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Investigating Student Perceptions of the Chemistry Laboratory
and Their Approaches to Learning in the Laboratory

By

Spencer Granett Berger

A dissertation submitted in partial satisfaction of the
requirements for the degree of

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in

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in the

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Committee in charge:

Professor Angelica M. Stacy, Chair

Professor Anne M. Baranger

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Abstract

Investigating Student Perceptions of the Chemistry Laboratory and Their Approaches to Learning in the Laboratory

by

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This dissertation explores student perceptions of the instructional chemistry laboratory and the approaches students take when learning in the laboratory environment.

To measure student perceptions of the chemistry laboratory, a survey instrument was developed. 413 students responded to the survey during the Fall 2011 semester. Students' perception of the usefulness of the laboratory in helping them learn chemistry in high school was related to several factors regarding their experiences in high school chemistry. Students' perception of the usefulness of the laboratory in helping them learn chemistry in college was also measured. Reasons students provided for the usefulness of the laboratory were categorized.

To characterize approaches to learning in the laboratory, students were interviewed midway through semester (N=18). The interviews were used to create a framework describing learning approaches that students use in the laboratory environment. Students were categorized into three levels: students who view the laboratory as a requirement, students who believe that the laboratory augments their understanding, and students who view the laboratory as an important part of science. These categories describe the types of strategies students used when conducting experiments.

To further explore the relationship between students' perception of the laboratory and their approaches to learning, two case studies are described. These case studies involve interviews in the beginning and end of the semester. In the interviews, students reflect on what they have learned in the laboratory and describe their perceptions of the laboratory environment.

In order to encourage students to adopt higher-level approaches to learning in the laboratory, a metacognitive intervention was created. The intervention involved supplementary questions that students would answer while completing laboratory experiments. The questions were designed to encourage students to think critically about the laboratory procedures. In order to test the effects

of the intervention, an experimental group (N=87) completed these supplementary questions during two laboratory experiments while a control group (N=84) performed the same experiments without these additional questions. The effects of the intervention on laboratory exam performance were measured. Students in the experimental group had a higher average on the laboratory exam than students in the control group.

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Dear Sir or Madam, will you read my book?
It took me years to write, will you take a look?

-John Lennon & Paul McCartney, Paperback Writer, 1966

Chapter 1: Introduction and Research Questions

Introduction

President Obama has called for an increase in the number of STEM (Science, Technology, Engineering, and Math) majors. According to the White House Office of Science and Technology Policy, the goal is to increase the number of STEM majors by 1 million over next 10 years (U.S. Office of Science and Technology Policy, 2014). To meet this goal, the President's 2015 budget includes an increase of 3.7 percent over the previous year in programs that will improve STEM education. This includes funding aimed at improving undergraduate education in the sciences. Given the increase in the number of STEM majors, introductory chemistry is often one of the largest courses at colleges and universities in the United States. Chemistry is required for students wishing to pursue engineering and pre-health careers, and many students also take introductory chemistry as a general science requirement.

Recently, there have been efforts to reform undergraduate chemistry education. Students in chemistry courses often memorize methods for problem solving, rather than understanding the chemical principles involved. These chemistry courses are often described as having great breadth and little depth. Studies show that students are often more capable of answering algorithmic questions as opposed to conceptual problems (Nakhleh, 1993; Sawrey, 1990). This type of algorithmic thinking also extends to the laboratory program. Students are often capable of performing laboratory procedures, but may lack an understanding of the chemistry involved. The 1994 American Chemical Society's Task Force on Chemistry Education cited the lack of inquiry skill development as one weakness of the laboratory program (Lloyd & Spencer, 1994).

In response to calls from the American Chemical Society, and in conjunction with the national funding dedicated toward improving undergraduate science education, several reform efforts exist to improve chemistry education at the K-12 and undergraduate level. Many of these reform efforts are focused on adding inquiry to the chemistry laboratory. Laboratory exercises are often described as cookbook, in which students simply follow directions without thinking. Adding inquiry elements to the laboratory is an attempt to make the laboratory more engaging for students. However, the term inquiry is often interpreted differently by different instructors. Despite the calls for added inquiry to the classroom, many chemistry classes are not inquiry-based, partly due to misconceptions regarding what inquiry means and how inquiry practices are enacted (Demir & Abell, 2010). Inadequate resources and a lack of professional development

opportunities have also contributed to a reluctance to adopt inquiry practices (Hofstein & Lunetta, 2004).

Current NGSS standards for K-12 Science Education and the College Board Standards for College Success call for a focus on science practices and developing experimental skills, rather than simply learning to perform laboratory techniques (NGSS Lead States, 2013; College Board, 2009). These updated standards reflect the current goals of laboratory education. Originally, the laboratory served to teach students techniques that they would use in the workforce. Now, with so many students taking introductory chemistry, many of whom will not become bench chemists, the laboratory has many purposes and goals. Instructors often do not agree on the purpose of the laboratory, as evidenced by a recent survey of faculty at several types of institutions (Bruck, Towns, & Bretz, 2010).

One goal of the laboratory is developing conceptual understanding. In the laboratory, students have the opportunity to connect their observations to concepts learned in class, and to actively connect theory to experiment. However, even with these reform efforts and new standards, it is unclear whether or not the laboratory is meeting the intended goals and learning outcomes. The laboratory is often thought to be an essential part of chemistry education, but there is mixed evidence to its effectiveness in instruction (Hofstein & Lunetta, 1982). A 2004 review of literature regarding the chemistry laboratory concluded that defining the goals of the laboratory and creating assessments to measure whether or not these goals are being met is central to laboratory reform (Hofstein & Lunetta).

This study focuses on students enrolled in introductory chemistry at a large public university. At the university where this study was conducted, faculty have made extensive modifications to support student conceptual understanding. Professors start each class period with a pre-class assignment designed to gauge student understanding of the current topic. Lectures frequently use demonstrations, and ask students to first make predictions about what they will observe. A substantial amount of class time is devoted to student small-group discussion, in order to promote active learning. The laboratory program at the institution where the study was conducted has also undergone significant reform. Laboratory experiments are being restructured as laboratory modules, in which students complete several weeks' worth of experiments on related topics, using similar techniques. Experiments are also being rewritten with an eye toward connecting the laboratory experiments to real-world examples.

This study investigates the relationship between students' beliefs about the laboratory program and their approaches to learning in the chemistry laboratory. Specifically, this study aims to gain a deeper understanding of what learning approaches students use in the chemistry laboratory, and how students' perceptions of the laboratory environment relate to these approaches. The last chapter of this dissertation describes an intervention aimed at fostering higher-level learning approaches in the laboratory.

Previous studies have shown a relationship between students' perceptions of the learning environment and their approaches to learning (Entwistle, 1991; Ramsden, 1979). This study expands on the current literature by describing student learning approaches in the unique learning context of the undergraduate chemistry laboratory. Because learning approaches differ between learning environments, it is important to ground studies of learning approaches in the appropriate learning context. This study provides a description of how students approach learning in the laboratory.

Research Questions

The overall research question for this dissertation is "How do students' beliefs about the laboratory influence their approaches to learning in the laboratory?"

In order to answer this research question, survey and interview methods were used. Surveys were used to capture information regarding the entire class population. Interviews were used to characterize learning approaches for a subset of students. Interviews were also used to examine certain students in detail for case studies.

The following research questions are addressed:

1: What are students' beliefs about the usefulness of the chemistry laboratory in high school and college chemistry?

Chapter 2 describes a survey instrument designed to measure students' beliefs about the usefulness of the laboratory. Students' ratings of how useful the laboratory was in helping them learn high school chemistry are compared to a number of other survey items describing their high school experiences in chemistry. This chapter characterizes students' beliefs about the utility of the laboratory and aims to understand what factors influence these beliefs.

2: What approaches do students self-report using while working in the laboratory?

Chapter 3 describes the development of the Laboratory Approaches Framework. This framework outlines learning approaches that students use in the chemistry laboratory. This chapter also explores the relationship between students' perceptions of the laboratory environment and their learning approaches through two case studies.

3: Does metacognitive questioning improve student performance in laboratory assessments?

Chapter 4 describes an intervention designed to encourage students to reflect on the laboratory procedures while performing experiments. Students in four laboratory sections completed the intervention worksheets, while students in four laboratory sections taught by the same graduate student instructors performed the same experiments without the worksheets. Exam scores for the two groups are compared.

Remember my friend that knowledge is stronger than memory,
and we should not trust the weaker.

-Bram Stoker, *Dracula*, 1897

Chapter 2: Understanding Student Perceptions of the Chemistry Laboratory

Introduction

A survey instrument was developed to provide insight into student perceptions of the laboratory learning environment in introductory college chemistry. The Laboratory Perceptions Survey was developed to measure student beliefs about the usefulness of the laboratory in learning chemistry, and to measure student perceptions of the laboratory environment.

The measures collected from the survey instrument were used to answer the first research question, “What are students’ beliefs about the usefulness of the chemistry laboratory in high school and college chemistry?” This chapter describes the survey instrument and provides an analysis of student responses. The findings from the survey measures reveal student perceptions about the laboratory environment, as well as what factors affect these perceptions.

Rationale

The Laboratory in Chemistry Education

In the United States, the laboratory program was a part of university-level chemistry education starting in the 19th century (Hofstein & Lunetta, 1982). Laboratory work also became prevalent in high school education, when Charles Eliot, the president of Harvard University, required physics and chemistry laboratory as an admission requirement (Rosen, 1981). Charles Eliot also served on the National Education Association’s Committee of Ten, which was formed in 1892 to recommend standards for the high school curriculum. The committee recommended 200 hours of chemistry in high school, half of which should be laboratory-based (U.S. Bureau of Education, 1893). Laboratory education was seen as an integral part of learning chemistry, as it was believed it was important to engage in the process of doing science to learn science (Hofstein & Lunetta, 1982). University laboratories in the early 1900s focused on learning techniques, and training students to perform qualitative analyses (Lloyd, 1992). These laboratory activities mostly served to confirm or illustrate chemical principles (Hofstein & Lunetta, 1982; Lloyd, 1992).

Educational reform efforts in the 1960s resulted in a shift from focusing on techniques to focusing on data interpretation, and increasing student interest in chemistry (Lloyd, 1992; Hofstein & Lunetta, 1982). More recently published educational standards for primary and secondary education have emphasized the importance of the laboratory in its capacity to teach scientific practices. The Next Generation Science Standards for K-12 Science Education have called for a focus on deeper understanding of content, rather than simply memorizing scientific facts (NGSS Lead States, 2013). These standards also focus on science practices and the process of science as opposed to just learning to practice specific laboratory techniques. The recently

published College Board Standards for Success (2009) also emphasize science practices (formulating scientific questions, making and justifying predictions, collecting and evaluating data, and constructing explanations based on evidence) as opposed to a pure focus on manipulative skills. Both of these standards reflect a shift in the goals of the laboratory program from techniques to broader experimental skills.

Undergraduate Laboratory Reform

Reforms are also occurring at the tertiary level. The needs of the general chemistry curriculum are changing, as general chemistry is often a service course that is required of many college majors. However, the curriculum of undergraduate general chemistry has largely remained the same since the 1960s. The American Chemical Society has created a task force to develop standards for general chemistry education at the undergraduate level (Cooper, 2010). Current ACS guidelines (2015) state that “to prepare students properly for the foundation laboratories, laboratories in introductory or general chemistry courses must be primarily hands-on, supervised laboratory experiences. Students need to be instructed in basic laboratory skills such as safe practices, keeping a notebook, use of electronic balances and volumetric glassware, preparation of solutions, chemical measurements using pH electrodes and spectrophotometers, data analysis, and report writing.” These goals for the laboratory program emphasize the importance of laboratory work.

Throughout the history of the laboratory program, there has been no standardized set of goals (Lloyd, 1992). The laboratory can achieve many goals, and there is much debate about its role in instruction, although it is widely regarded as important. Faculty also differ in their opinions of what students should gain from laboratory instruction. A survey by Bruck, Towns, and Bretz (2010) revealed that faculty identified several different goals for the general chemistry laboratory.

