have lower attraction between compound and absorbent and move faster along plate."		**Speed**- "Solvent can be polar, more rapidly a compound moves"

Table 3: Concept Mapping Data for Fall 2015. The rows highlighted in red indicate that the student provided at least one map which was not analyzable using the Novak & Gowin criteria. Any other reasons for disruption in analysis are also noted.

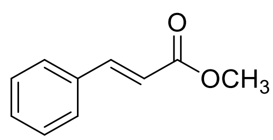
Laboratory Report Analysis

In our report analysis we analyzed student responses to the following questions:

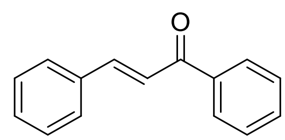
1. **The potential substrates are provided below:**



cis-stilbene



trans-methyl cinnamate



trans-chalcone

   a) **Rank the substrates from most polar to least polar.**
   b) **Based on your results from TLC, how do you know that your reaction went to completion? Draw the TLC plate which allowed you to identify your unknown.**
   c) **How did your melting point determination help you identify your unknown? Did your product melting point match any of the melting points of the standard products provided?**
   d) **What is the identity of your unknown substrate?**

2. **What is the solvent mixture you decided to use to elute your substrate and product? Explain in terms of polarity why that mixture was useful for determining reaction completion while comparing your product to the standard products provided in the lab.**

In our phenomenographic approach, we arranged the answers to the first question based on answers to parts a, b, c, and d. We then categorized the answers based on the unknown substrate the student was given. A sample of this can be seen in **Table 4.** Due to how each unknown behaved on the TLC plate and the melting points of the respective substrates, we thought we might have been able to uncover some way in which students were approaching the problem of identifying their unknown so we categorized the data based on unknown. Complete categorization results can be found in Appendix II.

Methyl Trans-Cinnamate (A,3)					
ID	Polarity (Most to least polar)	Polarity gradient	Melting point	TLC	Correctly Identify Unknown
2000	stilbene, cinnamate, chalcone	Incorrect	Melting point did not help identify unknown, mp did not match TLC results, MP=99C	Reaction did not go to completion, unknown spot showed 2 shadows indicating it still had hexane in it	No

Cis-Stilbene (B,1)					
ID	Polarity (Most to least polar)	Polarity gradient	Melting point	TLC	Correctly Identify
2005	Cinnamate, chalcone, stilbene	Correct	Looked up the table and compared the melting point with the standards provided. I got a melting point of 105C which matches with the mp of cis-stilbene dibromide.	You knew the reaction went to completion when all the starting material has been consumed. I was able to identify the unknown by matching the reaction product with the best standard	Yes

Trans-Chalcone (C, 2)					
ID	Polarity (Most to least polar)	Polarity gradient	Melting point	TLC	Correctly Identify
2003	Cinnamate, chalcone, stilbene	Correct	We were able to look at the table and find the compound that matched our melting point	Reaction went to completion because we could see the spacing in between the dots which allowed us to determine our unknown	Yes

Table 4: Example of Categorization of Question 1 Data based on unknown

We also categorized student answers to question 2 based on the themes we saw arising in their answers. An example of this technique can be found in **Table 5.** We wanted to look at how and why students chose the solvent mixtures they did to elute their unknown and determine whether their reaction went to completion. The emergent themes we saw in student's answers were about separation on the plate, polarity of substrates and products, and reaction completion. We also coded student answers for misconceptions to elucidate common alternative conceptions students were having when integrating concepts about TLC into their knowledge base.

ID	Solvent mixture	Separation	Reaction completion	Substrate polarity	Product polarity	Misconception
2010	We chose a solvent mixture of 50/50 H:E (hexane: ether)	So to see a separation + movement of both, we would need a solvent with a more medium polarity ratio.		In terms of polarity, we chose this ratio because we had an extremely polar substrate + one that wasn't		
2011	We used 50/50 ether/hexane				because when we did the TLC, our two spots that matched was that of P, the product, and 1- cis-stilbene	
2012	The solvent mixture used was 80%/20% 80% being hexane. The hexane is slightly more polar	This gave a better separation to compare to the products given.				The hexane is slightly more polar

Table 5: Results for student reports from question 2.