Outcomes of Laboratory Education

A review of the literature suggests that the goals of laboratory instruction in chemistry can be broken down into four categories: learning technical skills, increasing conceptual knowledge, gaining positive attitudes toward chemistry, and developing skills related to the process of scientific inquiry.

One of the early goals of laboratory instruction was teaching students technical bench skills that they could use in the workforce. Although presently most students who take general chemistry will not go on to become chemists, practicing laboratory skills and techniques continues to be a major goal of laboratory instruction. A 1997 survey in which over 200 colleges and universities responded identified learning skills as the second most important goal of the laboratory program (Abraham et al., 1997). A more recent survey of faculty in general chemistry also identified learning laboratory techniques as a key goal (Bruck, Towns, & Bretz, 2010). Current ACS guidelines also emphasize the importance of learning skills and techniques.

Several studies have demonstrated that participating in laboratory activities increases students' ability to perform manipulative skills relative to demonstrations (Yager, Engen, & Snider, 1969) or to watching filmed experiments (Ben-Zvi, Hofstein, Samuel, & Kempa, 1976). Some argue

that learning skills is important not just for the sake of gaining proficiency with laboratory skills, but because students need to understand laboratory techniques in order to perform investigations. Although instructors and curriculum developers have focused more on concept development than techniques, Hegarty-Hazel (1990) maintains that without techniques, students cannot do anything in the laboratory. In order to understand if their measurements are valid, students must understand the techniques that they are performing. Since time in the laboratory is limited, students should learn techniques that they will perform in multiple experiments or techniques that will be important in future courses or their careers (Hegarty-Hazel, 1990).

Another potential benefit of laboratory instruction is the development of chemistry concepts. In one study, students in an introductory biology laboratory who were classified as concrete or transitional learners learned concrete concepts through the laboratory (Purser & Renner, 1983). In a study by Atkinson (1990), students who scored highly on a retention test were able to recall not only the experiment they performed, but also the theory behind the experiment. Few of the other students were able to make these connections. Atkinson stresses that teachers must not assume that students are making the connections with lecture and lab, and that teachers should emphasize these links. The laboratory environment can also promote concept development through conceptual change. In the laboratory, students commonly make observations regarding their experiments. Students' beliefs and initial conceptions affect what they observe in the laboratory (Gunstone & Champagne, 1990). The laboratory provides an opportunity for students to create links between their old ideas or conceptions and their observations. In order to be effective at promoting conceptual change, students need more time in the laboratory to reflect on their data (Gunstone & Champagne, 1990). The laboratory can be used to aid in concept development, or it can serve as a place where concepts learned in lecture can be demonstrated. Kreitler and Kreitler (1974) assert that performing experiments does not lead to concept acquisition, but that students can further explore concepts that they have already learned through laboratory experimentation.

In the chemistry laboratory, students are able to see chemistry hands-on. Through performing experiments, students have the opportunity to act as scientists and observe chemical reactions taking place. Because of this hands-on nature, the laboratory has the capacity to increase positive attitudes toward chemistry and interest in science as a career (Pickering, 1993). Inquiry-based labs, in which students have a part in designing a procedure or experiment, can lead to increased student interest in chemistry (Cummins, Green, & Elliott, 2004). Gardner and Gauld (1990) claim that challenging and open-ended lab work may engage students. However, depending on students' experiences in the laboratory, practical work can lead to negative attitudes towards science. If there is not enough time to complete the experiments, this can lead to negative attitudes about lab and science in general. The authors assert that "merely being in the laboratory and doing lab work there do not, by themselves, foster scientific attitudes: it is the quality of the experiences that students have there that is crucial" (p. 150). Another study of students in a high school chemistry class in Singapore showed that when students perceived laboratory experiments as being related to lecture, they had increased positive attitudes toward chemistry (Wong & Fraser, 1996).

Another potential outcome of laboratory education is the development of metacognitive skills, or the ability to reflect on one's own thinking. Because students have the opportunity to connect their macroscopic observations with what they know about molecular-level chemistry, the laboratory provides a unique opportunity for students to reflect on their thought processes. The laboratory can promote metacognitive skills if the activity is designed to scaffold student reflection on their thought processes. In a case study of students in South Africa, Davidowitz and Rollnick (2003) showed that students who made flow diagrams prior to conducting experiments were able to use these diagrams as metacognitive resources that encouraged the students to think about the instructions and procedures. Kipnis and Hofstein (2008) showed that students engaging in inquiry labs asked higher-order questions compared to students engaging in traditional labs. Another structure of laboratory activities that promotes the development of metacognitive skills is the MORE framework, which stands for Model-Observe-Reflect-Explain. (Tien, Teichert, & Rickey, 2007). Laboratory activities structured using the MORE framework provide students with opportunities to students to explicitly reflect on their initial ideas and compare their initial predictions with their observed results.

Because the laboratory program is extremely expensive, some researchers question whether it is needed at all. Toothacker (1983) recommends eliminating college freshman and sophomore laboratories in physics, because even though the laboratory has the potential to increase positive attitudes toward science, there are much less costly ways of doing so. Several studies show that there is no benefit to laboratory instruction. Dubravcic (1979) revealed that there was no difference on exam performance between students who participated in laboratory activities and those who did not. It may be possible to teach laboratory skills through demonstrations, videos, or simulations (Martínez-Jiménez, Pontes-Pedrajas, Polo, & Climent-Bellido, 2003). Hawkes (2004) claims that students do not need laboratory experience to learn chemistry. He asserts that even though the laboratory can teach manipulative skills, most students taking general chemistry will not need to use these in the future. In a review of twenty years of research on the role of the laboratory in chemistry education, Hofstein and Lunetta (1982) conclude that "there is insufficient data to confirm or reject convincingly many of the statements that have been made about the importance and the effects of laboratory teaching" (p. 212). However, the authors point out that many of these studies that were reviewed only assessed the value of the laboratory in concept development, but did not measure creativity, problem solving skills, teamwork skills, or other potential benefits of the laboratory. In another review, Blosser (1980) agrees with the findings that the benefits of the laboratory program are unclear. She also stresses that the laboratory is a complicated environment, and it is important to consider the specific context and student population that is being studied.

The laboratory can achieve many goals and purposes. What the laboratory does achieve depends on the nature of the experiments, student attitudes, teacher attitudes, and how activities are structured. Most of the research on the purpose or goals of the laboratory has focused on the instructor perspective (Nakhleh, Polles, & Malina, 2002). This study is a response to Nakhleh, Polles, and Malina's call for more understanding of the student perspective of the laboratory.

Student Perceptions of the Learning Environment

Students differ in their perceptions of the learning environment, and these perceptions affect how and what students learn (Ramsden, 1979). Therefore, it is important to understand what students' ideas are regarding the purpose of the laboratory and its role in instruction. Gaining an understanding of students' perceptions of the laboratory will provide insight into what students are able to achieve in the laboratory. In a survey study of university students in Australia, Lizzio, Wilson, and Simons (2002) found that student perceptions of their learning environment affected both their approaches to learning and their learning outcomes. Students who perceived the workload as heavy were more likely to adopt surface-level approaches. Students' perceptions influenced learning outcomes both directly, and indirectly, by influencing their approaches to learning. Perceptions of teaching quality also affected the learning approaches chosen by students. These perceptions were not influenced by students' previous grades.

This study will add to what is already known regarding students' perceptions of the laboratory environment. Previous studies have shown that students' perceptions of the chemistry laboratory affect their attitudes toward chemistry (Lang, Wong, & Fraser, 2005), and that students have a generally favorable attitude toward practical work in chemistry (Sneddon & Hill, 2011).

The data will show what students' beliefs are about the usefulness of the laboratory in high school and college chemistry, and what reasons students provide for their beliefs. By understanding why students perceive the lab as useful or not useful in learning chemistry, educators can better understand the students' perspective. The data will also reveal which laboratory activities students find to be the most useful. Understanding what types of laboratory activities students find useful, and what features of these labs are perceived as useful will give awareness into students' ideas regarding laboratory education.

The relationship between student experiences in high school chemistry and their beliefs regarding the usefulness of the laboratory will also be explored. We expect the following:

- 1) Students will find the laboratory more useful in college than in high school
- 2) Students who designed an experiment or procedure will find the laboratory more useful
- 3) Students who have taken more chemistry courses will find the laboratory more useful
- 4) Students who performed experiments more frequently will find the laboratory more useful

Context of the Study

To provide context for the study, a description of the course structure and laboratory activities is presented below. Typically in undergraduate introductory chemistry courses, students take both a lecture and a laboratory component. The following section will orient the reader toward the specific features of the course in which this study was conducted.

This study was conducted with students enrolled in an introductory chemistry course at a highly selective public university. This introductory chemistry course includes a lecture component and a laboratory component.

For the lecture component, students attend one-hour lecture sections three times per week. Three different professors teach three lecture sections in a large lecture hall that can accommodate up to 500 students. The lecture is offered three times per day by three different professors who use the same lecture materials to ensure consistency between the different lectures. Students are able to attend any of the three sections, and all students in the course take the same exams.

The lecture component of this course has been re-designed to stress conceptual understanding instead of memorization of algorithms and facts. The course is divided into four major topic areas: matter, change, energy, and light.

The lecture was designed based on the following guiding principles:

- present material for each unit within a context that is familiar to students;
- present data that allows for students to discover the underlying patterns and use this knowledge as the basis for explaining the theories developed
- model the process of scientific thinking through the lessons; and
- provide opportunities for students to
 - participate and learn from each other; and
 - generate explanations, evaluate their ideas and revise these explanations

Before each class, students complete a pre-class assignment to prompt their initial ideas about the lecture topic. The pre-class assignments present students with data relevant to the lecture material and ask students to find patterns or draw conclusions from the data using what they already know. To assess student understanding during lecture, the professors use personal response devices (iClickers).

While the lecture did not make explicit reference to the laboratory experiments, the laboratory experiments did often cover the same topics as the lecture (e.g., when the lecture course covered thermochemistry, students did an experiment on heat of combustion of biofuels). The lecture course also made frequent use of demonstrations, emphasizing the value of observation and evaluating experimentally generated data. When performing demonstrations, professors would describe the experimental set-up carefully, ask students for predictions, perform the demonstration, and then ask students for observations and explanations.

For the laboratory component of the course, students attend one four-hour section per week. These sections have approximately 30 students and are facilitated by a graduate student instructor, who is typically a first-year graduate student in Chemistry. The first hour of this session is spent working problems in small groups related to lecture. Students work through problems in a discussion manual and are encouraged to draw conclusions by working together in small groups. The remainder of the laboratory period is spent conducting laboratory experiments.

Description of the Laboratory Activities

In the laboratory, students work in pairs to conduct experiments. Before the lab period, students complete pre-lab exercises that consist of a mixture of calculations and conceptual questions. Pre-lab questions often require students to look up information using the Internet, their textbook, or other library resources.

Domin (1999) classifies laboratory experiments into four types, based on the outcome (known or unknown), the approach (inductive or deductive) and the procedure (given or student-generated). A summary of the four types of experiments is presented in Table 1 below.

Table 1

Types of laboratory experiments as classified by Domin (1999).

<u>Type</u>	<u>Outcome</u>	<u>Approach</u>	<u>Procedure</u>
Expository	Known	Deductive	Given
Inquiry	Unknown	Inductive	Student-generated
Discovery	Known	Inductive	Given
Problem-Based	Known	Deductive	Student-generated

Out of the eleven weeks in which students complete laboratory experiments, eight of the laboratory experiments can be classified as expository, zero can be classified as inquiry, one can be classified as discovery, and two can be classified as problem-based. Laboratory experiments were classified according to the procedures provided in the Fall 2011 Laboratory Manual (Douskey, 2011).

At the time in which the data were collected, the laboratory curriculum was undergoing curricular reform. During the Fall 2011 semester, students performed both ‘old’ and ‘new’ laboratory experiments. In the old laboratory experiments, students would work for one week on one topic. Reform efforts to the laboratory curriculum have focused on structuring the laboratory into a series of modules, as opposed to stand-alone experiments. Rather than spending one week on one topic, students spend multiple weeks exploring the same topic through a series of experiments. This approach allows students to go more in-depth with the content and connect their findings from week to week. The new experiments also include components where different groups of students work on different aspects of the experiment, and must share data to reach conclusions.

In the Fall 2011 semester, two of these experiments used this modular approach. In the first module, Acids in the Environment, students performed two experiments investigating acid-base chemistry. In the first week, students examine the effect of dissolved carbon dioxide gas on the acidity of solutions. In the second week, students perform a titration to determine the concentration of an unknown acid. While these experiments used different techniques, both were tied together through introductory material in the lab manual concerning the effect of acids in the environment, and both used similar concepts. In the second module, Biofuels, students synthesized and characterized a sample of biodiesel. In the first week, students investigated the ecotoxicity of different biofuels by determining the effect of the biofuel on the growth of radish seeds. In the second week, students counted their radish seeds and synthesized biodiesel. Students performed a combustion of their biodiesel product in the third week of the module.

Assessment of student performance in the laboratory consists of three parts: pre-lab exercises (described earlier), in-lab notebook, and post-lab exercises. Students are required to maintain a laboratory notebook in which they record their data and observations. Students do not copy the procedure from their laboratory manual to their notebook before class; they are instructed to summarize the procedure in their notebooks as they are completing the experiment. At the end of

the laboratory period, students turn in carbon copies of their notebook pages to be graded. Post-lab exercises typically consist of a worksheet with both conceptual and calculation questions. Twice during the semester, students complete a formal written laboratory report.

As part of the laboratory portion of the course, students also complete a library research project. Students work in pairs to investigate a topic of their choice, which is generally a household product or some other material. In this project, students must learn about the molecular structure of their chosen topic, and explain how it works using chemical principles learned in the course. Students then present their findings in a poster session.

In this laboratory class, laboratory skills and techniques were not emphasized, although students gained familiarity with using various equipment. Concept building was stressed in the laboratory course, and lecture concepts were reinforced through post-lab questions. The development of positive attitudes toward chemistry was also a goal of the laboratory program. For each laboratory experiment, the laboratory manual included a section relating the experiment to real-world chemistry. This section was intended to expose students to applications of what they learned in class, and increase student interest in the laboratory experiments. The laboratory manual often included check-point questions that would prompt students to think about the experiment; however, these questions were not required. The last experiment included some aspects of experimental design, in which students could gain experience with inquiry.

Methods

Data were collected through responses to a survey administered online via surveymonkey.com in an introductory chemistry course. The survey includes items measuring student perceptions of the value of the laboratory, prior experience in chemistry, and demographic information. The survey was administered twice: once at the beginning of the course, during the second week of the semester, and once during the final week of instruction. Students were recruited to participate in the study via e-mail. Survey responses were collected from all students in the course who consented to participate.

Data Analysis

Logistic regression was performed to test the relationship between students' prior experiences in chemistry and how useful they rated their high school laboratories.

On the survey, students were asked to rate how useful the laboratory was in helping them learn chemistry. On the first survey, students rated their high school laboratory experience, and on the final survey, students rated this college laboratory course. Students were also asked to explain why they chose the rating that they did. The reasons that students provided were coded into categories.

Participants

Participants were students enrolled in first-year chemistry at a large public university. This course is intended primarily for non-chemistry majors who need to take chemistry as a pre-

medical or major requirement. Course enrollment is typically around 1300 students in the fall semester.

All students in the course were invited to participate in the study. Students who did not consent to have their responses collected were dropped from the sample. The final sample used for analysis includes students who responded to all survey items analyzed. Demographic information for this sample is provided in Table 2.

Table 2

Demographic summary of Fall 2011 response population.

Variable	Category	N	%
Major	Life Science/Biology	212	51.3
	Engineering	96	23.2
	Other	105	25.5
SES	Low-income or poor/Working-class	62	15.0
	Middle-class/Decline to state	171	41.4
	Upper-middle/Wealthy	180	43.6
Ethnicity	Chinese/Chinese-American	107	25.9
	Other Asian	125	30.3
	White	86	20.8
	Other	95	23.0
Gender	Female/Decline to State	232	56.2
	Male	181	43.8
Total		413	

Variables Created

Dependent variable

Student self-reported usefulness of the laboratory was measured by the survey question, “How useful was the laboratory in helping you learn chemistry?” Students indicated one of four responses choices: “Not at all useful,” “Not very useful,” “Useful,” and “Very useful.” For analysis purposes, responses were collapsed into a dichotomous variable in which “Not at all useful” and “Not very useful” were coded as 0 = “Not useful,” and “Useful” and “Very useful” were coded as 1 = “Useful.”

Independent variable

Data about students’ previous semesters of chemistry, previous frequency of chemistry lab, experiences designing an experiment or procedure in lab, college major, socioeconomic status, ethnicity, and gender were collected by student self-report from the available options on the survey. The dummy variables were created to describe student self-reports are described below.

Dummy variables created to represent previous semesters of chemistry: **sem_012** (0, 1, or 2 semesters) with **sem_345** (3, 4, or more than 4 semesters) as reference.

Dummy variables created to represent previous frequency of chemistry lab are **low_freq** (Did not take chemistry, Never, Once or twice a semester, Once a month), **high_freq** (Once a week, More than once a week) with **med_freq** (Twice a month) as reference.

Dummy variable created to represent students' experience designing a procedure or experiment: **design** (Designed an experiment = 1, Designed a procedure to solve a given problem = 1, did not design an experiment or procedure = 0)]

Dummy variables created to represent college major are: **engineering** (Engineering), **othermajor** (Physical Sciences, Mathematics, Humanities, Undeclared), with **lifesci** (Life Sciences/Biology) as reference.

Dummy variables created to represent socioeconomic status are **ses_high** (Wealthy, Upper Middle/Professional-Middle), **ses_low** (Working class, Low-income or poor), with **ses_med** (Middle-class, Decline to state) as reference.

Dummy variables created to represent ethnicity are **chinese** (Chinese/Chinese-American), **otherasian** (Japanese/Japanese-American, Korean/Korean-American, South East Asian, Filipino/Filipino-American, East Indian/Pakistani, Other Asian), **other_race** (Mexican/Mexican-American/Chicano, African American/Black, Spanish-American/Latino/Latina, International Student), with **white** (White) as the reference category. Students who selected multiple ethnicities were grouped with **other_race**, unless they selected multiple ethnicities that were grouped with **otherasian**, in which case they were included with **otherasian**.

Dummy variable created to represent gender: **male** (Male=1, Female or Decline to state = 0)

Data

Usefulness Ratings in High School and College Chemistry

Student ratings of how useful the lab was in helping them learn chemistry are presented in Table 3 below. Survey 1 refers to students' experiences with their high school chemistry laboratories, and Survey 2 refers to students' experiences in college chemistry. In high school, 54 percent of students rated the lab as useful, compared with 60 percent in college.

Table 3

Student ratings of the usefulness of the laboratory in high school and college chemistry.

	<u>Survey 1</u>		<u>Survey 2</u>	
	N	%	N	%
Useful	223	54.0	249	60.3
Not Useful	190	46.0	164	39.7
Total	413		413	

Reasons the Laboratory was Useful or Not Useful

Students were also asked on the survey to indicate why the laboratory was useful or not useful. These responses were grouped into categories. Table 4 below shows the student free responses for why the laboratory was useful in helping them learn chemistry. Table 5 below shows student

free responses for why the laboratory was not useful in helping them learn chemistry. The most common reason given by students that the laboratory was useful was that it related to or applied the lecture content for both high school and college chemistry. The most common reason that the laboratory was not useful differed in high school and college. In high school chemistry, the most common reason that the laboratory was not useful was that students simply followed a procedure without thinking about the steps they were performing. In college, the most common reason that the laboratory was not useful was that it did not relate to the lecture content.

Table 4

Student free responses answering why the laboratory was useful in helping learn chemistry.

	<u>Survey 1</u>		<u>Survey 2</u>	
	N	%*	N	%*
Labs related to or applied lecture content	78	35.0	112	45.0
Labs provided a visual or hands-on way of learning the content	67	30.0	52	20.9
Students learned useful lab skills	29	13.0	11	4.4
Lab was related to real life or real-world applications	24	10.8	21	8.4
Lab was more in-depth than lecture/went beyond lecture	31	13.9	40	16.0
Other	27	12.1	46	18.5

*Percent listed is percent of students who indicated that reason. Since some students indicated multiple reasons, the percentages do not add to 100.

Table 5

Student free responses answering why the laboratory was not useful in helping learn chemistry.

	<u>Survey 1</u>		<u>Survey 2</u>	
	N	%*	N	%*
Students did not do labs, or did labs infrequently	54	28.4	0	0.0
Labs did not relate to lecture content	32	16.8	85	51.8
Lab was busy work	2	1.0	18	11.0
Labs were too simple	45	23.6	15	10.4
Students merely followed procedure in lab/did not learn concepts	61	32.1	56	34.1
Lab contained too many errors, or was disorganized	8	4.2	10	6.1
Other	16	8.4	12	7.3

*Percent listed is percent of students who indicated that reason. Since some students indicated multiple reasons, the percentages do not add to 100.

Most Useful Laboratory Experiment

Students were asked to indicate which lab was the most useful in helping them learn chemistry on the final survey. Responses to this question are summarized in Table 6 below. The most common lab listed as the most useful was Lab 4: Acids in the Environment 2: Indicator Titration, with 43 percent of students naming this lab.

Table 6

Responses to the question "Of the laboratory experiments in Chem 1A, which was the most useful in helping you learn chemistry?"

	N	%
Lab 1: Airbags	19	4.6
Lab 2: Smells	23	5.6
Lab 3: Acids in the Environment 1: Preparation and Properties of Gases	4	1.0
Lab 4: Acids in the Environment 2: Indicator Titration	177	42.9
Lab 5: Equilibrium Investigations	32	7.7
Lab 6: Depolymerization of PLA	25	6.1
Lab 7: Biofuels 1: Estimating Relative Ecotoxicity	12	2.9
Lab 8: Biofuels 2: Synthesis of Biodiesel	10	2.4
Lab 9: Biofuels 3: Biodiesel Heat of Combustion	70	16.9
Lab 10: Solubility and Spontaneity	23	5.6
Lab 11: Molecules, Light, and Dyes	18	4.4
Total	413	

Prior Experience and Usefulness Rating

In order to determine if any of the prior experience measures had a significant effect on students' perceptions of the usefulness of the laboratory, a logistic regression model was used. Variables used in analysis are described in the methods section. Table 7 shows the summary of prior experience measures for students who rated the laboratory in high school as either useful or not useful. Logistic regression statistics are shown in Table 8.

If students designed an experiment or procedure, they were more likely to rate the lab as useful in helping them learn chemistry ($\beta = 0.67$, $p = 0.003$). Students who had lab less than twice a month were less likely to rate the lab as useful ($\beta = -1.61$, $p < 0.001$).

Table 7

Summary of prior experience variables by usefulness rating on Survey 1.

Variable	Category	not useful		useful	
Frequency of lab in HS	Once a month or less	47	24.7	9	4.0
	Twice a month	97	51.1	104	46.4
	Once a week or more	46	24.2	111	49.6
Previous semesters of chem	0, 1, 2	124	65.3	135	60.3
	3, 4, more than 4	66	34.7	89	39.7
Designed an experiment or procedure	Yes	60	31.6	127	56.7
	No	130	68.4	97	43.3
Total		190		224	

Table 8

Logistic regression model predicting usefulness rating.