We did not see shared ways of approaching the problem based on unknown, so we combined the student answers to postlab questions 1 and 2 and divided them based on student ability to identify their unknown and how they used the data collected about melting point and thin layer chromatography to give supporting evidence for the unknown they identified as shown by the examples in **Table 6.**

Correctly Identify Unknown and Well Explained	
Melting Point	**Thin Layer Chromatography**
"By obtaining the melting point, you can compare to the 3 known substrates melting point to help determine unknown"	"The 90% hexane/ 20% ether mixture has more variety b/w distance traveled by each substrate. It is easier to compare unknown to the 3 substrates." "The polarity of the eluent helped show variation on the TLC plate." "The most efficient…was the 4th solvent, the 90% hexane/ 10% ether, because hexane is very non-polar with higher percentages." "You can see what is more polar which doesn't travel far and what is least polar travels up the TLC plate with eluent."

Correctly Identify Unknown and Not Well Explained	
Melting Point	**Thin Layer Chromatography**
The melting point did not match up for #3 (cinnamate) so we concluded unknown A was #2 (cis-stilbene).	The reaction went to completion if there was significant separation on the TLC plate , our unknown was floating between #2 and #3" We used the solvent of 25% ether and 75% hexane… Because it showed the best separation compared to our other trials. Allowing the polar substances to travel the farthest.

Incorrectly Identify Unknown and Well Explained	
Melting Point	**Thin Layer Chromatography**
Our melting point matches that of trans methyl cinnamate dibrominated. By finding the melting point we ran compared with the provided melting points in determining the unknown.	The reaction went to completion because our starting sample is not at the same level as our product. The solvent mixture used was 80%/20% 80% being hexane. This gave a better separation to compare to the products given. The hexane is slightly more polar.

Incorrectly Identify and Not Well Explained	
Melting Point	**Thin Layer Chromatography**
The melting point obtained was 88C. This can be used to predict the compound check which unknown has the closest boiling point. This does not match with any of the given melting points.	The solvent has almost reached the top and all the compounds have been separated. The solvent used was 80% hexane, 20% ether. Hexane was used because it has a high polarity and this allows the compounds to move more rapidly

Table 6: Examples of combined student answers for questions 1 and 2 in the laboratory report. Misconceptions are highlighted in yellow.

This method allowed us to intuit the misconceptions students had impeding them from using thin layer chromatography. We coded student answers for misconceptions related to content and language use. The complete coded data can be found in Appendix II.

Combined Misconception Data from Student Reports and Concept Maps

We combined the misconception data from the concept maps and laboratory report analysis for each of the participants. We left them in the categories that we had generated when performing the original phenomenographic analysis: Correctly Identify Unknown and Well Explained; Incorrectly Identify Unknown and Well Explained; Correctly Identify Unknown and Not Well Explained; Incorrectly Identify Unknown and Not Well Explained. This was done to avoid a posteriori judgement about the students'

ability to understand Thin Layer Chromatography. A complete report of this data can be found in Appendix II.

Correctly Identify Unknown and Well Explained			
Map 1	**Map 2**	**Melting Point Report**	**Thin Layer Chromatography report**
Speed-"Polarity increase, components of mixture move faster" **Speed-** "Polarity decrease components of mixture moves slowly"			

Correctly Identify Unknown and Not Well Explained			
Map 1	**Map 2**	**Melting Point Report**	**Thin Layer Chromatography Report**
"Absorbent moves along plate"	**Compound spot sizes shows purity of compound** - "Size of spot deals with purity"		**Polarity Misconception**: Student did not assign polarity correctly 2 least polar standards both trans products. (The 2 trans products were more polar than the cis)

Incorrectly Identify Unknown and Well Explained			
Map 1	**Map 2**	**Melting Point Report**	**Thin Layer Chromatography Report**
Speed/Absorbent moves along plate "Polar absorbent moves slower" **Speed/Absorbent moves along plate -"Nonpolar absorbent moves quickly"**	**Speed/Absorbent moves along plate** "Polar absorbent moves slower" **Speed/Absorbent moves along plate** -"Nonpolar absorbent moves quickly" **Compounds are eluents**-"Eluent has multiple spots or stretched"		**Polarity Misconception**: The hexane is slightly more polar.