Variable	β	SE	odds ratio	p-value
design	0.67	0.23	1.95	0.003
low_freq	-1.61	0.29	0.20	<0.001
high_freq	0.34	0.27	1.41	0.202

Students who Changed Usefulness Rating

Comparing the results from Survey 1 and Survey 2, 58 percent of survey respondents had no change in their usefulness rating (Table 9). 74 respondents (18 percent) changed their rating from useful to not useful, and 100 respondents (24 percent) changed their rating from not useful to useful.

Table 10 shows the prior experience variables for both of these groups of students who changed their rating from high school to college. To examine the relationship between semesters of high school chemistry and change in usefulness rating, a chi-square test was performed. The relation between these variables was not significant, χ^2 (1, N=174) = 1.21, $p = 0.27$. To examine the relationship between frequency of laboratory in high school and change in usefulness rating, a chi-square test was performed. The relation between these variables was significant, χ^2 (2, N=174) = 33.56, $p < 0.001$. Students who had a low frequency of lab in high school were more likely to change their rating from not useful to useful. To examine the relationship between designing an experiment or procedure in high school and change in usefulness rating, a chi-square test was performed. The relation between these variables was significant, χ^2 (1, N=174) = 4.35, $p = 0.037$. Students who did not design an experiment in high school were more likely to change their rating from not useful to useful.

Grades for these two groups were also compared. There was no significant difference in midterm 1 percent score between students who changed from useful to not useful (M = 74.9, SD = 10.3) than students who changed from not useful to useful (M = 75.2, SD = 9.8), $t(172) = -0.22$, $p = 0.82$. There was also no significant difference in laboratory grade between students who changed from useful to not useful (M = 92.1, SD = 4.4) than students who changed from not useful to useful (M = 91.9, SD = 4.4), $t(172) = 0.34$, $p = 0.73$. Comparing lecture grades, there was no significant difference between students who changed from useful to not useful (M = 77.6, SD = 11.0) than students who changed from not useful to useful (M = 77.9, SD = 9.8), $t(172) = -0.19$, $p = 0.85$.

The reasons these students provided for their usefulness ratings are summarized in Tables 11-14. Students who found their high school laboratories not useful indicated that they were just following the procedure, the experiments were too simple, and laboratory experiments were infrequent (Table 11). This same group of students indicated that college laboratories were useful because they applied the lecture material (Table 12). Students who found their high school laboratories useful indicated that the laboratory related to lecture content and provided a visual or hands-on way of learning this content (Table 13). These same students found the college laboratories to not be useful because it did not relate to the lecture (Table 14).

Table 9

Summary of students who changed in their usefulness rating from Survey 1 to Survey 2.

	<u>N</u>	<u>%</u>
Useful → Not useful	74	17.9
Not useful → Useful	100	24.2
No Change	239	57.9
Total	413	

Table 10

Summary of prior experience variables for students who changed their usefulness rating.

	<u>Semesters of chemistry in high school</u>			Total
	0-2 semesters	3 or more semesters		
Useful → Not Useful	49 (66.2%)	25 (33.8%)		74
Not Useful → Useful	58 (58.0%)	42 (42.0%)		100
	<u>Frequency of laboratory experiments in high school</u>			Total
	Once a month or less	Twice a month	Once a week or more	
Useful → Not Useful	9 (12.2%)	26 (35.1%)	39 (52.7%)	74
Not Useful → Useful	55 (55.0%)	18 (18.0%)	27 (27.0%)	100
	<u>Experience designing an experiment or procedure</u>			Total
	Did not design an experiment or procedure	Designed an experiment or procedure		
Useful → Not Useful	38 (51.4%)	36 (48.6%)		74
Not Useful → Useful	67 (67.0%)	33 (33.0%)		100

Tables 11-12 represent students who found the laboratory not useful in high school chemistry and useful in college chemistry.

Table 11

Student free responses answering why the laboratory was not useful in helping to learn chemistry in high school.

	<u>N</u>	<u>%*</u>
Students did not do labs, or did labs infrequently	29	20.0
Labs did not relate to lecture content	17	17.0
Lab was busy work	0	0.0
Labs were too simple	24	24.0
Students merely followed procedure in lab/did not learn concepts	28	28.0
Lab contained too many errors, or was disorganized	5	5.0
Other	14	14.0

*Percent listed is percent of students who indicated that reason. Since some students indicated multiple reasons, the percentages do not add to 100.

Table 12

Student free responses answering why the laboratory was useful in helping to learn chemistry in college.

	<u>N</u>	<u>%*</u>
Labs related to or applied lecture content	45	45.0
Labs provided a visual or hands-on way of learning the content	18	18.0
Students learned useful lab skills	7	7.0
Lab was related to real life or real-world applications	5	5.0
Lab was more in-depth than lecture/went beyond lecture	17	17.0
Other	19	19.0

*Percent listed is percent of students who indicated that reason. Since some students indicated multiple reasons, the percentages do not add to 100.

Tables 13-14 represent students who found the laboratory useful in high school chemistry and not useful in college chemistry.

Table 13

Student free responses answering why the laboratory was useful in helping to learn chemistry in high school.

	<u>N</u>	<u>%*</u>
Labs related to or applied lecture content	28	37.8
Labs provided a visual or hands-on way of learning the content	24	32.4
Students learned useful lab skills	8	10.8
Lab was related to real life or real-world applications	12	16.2
Lab was more in-depth than lecture/went beyond lecture	6	8.2
Other	10	13.5

*Percent listed is percent of students who indicated that reason. Since some students indicated multiple reasons, the percentages do not add to 100.

Table 14

Student free responses answering why the laboratory was not useful in helping to learn chemistry in college.

	<u>N</u>	<u>%*</u>
Students did not do labs, or did labs infrequently	0	0.0
Labs did not relate to lecture content	40	54.1
Lab was busy work	6	8.1
Labs were too simple	12	16.2
Students merely followed procedure in lab/did not learn concepts	18	24.3
Lab contained too many errors, or was disorganized	5	6.8
Other	9	12.1

*Percent listed is percent of students who indicated that reason. Since some students indicated multiple reasons, the percents do not add to 100.

Discussion

Usefulness Ratings

On the survey, 54% of respondents said that the laboratory was useful in helping them learn chemistry in high school, compared with 60% of respondents indicating the laboratory was useful in college chemistry. It was expected that more students would find the laboratory useful in college. However, a significant portion of students rated the laboratory as not useful in both high school and college chemistry. Students were also asked to provide a reason for their usefulness rating. Because many students provided similar reasons, the reasons were grouped into categories in order to understand overall trends. These reasons are summarized above in Tables 4-5. Sample responses for each category are provided below in Tables 15-16. Table 15 shows sample responses for why the laboratory was useful, and Table 16 shows sample responses for why the laboratory was not useful.

Reasons for Usefulness Ratings

Students' reasons for why the laboratory was useful in helping them learn chemistry were similar in high school and college. The most common reason given was that the laboratory related to or applied lecture content, with the next most common reason being that the laboratory was visual or hands-on. In both of these reasons, the students are indicating that the usefulness of the laboratory is in helping them learn the lecture content, or that the laboratory is secondary to the lecture. A much smaller percentage of students listed reasons specific to learning in the laboratory. Only 14% (high school) and 16% (college) said that the laboratory was more in depth or went beyond lecture topics. This suggests that students see the value of the lab as it relates to learning lecture content, and not as it relates to learning laboratory or experimental skills.

Students' reasons for why the laboratory was not useful were different in high school and in college. The most common reason that the laboratory was not useful in high school was that students did not do labs, or that they did labs infrequently. In college, all students performed experiments each week, and no students indicated that labs were too infrequent. Students in high school were more likely to say that the experiments were too simple or too basic. Many of these students indicated that they were merely confirming material that they already knew, and they did not see the value in performing these simplistic experiments. The most common reason students gave that the lab was not useful in college was that it did not relate to the lecture content. Over half of students who said that the laboratory was not useful indicated that it did not relate to the lecture material. In both college and high school, approximately one-third of students said that they were just following the laboratory procedure and not thinking critically about the chemistry.

Table 15

Sample responses of reasons the laboratory was useful.

Reason	Sample Responses
Labs related to lecture content	They reinforced the material covered in lecture. Labs related to lecture and gave more practice and chances to learn about chemistry concepts than in lecture
Labs provided a visual or hands-on way of learning the content	I was able to see a physical model of what we were learning. The experiments helped visualize material taught in lecture.
Students learned useful lab skills	I learned about the importance of reading about the experiment prior to the lab, writing down any observations and data, and following safety guidelines. They gave me a better understanding of how to use the equipment. Taught me concepts and methods used in modern chemistry.
Lab was related to real life or real-world applications	Application of chemistry concepts made me realize how present chemistry is in everyday life. Connects theory with real-world applications.
Lab was more in-depth than lecture/went beyond lecture	They encouraged me to think deeper into the topic, making me learn more via reflection. It went further into the topics we were learning at the time, sometimes.

Table 16

Sample responses of reasons the laboratory was not useful.

Reason	Sample Responses
Students did not do labs, or did labs infrequently	We didn't perform many experiments. The students weren't really involved in the experiments, they were mostly demonstrations.
Labs did not relate to lecture content	Saw little connection between the lab and what we learned. I don't think they were closely correlated enough with the concepts we were trying to learn.
Labs were busy work	Lab was pretty much just a way to drain 4 hours of my day and not help me on the midterm. Lab felt like busy work instead of illustrating the chemical principle being used.
Labs were too simple	They usually proved something that was already known. They were a lot more simple than the rigor of the class.
Students merely followed procedure	I just followed the instructions/procedures, but I didn't always understand what I was doing. We usually rushed through experiments in class and did not really help me understand the underlying concepts. It didn't help me learn course material, just taught me how to conduct experiments.
Lab contained too many errors, or was disorganized	Poorly organized. Way too many factors of error that threw off our data. They were often inaccurate and did not properly teach us the concept because of our faulty data. They usually did not yield the results they were supposed to.

Most Useful Experiment

On the survey, students were also asked to indicate which laboratory experiment was the most useful in helping them learn chemistry. The most common choices were Lab 4: Acids in the Environment 2: Indicator Titration (43%), and Lab 9: Biofuels 3: Biofuels Heat of (17%).

In Lab 4: Acids in the Environment 2: Indicator Titration, students performed a titration to determine the molarity of a solution of hydrochloric acid. This lab aligned with lectures on acid/base chemistry. Lab 4 was the second experiment in a series of two experiments concerning acids and bases. The previous week, students conducted an experiment investigating the effects of gaseous carbon dioxide on acidity. That experiment did not use the same laboratory techniques and glassware, but students used indicators, which they also used in Lab 4, and both experiments dealt with similar concepts.

In Lab 9: Biofuels 3: Biofuels Heat of Combustion, students burned a sample of biodiesel in order to determine its heat of combustion. This experiment was the last experiment in a three-week module about biofuels. Students synthesized biodiesel in weeks 1 and 2, and performed the combustion in week 3. These experiments were aligned with lectures on heats of combustion and enthalpy of reactions.

Both of these experiments were labs that required students to write formal written reports. These laboratory experiments were also part of larger modules involving multiple experiments on the same topic.

Prior Experience and Usefulness Rating

A logistic regression model was used to determine the contribution of students' high school laboratory experiences on respondent rating of how useful the laboratory was in high school. The frequency of laboratory experiments in high school and whether or not students designed an experiment or procedure were significant predictors of usefulness rating. Students who performed experiments more frequently in high school were more likely to rate the lab as useful, and students who designed an experiment or procedure were more likely to rate the lab as useful. The number of semesters of chemistry students had did not have a significant effect on their usefulness rating. These results suggest that the amount of chemistry students have taken does not affect their perception of the laboratory, but the quality of their laboratory experience does have a significant effect.

Students who Changed Usefulness Rating from High School to College

Most of the students (58%) did not change in their usefulness rating from high school to college chemistry. One hundred students (24%) rated the lab as not useful in high school rated the lab as useful in college, and 74 students (18%) rated the lab as useful in high school, but not in college.

Students who increased in their perception of the usefulness of the laboratory tended to have poorer quality experiences with the laboratory in high school. These students were less likely to have designed an experiment or procedure, and did not do experiments as frequently. The most common reasons listed that the laboratory was not useful in high school were that students just followed procedure, the experiments were too simple, and students did labs infrequently. The most common reason that the laboratory was useful in college chemistry was that it related to the lecture content.

Students who decreased in their perception of the usefulness of the laboratory tended to have higher quality experiences in high school. These students were more likely to design an experiment or procedure, and performed experiments more frequently. The most common reason students gave that the laboratory was useful in high school was that it related to lecture, and the most common reason that the laboratory was not useful in college chemistry was that it did not relate to the lecture.

These findings are consistent with other studies regarding student perceptions of the laboratory environment. In a study of high school students in Singapore, Lang, Wong, and Fraser (2005) found that open-endedness, or the degree to which the laboratory emphasized an open-ended

approach to experimentation, and material environment, or the degree to which the materials were adequate, were both significant predictors of gifted students' attitudes toward chemistry.

The fact that perceptions of open-endedness correlated with increased positive attitudes toward chemistry is consistent with our finding that students who designed an experiment or procedure were more likely to perceive the lab as useful.

The finding that perceptions of adequate material environment were related with increased attitudes toward chemistry is also consistent with our findings that several students listed "lack of resources" as a reason that the lab was not useful. In our coding of reasons, lack of resources was not a separate category. Students who cited lack of resources as the reason that the lab was not useful were either grouped with "Students did not do labs, or did labs infrequently" or "Labs were too simple" based on their specific comments.

In a study of student perceptions of undergraduate chemistry in Scotland, Sneddon and Hill (2011) found that students suggested linking theory to practical work as the main area in which their undergraduate chemistry courses could improve. When these students were asked about the most important goals of laboratory, they listed illustrating theory and learning experimental skills. These findings are consistent with our findings that students who perceive the laboratory as related to the lecture content find the laboratory useful, and students who perceive the laboratory as not related to the lecture content find it not useful. The result that students listed illustrating theory and learning experimental skills as the most important goals of the lab also aligns with our result that students thought the laboratory was useful because it provided a visual way to learn lecture content.

When asked which laboratory experiments were the most useful in helping them learn chemistry, students cited Lab 4: Acids in the Environment 2: Indicator Titration (43%), and Lab 9: Biofuels 3: Biofuels Heat of (17%). Both of these experiments were part of multi-week investigations on the same topic. Modular labs have also been linked to increased content knowledge in other contexts. In the MORE (Model-Observe-Reflect-Explain) framework, students who completed related experiments in modules had higher content knowledge as measured by final exam performance than students who did not (Rickey, 1999).

Both of the laboratory experiments that students cited as the most useful were also labs in which students were required to write formal written laboratory reports. Writing in science has been shown to increase content knowledge (Rudd II, Greenbowe, Hand, & Legg, 2001). Students using the Science Writing Heuristic, a scaffold for writing laboratory reports, had increased performance on a lecture exam and increased performance on a lab practical task, even though they spent the same amount of time on their writing assignment as their peers did on other post-lab questions. This suggests that writing leads to deeper learning, which is consistent with our result that students indicated that they learned the most from the experiments in which they were required to write formal reports.

Conclusions

Students who have a more substantive experience with the laboratory are more likely to perceive the laboratory as a useful component of chemistry education. These students are more engaged with the laboratory and view it as valuable in learning chemistry.

In examining whether or not students rated their high school laboratories as useful, two prior experience measures were significant predictors of usefulness: the frequency with which students attended lab, and whether or not students designed an experiment. Students who performed experiments once a month or less were less likely to think that the laboratory was useful in helping them learn chemistry. The number of semesters of chemistry was not a significant predictor of usefulness rating, suggesting that students need laboratory experience, rather than chemistry experience, to appreciate the contribution of laboratory education. One explanation is that when students are designing labs, they are more engaged in the process of experimentation. If students are simply following the procedure, they are not participating in the laboratory in a meaningful way, and do not see the value in performing experiments. An alternative explanation is that the students who found the laboratory to be more useful were higher-performing students. Comparing the grades of the students who rated the lab as useful and the students who rated the lab as not useful, there was no difference between the two groups. Because there was no difference in grades between these two groups, this explanation can be rejected.

The reasons students listed that the laboratory was useful or not useful also indicate students' beliefs about the purpose and the value of the laboratory. The main reasons that students listed for the laboratory being useful in helping them learn chemistry were that the laboratory related to or applied lecture content, and that the laboratory provided a hands-on or visual way to learn the content. These reasons indicate that students view the laboratory as primarily useful in helping them learn the lecture content. Only a small percentage of students said that the laboratory allowed them to think more deeply about content, or discussed laboratory skills that they learned. Considering the goals identified in the literature of learning technical skills, increasing conceptual knowledge, gaining positive attitudes toward chemistry, and developing skills related to the process of scientific inquiry, student perceptions of the value of the laboratory differ from these goals. Students focused more on the laboratory as a supplement to the lecture, rather than having its own goals and purposes.

Students did not find laboratories in which they felt that they were simply following the procedure to be helpful in learning chemistry. This indicates that it is not enough for students to just do experiments, but they must engage in the process to learn chemistry through experimentation. Also, labs that were too simple were not useful. In comments, several students indicated that their high school laboratories were not useful in helping them learn chemistry because they were simply performing experiments to confirm what they already knew. In order for students to have a meaningful laboratory experience, students need to have a laboratory problem that is difficult enough to be engaging.

The fact that students rated Labs 4 and 9 as the most useful also reveals students' ideas about what types of laboratory activities help them learn chemistry. Both of these laboratory experiments were part of larger modules on the same topic. Performing experiments that are part

of larger modules may reduce cognitive overload. If students are familiar with the techniques and concepts used in the experiment, then they will be able to engage and think about the procedure. In laboratories, students must process a large amount of information, and reducing this cognitive load can lead to increased understanding of the experiment (Johnstone, Sleet, & Vianna, 1994).

Both of these laboratory experiments also involved written laboratory reports. One alternate explanation is that students spent more time on these experiments since they had to complete formal written reports. While this is possible, another study found that the act of writing led to increased content knowledge even though students did not spend more time on these assignments (Rudd et al., 2001). Another alternate explanation is that students found these labs more useful because these experiments were tied more directly to the lecture content. While all of the laboratory experiments were related to lecture content, it may have been easier for students to draw parallels between the titration labs and lectures on acid-base titrations than for other topics.

Most of the students' beliefs about the usefulness of the laboratory were the same in high school and in college chemistry. However, a significant percent of students (40 percent) changed in their usefulness rating from high school to college. Students who increased in their perception of the usefulness of the laboratory tended to have infrequent exposure to laboratory experiments in high school in which they did not have opportunities to design their own experiments. Students who decreased in their perception of the usefulness of the laboratory tended to have frequent laboratories in high school in which they had opportunities to design their own procedure or experiment. These findings indicate that students who have meaningful experiences in the laboratory in which they are able to design an experiment find the laboratory much more useful.

Implications

The laboratory can be very effective in increasing student attitudes toward chemistry, content knowledge, laboratory skills, and inquiry skills. However, if laboratory activities are structured in such a way that the experiments do not require students to engage with the procedures, the laboratory will not reach its potential to be an effective instructional tool. We recommend laboratory experiments that are modular, incorporate elements of design, and that are difficult enough to engage the students.

The way students perceive the laboratory affects their approach to learning in the laboratory and what they gain from laboratory instruction. Students who perceive that the laboratory is related to the lecture are more likely to perceive the laboratory as useful. In this course, a significant portion of students did not see the laboratory as related to the lecture, even though several students thought the laboratory was related. It is important for instructors to highlight the connections between the laboratory portion of the course and the lecture portion of the course.

Students are often assessed in the laboratory through written reports or post-lab calculations, which may assess content knowledge but often fail to capture other outcomes of the laboratory, such as the ability to interpret data, formulate questions, and design an experiment. Student performance as measured by written examination is only weakly correlated with performance on assessments of their practical skills (Ben-Zvi, Hofstein, Samuel, & Kempa, 1977). The manner in

which students are assessed signals to students what is important and what they should focus on. The types of assessments also signal to students what assignments are important. If the laboratory portion of the course counts for a small percentage of the grade, this sends a message to students that the laboratory is less important than the lecture.

When designing a laboratory course, it is important to have clear goals for laboratory outcomes, and assessments that align with these goals. If the goals of the laboratory are made clear to the students, the students will understand what they should be learning from the laboratory. Students also benefit from explicit connections between lecture material and laboratory material. Some students are able to make these connections themselves; however, as seen from this study, students in the same course perceive the lecture as both related to and not related to the laboratory.

Students also need time to reflect on their data so that they understand what data they have collected and why. If students simply follow the procedures without understanding them, they will not gain as much from the laboratory. Allowing students to design part of the experiment or procedure gives students an opportunity to engage in the process of experimentation.

They say I've got to learn but nobody's here to teach me.
If they can't understand it, how can they reach me?

-Stevie Wonder, Artis Leon Ivey Jr., Doug Rasheed,
& Larry Sanders, *Gangsta's Paradise*, 1994

Chapter 3: Student Approaches to Learning in the Chemistry Laboratory

Introduction

This chapter describes the development of the Laboratory Approaches Framework. This Framework characterizes students' approaches to learning in the instructional laboratory. The data collected for this chapter were used to answer the second research question, "What approaches do students self-report using while working in the laboratory?"

This chapter also describes two case studies comparing students with different learning approaches as described by the Laboratory Approaches Framework. These case studies highlight the relationship between students' beliefs about the purpose of the laboratory and their approaches to learning.

Rationale

Learning approaches

The concept of learning approaches was first introduced by Marton and Säljö in 1976. Marton and Säljö characterized *deep* approaches as approaches in which students aim to understand the intent or meaning of the content they are learning, in contrast to *surface-level* approaches, in which students aim to remember the content. While Marton and Säljö's original characterization of deep and surface level approaches was based on a reading task, these general styles of approaches can be extended to other learning contexts. The specific behaviors that students engage in when taking a deep or a surface approach will depend on the nature of the task and the specific learning environment.

Learning approaches are affected by several factors, including student perceptions of the learning environment (Entwistle, 1991; Ramsden, 1979), student perceptions of content relevance (Minasian-Batmanian, Lingard, & Prosser, 2006), the method in which students are assessed (Scouller, 2006), and the teaching methods used (Trigwell, Prosser, & Waterhouse, 1999). Because student learning approaches are context-dependent, it is important to situate student learning approaches in the learning environment.

This study provides a description of learning approaches of undergraduate students in the chemistry laboratory environment. Since student learning outcomes are related to the ways in which students approach learning, characterizing approaches to learning in the laboratory will allow researchers to better understand what outcomes students can achieve in the laboratory. The aim of this interview study is to describe and characterize the different types of learning approaches that students adopt while working in undergraduate chemistry laboratories. This

chapter will also examine the relationship between students' perceptions of the laboratory environment and their learning approach through case studies.

Methods

Framework Development

A stratified sample of 18 students enrolled in an introductory chemistry course at a large public university was interviewed during the middle of the semester. Demographic data were collected to ensure that the sample of students was representative of the whole class population. The interview was conducted to understand how students approach learning in the laboratory. The interviews were semi-structured, with follow-up questions depending on individual student responses. Students were interviewed in the middle of the semester to ensure that they had some familiarity with the course structure and the laboratory activities in the course. Interviews were transcribed using InqScribe. Since students attend lab sections on different days, interviews were scheduled after the student's lab section had met for that week to ensure that all students had completed the same number of laboratory experiments.

A framework describing students' approaches to learning in the laboratory was developed using student interview data. The framework describes students' approaches to learning in four categories: beliefs about learning in the laboratory, working with experimental procedures, evaluating data, and questioning peers/instructor. Students were assigned individual codes for each of these categories, and an overall code combining each of these four categories that describes their approach level.