Incorrectly Identify and Not Well Explained			
		Melting Point	Thin Layer Chromatography
Reaction occurs in TLC- "Polar solvent reacts with compound mix"	**Reaction occurs in TLC**- "Polar solvent reacts with compound mix"		**Reaction on TLC**-The chalcone is only slightly polar which would be able to react to the non-polar hexane.

Table 7: Combined misconception data from student laboratory reports and concept maps

From the combined misconception data, we were able to see that the types of misconceptions that students had when performing the experiment and reconciling the melting point data with the thin layer chromatography data. Those misconceptions are summarized in **Table 8.** This showed that the types of misconceptions that students had fit into four areas. The first area is confusion about what concepts relate to thin layer chromatography. Students showed that they thought the mechanism of the reaction being measuring was occurring on the TLC plate, and that molecules can be seen using an ultraviolet lamp. Students who held these misconceptions had difficulty understanding what TLC is for. The second category of misconceptions were about terminology. Students who held these misconceptions had difficulty with what the words eluent, absorbent, melting point, and chromatogram meant. The third group of misconceptions were those regarding polarity. A prevalent misconception was that hexane was a polar solvent and confusion around how the polarity of the plate and the solvent interact with the compound being analyzed. The final set of misconceptions arose from confusion as to whether or not there was a reaction occurring when performing TLC, how to read a TLC plate, and that the placement of the spots on the TLC plate after elution had to do with speed.

Misconceptions from Student Concept Maps and Laboratory Reports	
General Confusion About TLC • Molecules can be seen with the UV lamp • TLC confused with solvent extraction • Proton number can be found using TLC • TLC can be found using melting point • Electrophilic addition mechanism occurs on TLC plate	**Polarity** • Connection between melting point and polarity • Connection between eluent polarity and compound polarity • Solvent polarity • Spot distance and polarity • How polarity affects retention factor (Rf)
Terminology • Melting point and boiling point • Absorbent moves along plate or is the mobile phase • Eluent is stationary phase • Compounds being analyzed are called eluents • Stationary phase is called chromatogram	**Reading TLC plate, what is occurring on TLC plate?** • Reaction occurs during TLC • How to Read a TLC plate • Compound spot size shows purity • Speed and distance • Reaction progress is running a TLC • When TLC is done, Reaction is complete. • When compounds have separated, reaction is complete

Table 8: Misconceptions from concept maps and laboratory reports categorized by type

Conclusion

Our results from the concept mapping analysis and laboratory report analysis of the 37 students sampled are presented here. The concept mapping analysis technique we selected from the literature presented difficulties with our data set, therefore, not all student maps were analyzed using that criteria. Misconception data was extracted from the concept maps, as well as the laboratory reports. Our phenomenographic approach revealed that students held misconceptions regarding speed, polarity, and reaction completion as related to thin layer chromatography. When we combined the misconception results from both the concept maps and laboratory reports, we were about to gain a holistic understanding of how students approached thin layer chromatography and issues they had with understanding the technique.

V. Discussion

This section provides a discussion of the results found in our study. The majority of the results in the last chapter offer insights about the nature of the misconceptions that students hold about polarity and thin layer chromatography. The misconceptions uncovered by our study are connected to the relevant literature.

Concept Map Analysis

Unlike other studies using concept mapping as a pre and post assessment, we found that the scoring criteria did not give us a conclusive way of measuring changes in student conceptual understanding (Yaman & Ayas, 2015; Burrows & Mooring, 2015). We found that many students did not provide maps which were very different from one instance to the next. Frequently, the highest point value codes could not be used on the maps as the criteria of *hierarchy* and *cross-link* were not met by the map. Since the *proposition* code was only worth one point and the maps were fairly small, using these codes had a high impact on the final total. Reducing the map to a final value did not give a fair representation of students' conceptual knowledge.

It was easy to see the differences in conceptual structure from one student to the next, but our aim was to see change in conceptual understanding after the guided inquiry experience in a single individual. Significant change was not shown by the numerical totals from the pre and post maps of a single student. This problem is reflected in the literature which shows that concept maps can be used to see the differences between individuals, in a single individual over a long time span, or after extensive structural intervention (Burrows & Mooring, 2015; McClure, Sonak, & Suen, 1999; Ruiz-Primo & Shavelson, 1996). There was likely not enough conceptual change related to TLC occurring during the course of the semester to be tracked by concept mapping. The scoring criteria would be more appropriate if students provided larger and interconnected maps. For students to create complex maps, they need training on how to use concept maps as learning tools and in class time needs to be dedicated to instructing students on how to create the maps (Novak & Gowin, 1984).

The literature shows that low scores on concept maps indicate that a closer look is needed to identify misconceptions (McClure, Sonak, & Suen, 1999). Many of the concept maps analyzed using the scoring criteria received low scores. From the warranted misconception analysis, we hoped to glean information about how students construct concepts related to Thin layer chromatography and how it works. From this analysis, we were able to see that many students had difficulties with understanding the difference between performing Thin Layer Chromatography analysis and what it meant to perform a reaction. This analysis also revealed terminological issues with the meaning of *absorbent, eluent, mobile phase, stationary phase,* and *chromatogram*.

Some of the difficulty in constructing the maps and the consequent misconceptions represented on the maps may have occurred due to student's low exposure to concept mapping. The laboratory section was likely the first time the majority of students had used concept mapping which may be part of the reason why so many of students provided maps which we could not analyze. Without significant training in concept mapping, the technique can be difficult for students to grasp (Novak & Gowin, 1984; Ruiz-Primo & Shavelson, 1996). We provided a handout which walked students through how to create a concept map and directions for using CMapTools, a free software which can be used to generate concept maps. A copy of these instructions can be found in Appendix I. However, if students were unsure about how to

construct the map properly, they may have made connections which represent misconceptions to a reader of the map, but do not truly represent the level of understanding that those students have of thin layer chromatography. We recommend that students are introduced to the technique of concept mapping in the lecture, and are shown how to use it as an effective study method before using it as an assessment tool (Ruiz-Primo & Shavelson, 1996; Carey & Shavelson, 1989).

Laboratory Report Analysis

From the phenomenographic laboratory report analysis in which we categorized student responses to two of the post laboratory report questions based on students' ability to identify their respective unknown substrates and explain how melting point and Thin Layer Chromatography data allowed them to make conclusions about their reaction completion and compound purity. We then coded the students answers with misconceptions and issues with scientific language use. The low frequency of the language use code prevented us from saying anything significant about student misconceptions from the laboratory report as related to thin layer chromatography and polarity.

We found that there were common misconceptions between each of the four categories of students regarding Thin Layer chromatography. We saw that the group of students who were able to identify their unknown Correctly and Explain Well held misconceptions about reaction completion and how separation on the TLC plate related to this. Students confused the difference between the completion of the reaction and the TLC analysis being completed. If the spots on the plate were separated the TLC analysis would be completed, but this does not necessarily indicate anything about the reaction being analyzed being completed.

The group of students in the middle, meaning that they were the students who Correctly Identified the Unknown but Explained Poorly, and those who Incorrectly Identified the Unknown but were able to Explain Well held misconceptions about reaction completion and what separation means on the TLC plate and also held misconceptions about polarity. Students who struggled with polarity had misconceptions about hexane being a polar solvent. Misconceptions arising from emergent properties that must be interpreted from chemical representations such as polarity from chemical structure are reflected in the literature (Ozmen, 2004; Kozma & Russel, 1997). Students also held misconceptions about the impact of the solvent and the plate on how far their substrate and product traveled. One of the ways of representing chemical properties is through thin layer chromatography, and we are seeing that students are struggling with connecting the concept of polarity to how solvent and chromatography plate function (Kozma & Russel, 1997).

The final group, Identified Unknown Incorrectly and Poorly Explained, held misconceptions about reaction completion and separation on the TLC plate, polarity of solvents and compounds, and made a false connection between speed and distance traveled on a TLC plate. This misconception indicated that these students thought that the spots moved faster in certain solvents which was why they traveled farther up the plate. Misconceptions of this type are not surprising as it is known that high school students and first year undergraduate students have difficulty differentiating between observable phenomena and the particulate chemical explanation (Kozma & Russel, 1997; Grove & Lowery-Bretz, 2012; Tumay, 2016; Griffiths & Preston, 1992). Students who hold this misconception equivocate speed with distance traveled on the chromatography plate. The compound spot moving farther does not indicate that it is moving faster, rather, that the compound has a greater affinity for the mobile phase than it does for the stationary phase.