Case Study Analysis

To explore the relationship between students' learning approaches in the laboratory and their beliefs about the purpose of the laboratory, two students were further analyzed via case studies. The students in the case studies were interviewed three times during the semester: at the beginning, middle, and end. The interview at the beginning of the semester was used to characterize student thinking regarding their prior experiences in high school. In the final interview, students reflected on their laboratory experiences in college chemistry. The interview during the middle of the semester was used to describe student approaches to learning in the laboratory environment. Interviews were transcribed using InqScribe.

The two students selected for case studies were chosen because they represent different learning approach levels (as described in this chapter). Student 1 was characterized as having a Level 3 approach to learning in the laboratory. She earned a grade of 78 in the lecture course, which places her in the 52nd percentile, and corresponds with a letter grade of "B". In the laboratory, Student 1 earned a grade of 95, which places her in the 70th percentile for the class. Student 22 was characterized as having a Level 1 approach to learning in the laboratory. She earned a grade of 75 in the lecture class, which places her in the 44th percentile, and corresponds with a letter grade of "B". In the laboratory, Student 22 earned a grade of 94, which places her in the 62nd percentile for the class.

Participants

Participants were students enrolled in a first-year chemistry course at a large public university. This course is intended primarily for non-chemistry majors who need to take chemistry as a pre-medical or major requirement. Course enrollment is typically around 1300 students in the fall semester. The course is the same as the course described in Chapter 2, Understanding Student Perceptions of the Chemistry Laboratory.

Data Collection

During the second week of the semester, a survey was sent out to the entire class through the course website. The survey was accessed through an online survey tool (surveymonkey.com). On the survey, students were asked to indicate if they were willing to participate in individual interviews. Students who indicated that they were willing to participate were asked to provide an e-mail address by which they could be contacted to schedule an interview. A recruitment e-mail was sent to these students inviting them to participate in the individual interviews. From the students who responded, a stratified sample was chosen for interviews to ensure that the sample was representative of the whole class population. Demographics considered in selecting students were SES, major, gender, and ethnicity. Table 17 shows a comparison of demographic information between the class and the interview sample. The class sample includes responses from students who answered all demographic questions, and were still enrolled at the end of the semester.

Each student was interviewed in the middle of the semester to ensure that students had familiarity with the course and the laboratory environment. Students were asked questions about their perceptions of the laboratory environment, their experiences working in groups in the laboratory, and their thoughts on the value of the laboratory component of the course. The interview was semi-structured, and follow-up questions were asked as appropriate per each student's individual responses. Students were also asked to look at two laboratory procedures: one that they had completed, and one that they had not completed. Students were then asked to 'think aloud' and describe how they had approached or would approach completing the laboratory experiment. Similar think-aloud protocols have been used in education research to document students' cognitive processes (Ericsson & Simon, 1993; De Grave, Boshuizen, & Schmidt, 1996; Kuusela & Paul, 2000). The complete interview protocol can be found in Appendix A.1. Interview protocols for the additional interviews used in case studies can be found in Appendix A.2.

Table 17

Demographic data of Interview Sample and Fall 2011 Class.

Number of students (N) and percentage of sample population (%) represented, for students self-reporting in each demographic category.

Variable	Category	Fall 2011 Sample		Interview Sample	
		N	%	N	%
Major	Life Science/Biology	394	50.0	12	66.7
	Engineering	188	23.9	4	22.2
	Physical Science/Mathematics	27	3.4	0	0
	Humanities	21	2.7	0	0
	Undeclared	100	12.7	1	5.6
	Other	58	7.4	1	5.6
SES	Low-income or poor	65	8.2	2	11.1
	Working-class	75	9.5	0	0
	Middle-class	291	36.3	8	44.4
	Upper-middle or professional-middle	329	41.8	7	38.9
	Wealthy	19	2.4	1	5.6
	Decline to state	9	1.1	0	0
Ethnicity	Chinese/Chinese-American	201	25.5	5	27.8
	East Indian/Pakistani	58	7.4	3	16.7
	Korean/Korean-American	65	8.2	2	11.1
	South East Asian	32	4.1	2	11.1
	Other Asian	28	3.5	0	0
	Mexican/Latino/African-American/Black	25	3.2	0	0
	White	169	21.4	4	22.2
	Mixed	139	17.6	2	11.1
	Other	48	6.0	0	0
	Decline to state	23	2.9	0	0
Gender	Female	425	54.0	12	66.7
	Male	355	45.1	6	33.3
	Decline to state	8	1.0	0	0
Total		788		18	

Framework Development

Using a grounded theory approach (Glaser & Strauss, 1967; Taber, 2000), a framework describing student approaches to learning chemistry was developed. An initial subset of the interview videos was watched and from these videos, an initial framework of three levels of approaches was constructed.

These three levels were further refined into four categories describing students' approaches to learning in the laboratory: beliefs about the purpose of the laboratory, working with experimental procedures, evaluating data and experimental results, and questioning peers/GSI.

1) Beliefs about the purpose of the laboratory: Students' interview answers about the purpose of the laboratory and the role of the laboratory in learning chemistry were the primary source of evidence used to categorize students' beliefs. Beliefs ranged from believing that laboratory activities add no value to learning chemistry to believing that the laboratory is essential for learning and understanding chemical concepts.

2) Working with experimental procedures: Students' self-report of their approach to following procedures given to them in the lab manual were used as evidence of how students interpret and work with experimental procedures. Approaches ranged from simply following the instructions to thinking about the purpose of the procedures before carrying them out.

3) Evaluating data and experimental results: Students' self-report of how they judged the correctness of their results and what they would do about an unexpected result were used to categorize how students evaluated data in the laboratory. Levels of evaluation ranged from comparing with the correct answer to evaluating results based on the limitations of the laboratory procedure.

4) Questioning peers/instructor: Students' self-report of what types of questions students are asking peers and the graduate student instructor during laboratory activities were used to assign levels of questions asked. Questions ranged from questions about clarifying laboratory procedures to questions about chemistry concepts related to laboratory exercises.

After the framework was refined, each student was assigned a level (1-3) for each of the four categories. The levels are labeled below (from lowest to highest):

Level 1 – Lab is a requirement

Level 2 – Lab augments understanding

Level 3 – Lab is a part of science

Students were also assigned an overall approach level based on their scores in the different categories. The overall approach level represents the level primarily expressed by the student. The overall approach level attempts to capture how the student approaches learning in the laboratory, as a sum of all of the individual categories.

A second, independent researcher not involved with the study coded 6 videos, which represents 33% of the sample. The directions provided to the second independent researcher to be used in coding are below in Figure 1.

Figure 1: Directions given for coding videos with the Laboratory Approaches Framework.

Laboratory Approaches to Learning Framework – Directions for Video Coding
While watching each video, assign codes for each of the categories listed: beliefs about the purpose of the laboratory, working with experimental procedures, evaluating experimental data and results, and questioning peers/instructor.
It is possible that a student will provide multiple responses that could be coded for different levels during the interview. In this case, code the student as the highest level mentioned during the interview. For example, if a student indicated that he/she asked both procedural (level 1) and conceptual (level 3) questions during the lab, that student would be coded as level 3.
If a student does not mention one of these categories in a particular video, leave that code blank.
Once the video has been coded for all of the categories, assign an overall laboratory approach level code. The overall code is equal to the code that was assigned the most frequently. If two or more codes are assigned with equal frequency, the overall code should equal the highest code assigned.

Inter-Rater Reliability for Laboratory Approaches Framework

Two independent researchers’ coding of a subset of 33% of the videos showed overall agreement of 90% with Cohen’s Kappa = 0.83. The inter-rater results are presented in Table 18 below.

Table 18

Inter-rater reliability calculations for laboratory approaches framework.

<u>Category</u>	<u>Agreement</u>	<u>Cohen’s Kappa</u>
Beliefs	100%	1
Procedures	66.7%	0.33
Data	100%	1
Questions	83.3%	0.71
Overall Approach	100%	1
Total	90%	0.83

The complete Laboratory Approaches Framework is shown in Figure 2 below. This characterizes the beliefs and behaviors shown by students in each category at each level.

Figure 2: Laboratory Approaches Framework.

		What this looks like in the laboratory...			
Level	Label	Beliefs about the purpose of lab	Working with experimental procedures	Evaluating data/results	Questioning peers/instructor
3	Lab is a part of science	<p>Believes that the laboratory is an important part of chemistry.</p> <p>Understands that laboratory exercises are related to course content, and takes the initiative to make these connections</p> <p>Understands that chemical knowledge and data are derived from experimentation</p> <p>Views lab as valuable in terms of learning skills or techniques, because those skills and techniques can be used to gain chemical knowledge</p>	<p>Connects laboratory procedures to chemical concepts learned in class.</p> <p>Thinks critically about the chemical reasons for carrying out the procedures in the lab manual</p> <p>Connects procedures to molecular-level chemistry ideas</p> <p>Tries to understand procedures in terms of chemical concepts</p>	<p>Evaluates results by connecting observations and data to chemical concepts.</p> <p>Analyzes experimental steps to figure out what specific step could lead to discrepancies with data</p> <p>Identifies effects of errors on final values (e.g., if the error identified would cause a calculated number to be greater or less than the expected result)</p> <p>Uses chemical concepts to explain results</p>	<p>Questions focus on understanding chemical concepts.</p> <p>Asks questions to understand chemical reasons for performing experimental procedures</p> <p>Asks if they are thinking about concepts correctly</p>
2	Lab augments understanding	<p>Believes that the laboratory adds some value to learning chemistry.</p> <p>Understands that laboratory exercises are related to course content</p> <p>Views laboratory exercises as valuable for demonstration purposes</p> <p>Views lab as valuable in terms of learning skills or techniques.</p> <p>Believes lab is valuable because it provides increased time on task</p>	<p>Realizes that laboratory experiments are related to classroom concepts, but does not actively make these connections.</p> <p>Asks other sources (book, GSI, peers) to explain how procedures connect to chemistry concepts.</p> <p>Realizes that there are connections that the student is not making to classroom material</p> <p>Recognizes that terms used in the laboratory are related to classroom content</p> <p>Questions reasons for procedural steps</p>	<p>Evaluates results by connecting discrepancies in data to errors in the overall procedure.</p> <p>Realizes that discrepancies in data may be due to procedural errors</p> <p>Does not connect errors to specific steps in the procedure</p> <p>Does not connect errors in procedure to effects on final values</p>	<p>Questions focus on understanding how to do experiments.</p> <p>Asks questions about how to do procedures or calculations</p> <p>Asks others what the connections to concepts are</p>
1	Lab is a requirement	<p>Believes that the laboratory is simply a requirement.</p> <p>Believes that chemistry can be learned solely from a textbook</p> <p>Does not believe that the laboratory adds any value to learning chemistry</p>	<p>Does not connect laboratory procedures to concepts learned in class.</p> <p>Does not make any attempts to connect procedures to molecular-level chemistry</p> <p>Does not try to understand chemical concepts or reasons for performing procedures</p>	<p>Does not engage in evaluation, or asks others to evaluate results.</p> <p>Judges correctness of experimental results by comparing with others or with known value</p> <p>Does not consider effects of procedure on results</p> <p>May ask instructor to evaluate results for them</p>	<p>Questions focus on doing the procedure correctly.</p> <p>Asks questions to confirm correctness of procedures or calculations</p>

Description of Laboratory Approach Levels

Student approaches to learning in the laboratory were divided into three levels. A description of each of these levels is provided below.

Level 1: Lab is a requirement

For the Level 1 student, the laboratory portion of the course is simply a requirement. This student believes that laboratory work is not necessary, or even useful, for learning chemistry. The Level 1 student may indicate that he or she thinks chemistry can be learned solely from the textbook, and that the laboratory adds no value to learning chemistry. When working in the laboratory, the Level 1 student does not try to understand the reasons for performing the procedures. This student performs the procedures because he or she is instructed to do so in the laboratory manual, and performs them without attempting to make any connections to what is happening at the molecular level. When evaluating results obtained in the laboratory, the Level 1 student judges the correctness of data by comparing with other students or with a known value. This student believes that the experimental results are correct if they match with the results of the other students. In evaluating experimental results, the effects of the experimental procedure are not considered. The Level 1 student is asking, “Am I doing this correctly?” Questions are asked only to confirm the correctness of procedures or calculations. Sample responses of a Level 1 student for each category are presented in Table 19 below.

Table 19

Level 1 sample responses.

Beliefs about the purpose of the laboratory	What this looks like in the laboratory...		
	Working with experimental procedures	Evaluating data/results	Questioning Peers/Instructor
“[In lab] we do do calculations, but like, I guess those are kind of just more like looking [...] in the lab manual it has before the procedure it just has the explanation or the pre-lab part, it’s just like looking at that and copying what they did, so it’s like not really learning, just like plugging and chugging what they have”	<p>[when describing procedure] “It’s just like measuring out borax, mixing it, putting it in ice bath”</p> <p>“More along the lines of working with each other getting the lab done so it’s um...a lot of the times it’s like get this beaker, get this flask, oh no we forgot this step, oh let’s do this, let’s do that, put those numbers into the equation, ok, we’re done”</p>	<p>[when discussing an unexpected result] “first I contacted my lab partners, then we went to office hours, my GSI showed me how basically what we had done is the answer is something like - 10000 and I got 11000, she was explaining how a change can be negative or positive”</p> <p>“I guess if I had time I could do more trials and see if it’s consistent”</p>	<p>“In the beginning a lot of confusion, trying to find the people who know what they’re doing, try to go along with them”</p> <p>“I wasn’t sure if we were doing it right, I asked my GSI”</p>

Level 2: Lab augments understanding

The Level 2 student understands that there are connections between lab and lecture even if he or she does not understand the connections. This student believes that lab work is important because it is another method of learning chemistry, or because it provides a way to “see” chemistry. When performing the procedures, the Level 2 students may wonder why they are doing a particular procedure, but they do not make any effort to connect procedural steps to chemical concepts. In evaluating results, the Level 2 student judges correctness of experimental data by considering how the procedure could affect the obtained results. However, this student does not connect the results with specific errors or steps in the procedure. A typical comment made by a Level 2 student might be that the procedure is “not perfect”, or “not 100% accurate”. These comments indicate that the student considers that the procedure may lead to errors, but these students do not make the connection between specific steps in the procedure and the errors or discrepancies that they observe. When working in the laboratory, the Level 2 student asks questions about how to do procedures or calculations. This student is concerned with understanding *how*, as opposed to the Level 1 student, who simply wants to obtain the correct result. Sample responses for a Level 2 student are presented in Table 20 below.

Table 20

Level 2 sample responses.

Beliefs about the purpose of the laboratory	What this looks like in the laboratory...		
	Working with experimental procedures	Evaluating data/results	Questioning Peers/Instructor
“Lab is really helpful...more hands on way to learn the concepts...guess it’s like a different approach, different approaches help me to learn better” “concrete example to attach concepts to” “different way to learn same topic” “more reinforcement, more practice”	“I just remember like trying to figure out why we had two different wicks, what the purpose of that was...I was reading on my own, I asked my GSI...still don’t know why, it’s like Shakespeare, I don’t understand it” “I wasn’t sure why we were doing this”	“I wasn’t sure if we were accurate or not, we didn’t have time to calculate percent error” “I’m not sure if ours was like not purely biodiesel so that’s one consideration...it could be that we didn’t have it set up right there’s a bunch of different factors...not perfect lab procedure” “I checked my value for C...compared with my lab partner...I’m thinking we must have had an error somewhere, I have no idea...”	“just like properly executing steps, technique things” “I asked my GSI if it could touch the oil or if it should be up on the top of the beaker”

Level 3: Lab is a part of science

The Level 3 student believes that laboratory work is an important part of learning science, because chemical knowledge is derived from experimental data. This student actively tries to make connections between laboratory procedures and chemical concepts while performing laboratory experiments, and tries to make connections between their macroscopic observations and the chemistry happening at the molecular level. When evaluating their experimental results, Level 3 students consider which steps of the procedure may have affected their results. In addition to considering specific steps of the procedure, these students are able to determine how their results will be affected (for example, if they should expect a higher or lower value). While working in the laboratory, the Level 3 student asks questions focused on understanding the conceptual connections to their laboratory work. Sample responses for a Level 3 student are presented in Table 21 below.

Table 21

Level 3 sample responses.

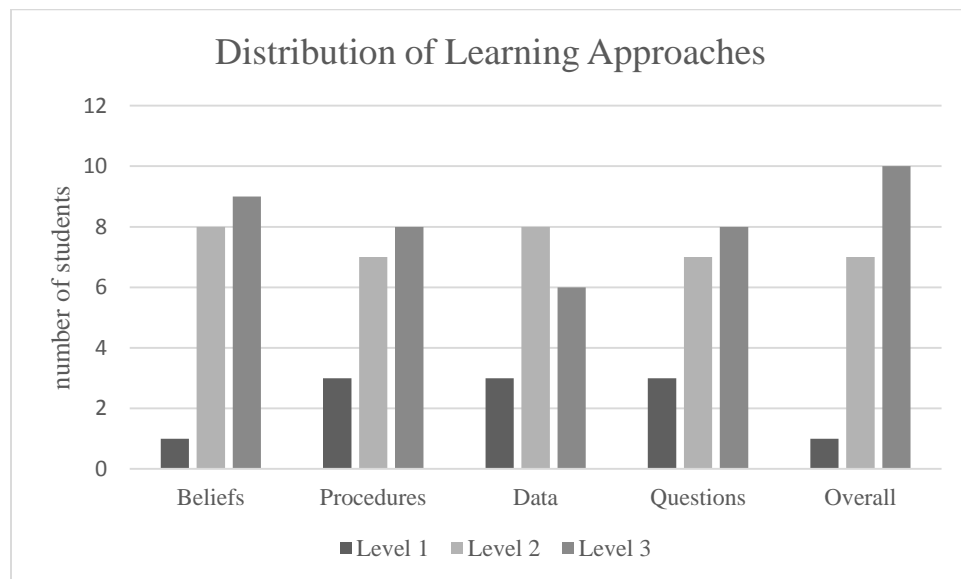
Beliefs about the purpose of the laboratory	What this looks like in the laboratory...		
	Working with experimental procedures	Evaluating data/results	Questioning Peers/Instructor
<p>“I think it helps me figure out the concepts, solidifies that, it takes it to another level when you do the lab, not just the problems, [lab] requires a greater deal of understanding. I feel like it’s more involved, when you work on problems you can get them wrong, look up the answer... With the lab you want to understand what you’re doing first, there could be repercussions”</p>	<p>“You kind of look at the steps that they tell you to do, and you wonder why you have to do some of these steps and how important they are and then you go back to the concept and you say ok well doing this would help it to... I don’t know but just when you look at the steps then you figure out what’s behind them, figure out the concepts”</p> <p>“I thought we stirred it to make the molecules move around more so the change in temperature would be more uniform”</p>	<p>“well if it’s lower it would not be a problem, because heat is escaping, if it’s higher, that would be weird, I would check instrumentation, check ethanol, make sure that I calculated that correctly”</p> <p>“I thought about oh, it’s important [to use the same amount of water] because of this calculation”</p>	<p>“Why are we doing this step?”</p> <p>“useful to have conversations about what is going on”</p> <p>“for the Le Châtelier’s principle, HInd goes to H+ and Ind-, how that works”</p>

Distribution of Students into Learning Approach Levels

The number of students in each level and category are shown in Figure 3 below. Most students were coded as Level 2 or Level 3 for all of the categories. Compared with the Beliefs category, more students showed Level 1 approaches in the categories of Procedures, Data, and Questions.

Figure 3: Bar graph of student distribution into Laboratory Approach Categories.

Figure 3 shows the number of students coded in each level (1, 2, or 3) for each category described in the Laboratory Approaches Framework. The overall approach code is also shown.



Case Studies

Student 1, Level 3 Approach

Student 1 was coded as having a Level 3 approach to learning in the chemistry laboratory. During laboratory periods, Student 1 worked with her partner to discuss the procedures before performing the experiment so that she would understand the underlying principles. She and her partner also took care to detail their observations and actively engaged in connecting their observations to the lecture material. The transcribed interviews for Student 1 can be found in Appendix B.1.

Interview 1

Student 1 did not take chemistry in high school, but she had prior laboratory experiences in high school biology and physics. In high school, she rated the laboratory as not useful. She thinks that in order for the laboratory to aid in learning, it needs to be engaging and allow students to have opportunities to explore concepts for themselves. In college, she finds that the laboratory is helpful in preparing for midterms, and she rated the lab as useful.

In the first interview, Student 1 describes her experiences with her high school laboratory classes.

1. Student 1: It was supposed to have something that was pH 9 and our teacher would be like well it was actually pH 6, and we were like this drastically affects this experiment, this is moderately dysfunctional, we had to submit labs for IB, we would have error paragraphs that were like this long, they were just massive, and then our results and conclusions were always this is what should have happened, it didn't, and this is why this happened, so, we did all right with grading but things were definitely not the best, scales were always unbalanced
2. Interviewer: How did that affect your learning in the lab?
3. Student 1: It made it a lot more difficult because you knew what you were supposed to be seeing but you never saw it, you never saw how something worked, you never really, because I know that like again I'll compare it to this chem lab, in this chem lab the experiments are pretty simple which I'm pretty happy with, I don't want to be doing anything complicated, my lab experience has not been the best, but they always work, you can always think about them, you can always think them through, you have to do your calculations and think about how your calculations are going to work and it's always functional, I think that with our other lab they tried to do, we had gel electrophoresis things that they tried to do and they just went horrible because our teacher put in too much dye, she was like you should put in 10 drops, and you needed like half of one, so I think that you just couldn't see what it needed to see, and it just made the learning, like this lab was supposed to be illustrating this concept and it's not, so I am slightly confused was basically my lab experience.

In describing her laboratory experiences in high school, Student 1 indicates that the laboratory was often frustrating because the equipment was not working properly. Due to the problems with the equipment, the experiments often did not yield the expected results. Student 1 contrasts her experience in her high school laboratory classes with her college chemistry course, in which all of the laboratory experiments are functional. Student 1 states that because the laboratory experiments work, this allows her to think through her calculations and her observations. She is not focused on simply obtaining the “correct” result just to get the right answer; rather, she realizes that having functional equipment will allow her to trust her results and think about why she is observing what she observes in the laboratory.

4. Interviewer: Do you think it [the laboratory] was useful?
5. Student 1: The labs...were not entirely useful as far as learning the concepts but I would say that we got very creative as far as how we approached and analyzed our data so that was good and sometimes we would get creative about trying to change our apparatus or change the experiment to fit what we had because it's like well, if we do this experiment it's not going to work so why don't we just switch it to this experiment so you do have to kind of shift the parameters of what you were trying to do sometimes, so I guess that that was a good exercise in creativity and experimental design, but on the bright side.

Student 1 says that the laboratory experiments in high school were not useful in helping her learn the concepts because the experiments often did not work properly. However, she does note that when she had to change procedures due to a lack of equipment, she had to think about what she was doing and what she was trying to measure. This shows that Student 1 is taking a higher-level approach with the laboratory; instead of simply following the procedures, she is thinking about what the procedures will accomplish.

Later in the interview, when asked to explain her survey responses, Student 1 indicates that the experiments she performed in high school were often too simple to be useful.