These conclusions are summarized in the figure titled **Student Misconceptions from Laboratory Report Analysis**.

Student Misconceptions from Laboratory Report Analysis

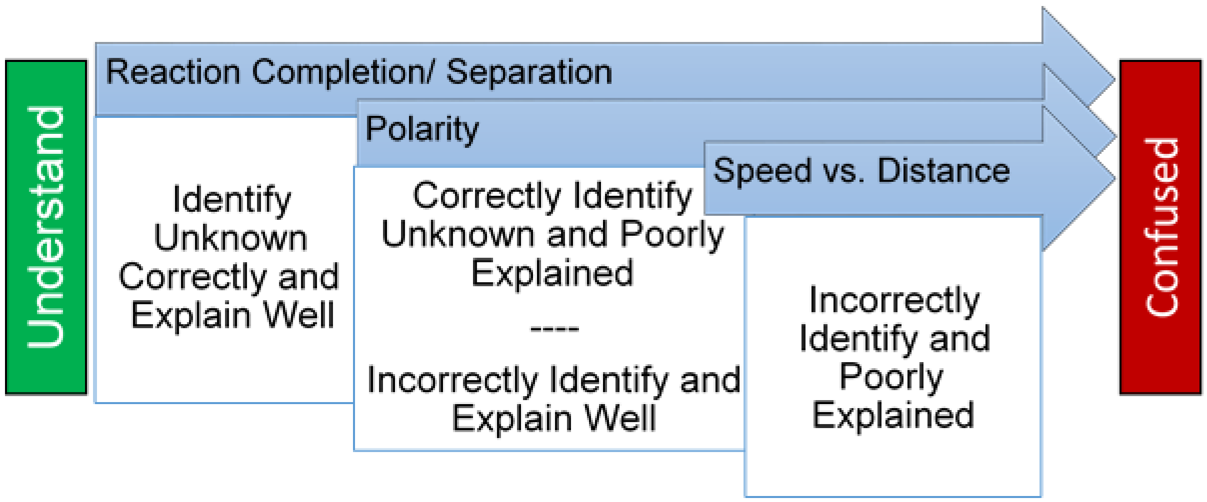


Figure 5

Combined Misconception Data

When we combined the misconception information from both the concept maps and the laboratory reports we found that students held misconceptions fell into the following themes: what can be measured by TLC, the terminology regarding thin layer chromatography, polarity in relation to thin layer chromatography, and what was occurring on the TLC plate.

What can be measured by TLC

Some of the students had difficulty placing TLC within the context of the course as they seemed to confuse it with techniques they had learned in the laboratory, such as solvent extraction and melting point determination. This lack of organization is unsurprising in an expository format as students are not encouraged to make connections between different techniques in the course. Much of the Organic Chemistry I Laboratory course is focused on teaching students the techniques they will need to perform the experiments at the end of the semester and in the second semester laboratory course. However, the curriculum does not focus on teaching students how the techniques are used by organic chemists. This may be the source of these misconceptions. To alleviate these misconceptions instructors need ask students teleological questions in the lab and encourage them to provide particulate explanations.

Terminology

A portion of the misconceptions that we saw when addressing misconception data from the maps and the reports were related to terminology. Students had difficulty using the specialized vocabulary which chemists used use to describe thin layer chromatography. The meanings of the words *eluent*, *mobile phase*, *absorbent*, and *stationary phase* were frequently confused. Chemistry needs to be presented to

students as a linguistic endeavor as much as it is a quantitative endeavor (O'Reilly & McNamara, 2007; Pyburn, Pazicni, Benassi, & Tappin, 2013). When taking general chemistry courses, students are given the notion that provided they are able to do the math, they can achieve high scores in the course (Grove & Lowery-Bretz, 2012). This is an issue for students as they continue into organic chemistry as they are hindered by thinking they can get away with not learning chemical vocabulary. Strong linguistic skills may help students integrate chemical knowledge and concepts into their preexisting knowledge structures (Kozma & Russel, 1997; Hoffmann, 1995).

Polarity

Identifying the polarity of the unknown compounds in relation to the mobile and stationary phase was a challenge for many students. This shows that students have difficulties when relating general chemistry content knowledge to organic chemistry which is reflected in students' misunderstanding about the level of metacognition required to understand organic chemistry (Grove & Lowery-Bretz, 2012). As Tumay recognizes, students do not realize that they need to think about chemistry concepts in a systematic way (Tumay, 2016). The lack of systemic thought impedes students from reconciling the plate polarity with the mobile phase polarity, and the compound polarity. Students who held misconceptions about polarity did not seem to be able to recognize the polarity differences between the two solvents they were using to create the mobile phase. This makes sense when looking at a recent study that found that organic chemistry students who could identify hydrogen bonds correctly were often unable to apply the concept of hydrogen bonding to physical properties and spectra in the lab (Henderleiter, Smart, Anderson, & Elian, 2001). If students are struggling with hydrogen bonding as an intermolecular force, our findings that organic chemistry students cannot identify polar and nonpolar compounds and their representations in the lab are understandable.

Reading TLC plate: What is occurring on TLC plate?

The most prevalent misconceptions we found from our analysis were related to reaction completion and reaction progress as seen on a TLC plate. Students struggled with determining purity of their product, reaction completion, and whether their TLC analysis was done. When a thin layer chromatography analysis is performed, there are interactions which will happen between the compound, the plate, and solvent(s), but these students seemed to think there is a reaction occurring. We found this from asking questions about reaction progress and reaction completion and requiring students to include *reaction progress* as a concept on their concept maps. When using Thin Layer Chromatography for the first time to measure reaction completion as students were doing in this lab, it is reasonable that they would not realize that they are not performing a reaction when doing TLC. The misconceptions about speed and distance were also very prevalent in the both the concept maps and laboratory reports. These misconceptions are not reported in the relevant literature as the majority of the literature focuses on general chemistry courses, and the literature which focuses on organic chemistry is concentrated on students' ability to understand mechanisms.

Conclusion

Our discussion covers findings from this study as related to misconceptions about Thin Layer Chromatography and the experiment that students performed. We found that student concept map

scores did not change significantly to warrant the analysis recommended by Novak and Gowin. Therefore, we focused on finding misconceptions from the concept maps. From the concept mapping analysis, we found misconceptions related to terminology and reaction completion. When we turned to the laboratory reports for phenomenographic analysis, we found that students also held misconceptions about polarity as it pertained to the compounds being analyzed, the plate, and the mobile phase. In addition to these misconceptions, students held misconceptions about the difference between reaction progress, reaction completion, and running a thin layer chromatography analysis. Student misconceptions about terminology and polarity are reflected in the literature, but misconceptions about how to read a chromatogram are new findings.

VI. Conclusion and Implications

In this study we report on the findings from analysis of classroom artifacts collected from a guided inquiry experiment designed for the Organic Chemistry I Laboratory course. The laboratory was designed to give students an authentic research experience in designing a solvent mixture for thin layer chromatography analysis of and unknown substrate and product. Our study contributes information about student misconceptions in organic chemistry which expands the small amount of literature which focuses on this population.

Research Questions Revisited

1) Does student understanding of the chemistry behind Thin Layer Chromatography change after a guided inquiry experience?

We were not able to find conclusive results which showed that student understanding of thin layer chromatography changed after the guided inquiry experiment. Our research methods were not ideal for answering questions about the level of student understanding students had before and after the guided inquiry experiment. We could not see significant change in students' the concept maps before the experiment and after the experiment. We would likely to generate a survey or interview students to gain an understanding of how student's concepts about thin layer chromatography changed, if they did change at all after performing the guided inquiry.

2) Do students persist in having misconceptions about polarity as they learn about TLC?

We were able to gain an understanding of the struggles students face in applying general chemistry content knowledge in the organic chemistry laboratory by investigating student misconceptions about Thin Layer Chromatography as it requires an understanding of polarity and intermolecular forces to use effectively. Our findings support findings in the literature, and expand on how students apply their chemical conceptual knowledge, or lack thereof, to solve chemical problems.

Students in our study held misconceptions about polarity and intermolecular forces which hindered them from applying that knowledge to Thin Layer Chromatography. Our results reinforce the findings reported by Akkuzu and Uyulgan that students' inability to grasp general chemistry topics of intermolecular and intramolecular forces prevents them from accurately transferring that content to learning organic chemistry (Akkuzu & Uyulgan, 2016). Unfortunately, our results support the assertion that most students arrive in chemistry courses with an inappropriate amount of background knowledge (Snow, 2002; Pyburn, Pazicni, Benassi, & Tappin, 2013; O'Reilly & McNamara, 2007).

A renewed focus on students' language comprehension in chemistry is appropriate as it is a limiting factor in accruing scientific and chemical knowledge (Ausubel, 1963; O'Reilly & McNamara, 2007; Pyburn, Pazicni, Benassi, & Tappin, 2013). Students need to be directly asked about what concepts mean in organic chemistry as there is a great deal of vocabulary which students are expected to add to their knowledge base throughout the lecture and laboratory course. Part of the reason why students generate misconceptions about chemistry is from the instructors' assumption about the level of students' prior knowledge when teaching them (Ozmen, 2004). Since students are not bringing the general chemistry content knowledge they ought to be when entering organic chemistry, organic chemistry instructors would behoove themselves to reinforce knowledge about intermolecular and intramolecular forces when teaching students about functional groups. An example of a

recommendation we would make is when teaching students about alcohols as a functional group, it is appropriate to point out that alcohols will have polar covalent bonds between the oxygen and hydrogen atoms, and will also have the potential for hydrogen bonding with other alcohol groups and water molecules. This approach connects general chemistry content knowledge to organic chemistry in way that will hopefully allow students to connect this previous experience to the new experience of learning about functional groups.

Laboratory and Lecture Connection

A great deal of educational psychology implies that students must rearrange their conceptual framework to fit new knowledge, but students must do this rearranging within the context of their previously held conceptions about the subject (Ozmen, 2004; Pyburn, Pazicni, Benassi, & Tappin, 2013). If the laboratory course is intended to enforce lecture material, instructors need to be intentional about how they direct students in understanding physical observations. If we want students to be able to use the chemical content they learn in lecture, such as identifying functional groups, we need to engage students in recognizing the significance of general chemistry concepts as they apply to organic chemistry rather than expect them to make the connections entirely on their own. Our findings show that students often do not have basic chemical content knowledge expected of students taking organic chemistry such as a generalizable understanding of polarity. Students in the laboratory need to be reminded of emergent properties as they pertain to organic chemistry to understand macroscopic phenomena in a particulate manner. For students to make valid connections between general chemistry and organic chemistry content, they need to be engaged in solving a problem so they can be guided in creating the knowledge for themselves.

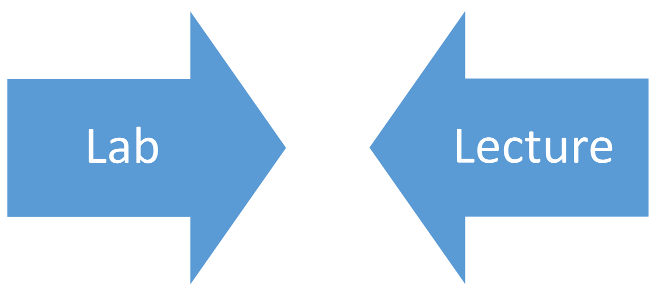


Figure 6: Bridging the gap between organic chemistry lecture and laboratory

Current and Future Work

This study is focused on preliminary data collected from the Organic Chemistry I Laboratory course during the Fall 2015 semester. We have collected classroom artifacts from two additional semesters of the laboratory course for analysis in an effort to generalize our results. Our future work will be focused on revising the laboratory experiment to close some of the gaps in student understanding. We are generating a guide for teaching assistants to encourage them to facilitate classroom discussion which will help students to think in a particulate and systemic manner when approaching chemical problems.

If time allowed, we would like to interview students using a semi-structured interview format to gain direct input about where the misconceptions found in this study come from. The misconceptions about

speed and distance are particularly interesting, as well as those about reaction completion determined from a chromatogram produced from Thin Layer Chromatography analysis. These misconceptions warrant more investigation as they are not found in the chemical and science education literature. A pre and post interview would also allow us to further measure the impact of the guided inquiry experiment on student conceptions about Thin Layer Chromatography.

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