6. Student 1: Because if you're just repeating something that's been repeated 5 million times and you already know, something that you can already visualize, like I've already seen this happen.
7. Interviewer: What would be an example of that?
8. Student 1: I'm not sure, I just always think of my physics labs where it's like, hey, the block dropped, like, gravity is working, we actually had experiences where we're like, we're going to drop a block and figure out that gravity works, and for me those were just kind of a little bit too boring and illustrated, this could have easily been a class demo where we dropped a block, and it fell, like, our results table was like it fell, it fell, it fell

In her interview, Student 1 indicates that experiments that are too simple are not useful. The experiments in her high school physics class that only served to demonstrate very basic principles were not useful, because did not allow her to visualize anything that she had not seen before.

Student 1 describes her experiences in her high school classes differently than she describes her experiences in college chemistry. In her high school laboratory classes, Student 1 was frustrated because the laboratory experiments did not work properly, so she was not able to make the appropriate observations. Her high school classes also featured experiments that were too simplistic, which were not useful to her because they only demonstrated known principles. In college chemistry, Student 1 indicates that the simplicity of the experiments is a good thing, because this allows her to really think through the entire procedure and how the calculations will connect to the class material.

Interview 3

On the final survey, Student 1 indicated that the laboratory in college was useful in helping her learn chemistry. In the beginning of the interview, she describes what she has learned from the laboratory.

1. Interviewer: So what do you think that you have learned from the laboratory?
2. Student 1: I think that the laboratory has reinforced the practical applications of the concepts, I don't think that the laboratory has really taught me the new concepts because that's what lecture is for, but it's definitely reinforced them and it's made it so that, really, I think the most useful thing about laboratory is when I am sitting down and taking a midterm or having to think about a chemistry problem in any sort of way, I have something tangible where if I don't remember which way things usually go or if I don't remember how to calculate things or if I don't remember whether my ΔH should be positive or negative, I can think back on lab and on what I've seen in lab and it helps me remember. So for me it's more of like a memory device, this honestly helped me remember the concepts, and even though it demonstrates pretty basic concepts, you know, we're not going into exciting electrons in a Chem 1A lab and observing the energies, well you sort of are with the color thing, but you know, we're not like doing the really, I would say that we aren't doing advanced concepts, we are more reinforcing basic concepts, sometimes you need that picture that you can go back and draw on and that picture in addition to that concept can help you answer questions in general.

When talking about her experiences in the college chemistry laboratory, Student 1 says that the purpose of lab is not to teach new concepts, but to reinforce concepts from lecture. She thinks that the laboratory is useful because it illustrates concepts that she has learned in the lecture class, and it helps her think through chemistry problems by giving her something visual to connect to. Student 1 thinks that the laboratory is useful because it helps her remember the concepts, since she can connect these to her experimental observations. Because she is able to remember her observations, she uses this information to help her solve other related chemistry problems.

3. Interviewer: OK. So do you think that the laboratory is valuable?
4. Student 1: Yes.
5. Interviewer: Why is that?
6. Student 1: Because it does reinforce those concepts, you do need a laboratory, because I know, especially coming into college this is going to be the first lab class that a lot of people take in college, there's like 1200 kids taking it or something, and I think it's really important to have this experience in lab where they teach you not just concepts but they also teach you a little bit about lab, like, I didn't know the difference between a beaker and a flask, I mean, that's a good thing to know, I didn't know how to pipet, I didn't know how to titrate, so I would say that learning those basic concepts is a really vital and important part of this lab because otherwise when you go into other labs and they just say titrate this you're not going what do you mean? So I would say that that's really valuable and then again just having that picture that you can attach on to when you're sitting on that midterm and kind of freaking out a little bit has been really useful, having some sort of tangible picture, because they can talk about the absorption spectra and they can talk about how you would make a Beer's law plot but until you really apply it yourself it's kinda hard to figure out whether you know it or not.

Student 1 thinks that the laboratory is valuable because it teaches laboratory skills and techniques. She also thinks that the laboratory is valuable because it helps her with the midterms. Student 1 makes connections between her observations and lecture concepts to help solve chemistry problems. She also finds value in the act of performing laboratory experiments and analyzing her own data. She states that doing the labs helped her assess her own knowledge of the lecture material.

Student 22, Level 1 Approach

Student 22 was coded as having a Level 1 approach to learning in the chemistry laboratory. When describing her approach to working in the laboratory, Student 22 is focused on completing the procedure. She does not report engaging in discussions with her group members about how the laboratory experiments connect to course content. She states that doing the experiments is not helpful because she is simply following the calculations from the laboratory manual, rather than thinking through them for herself. The complete transcribed interviews for Student 22 can be found in Appendix B.2.

Interview 1

Student 22 took one year of chemistry in high school, and in her chemistry class, she performed experiments approximately once a month. On her survey, she indicated that she did not find laboratory useful in high school or in college.

In the first interview, Student 22 describes her experiences with the laboratory in high school chemistry.

1. Interviewer: So tell me a little bit about your experiences with the lab in high school, so you said that you did lab about once a month, and you followed a given procedure, and you said that you would calculate the molarity of solutions, and you said that all of the chemistry labs were just all right, so tell me what you mean by that.
2. Student 22: Um, I think, cuz I was in regular Chemistry, I wasn't AP, so we didn't do as many labs as the AP class, so a lot of them were pretty simple and um I don't know, I think like for Chem here, like, I feel more stressed to do lab because they're actually graded more critically than it was in high school, so the one in high school wasn't as stressful as the one here.
3. Interviewer: So why is the one here more stressful?
4. Student 22: Cuz like, the grading, yeah.
5. Interviewer: The question on the survey asked you to rank how useful the lab was in helping you learn Chemistry, and you said it was not very useful.
6. Student 22: I think part of it was that I had it in 10th grade so it was a long time ago so I don't remember it now, but, um, yeah, I think that's like the main factor, and also like we didn't go over that many labs because it was just regular Chemistry.

In her high school chemistry, class, Student 22 says that the laboratory experiments were not useful because she did not do experiments frequently, and the experiments that she did were too simplistic. She finds the laboratory experiments in college stressful because they are graded more strictly.

7. Interviewer: So would you say the lab in Chem 1A is different?
8. Student 22: Um, I guess it's different, also, because there's more resources too than there was in high school, so we actually get to like explore more and actually learn.
9. Interviewer: So do you think the lab in Chem 1A is more useful in helping you understand the chemistry, or not useful?
10. Student 22: It's related to what we're learning but it doesn't really, I feel like it doesn't help me as much, like for the midterm.

In college chemistry, Student 22 says that the laboratory is related to what she is learning in class, but she doesn't find the laboratory useful because it doesn't help her with the midterms. She acknowledges that her college class does experiments with more frequency, so there is potential to learn, but she doesn't find the lab that useful.

In a later part of the interview, Student 22 clarifies some of her survey responses.

11. Interviewer: There was another question on the survey that asked you to describe three key features of a good scientific experiment, and the first one you said was accurate measurement. So why is that important?
12. Student 22: Um, if you don't have accurate measurement then you won't get the right results

In line 12, Student 22 indicates that she thinks it is important to get the correct results when doing an experiment. She does not focus on what she is learning, but rather on obtaining the correct results.

In a later portion of the interview, Student 22 describes her thoughts about the laboratory in college chemistry.

13. Student 22: You know like in those movies you see all this bubbling and fire and all that kind of stuff, here it's just kind of like really safe which I guess is good for us, it's just like, that was my expectations.
14. Interviewer: Do you like the lab in Chem 1A?
15. Student 22: Um, it's ok.
16. Interviewer: What do you like or dislike about it?
17. Student 22: Um, I guess, sometimes they're kind of boring, like the titration lab, that was really long, and, just like the length of it, it takes a long time to do, and I guess the good part about it is, um, our GSI, she's pretty nice about it and she helps out.

Here, Student 22 indicates that she finds the laboratory experiments in college chemistry to be long and boring. This belief affects the way in which she approaches learning in the laboratory.

Interview 3

In the third interview, Student 22 talks about what she learned from the laboratory.

1. Interviewer: So what do you think that you have learned from the laboratory?
2. Student 22: I definitely learned what the equipment are called, um, how to write better lab reports, um, and I guess just like some of the real-life applications that the labs are related to, like the biodiesel stuff, you know how for the pre-lab it has the information that you can read about it, for that chemical or whatever you're using, that kind of stuff.

Student 22 says that the laboratory helped her learn about the different types of equipment used and also helped her learn scientific writing. She also notes that the information in the laboratory manual helped her learn about the real-world connections of the experiments performed in class.

3. Interviewer: Do you think the laboratory is valuable?
4. Student 22: Well, like, it's not on the low end because it is valuable, you do learn stuff out of it, but it's not too valuable because, I don't know, I think, I don't know, I don't see it much on the higher end.
5. Interviewer: What do you mean by that?
6. Student 22: Like, I guess it's just like how you set your, I don't know, set your values I guess? Like, if I were to, if you had a test to study for or a lab to study for the night before I would probably study for the test instead of the lab, I would prioritize that kind of second or third.
7. Interviewer: Why is that?
8. Student 22: Um, I don't know, I don't see it as important I guess? Like maybe, um, like, I know it's important to read the lab beforehand so that you're well prepared and stuff, but that's something that you can do last minute and you'll do okay on it.

When asked about the value of the laboratory in college, Student 22 indicates that the laboratory is not very valuable because she prioritizes the exams over the laboratory. She notes that she can obtain reasonable scores on the laboratory if she is not prepared, but that this approach will not work for the midterms. In this part of the interview, Student 22 shows that the grading scale of the course affects her approach to studying.

9. Interviewer: So what skills, if any, do you think that you have gained from the laboratory?

10. Student 22: Um, I guess like, what I've learned, like what kind of tools, what the equipment is called so then I can easily access it faster, and just like knowing, cuz like a lot of the procedures like kind of repeat throughout the labs so like if you see it then you automatically know what to do, like the first time you do it, if you first see it you ask around and you're kind of confused, so I guess doing it repeatedly helps you do it better the next lab, or like, um, yeah, I don't know.

Student 22 says that she has learned about the different equipment used in the laboratory. She also says that it is easier to perform experiments in which she is familiar with the procedure and equipment. By being familiar with the equipment, she is more able to focus on other aspects of the laboratory experiment.

Discussion

Laboratory Approaches Framework

Based on coding the student interviews according to the Laboratory Approaches Framework, 10 students were coded as Level 3, 7 students were coded as Level 2, and 1 student was coded as Level 1. The fact that a majority of the students were at the highest level was unexpected. This may be because students were coded for the highest level mentioned in their interview, which might not capture the majority of their behaviors in the laboratory.

While most students were coded at a Level 2 or Level 3 overall, the distribution of students into approach levels differed for each category within the coding scheme. Most students were coded as Level 2 or Level 3 for beliefs, which suggests that most of the students in the interview sample thought that the laboratory adds some value to learning chemistry.

In all of the other categories (working with experimental procedures, evaluating data, and questioning peers/instructor), there is a larger percentage of students coded as Level 1. Considering the category working with experimental procedures, students coded as Level 1 report following the procedural steps without making connections to what they are actually doing. If students are not prompted to think about the reasons for performing the steps, they may approach the laboratory exercises as cookbook, or simply follow the steps without understanding why they are doing what they are doing. A significant percentage of students were coded as Level 1 in the category evaluating data. When evaluating experimental results, Level 1 students compare the results with a known value or with the values obtained by other students. These students are not engaging in the process of evaluating their experimental data or results. Students also showed more Level 1 behavior in the types of questions that they reported asking during the laboratory period. The Level 1 student is focused on finishing the experiment, so their questions focus on completing the procedures correctly without understanding the scientific process or concepts.

Case Studies

To examine the relationship between students' perceptions of the laboratory environment and their approaches to learning, two case studies were explored. The case studies of Student 1 and Student 22 demonstrate the range of approaches that students self-reported using in the laboratory, and how their beliefs and previous laboratory classes shaped these approaches.

In both of these cases, the students' experiences with the laboratory in high school affected their initial perceptions of the laboratory environment. Student 1 reported that the laboratory in high school was not useful because the experiments were simple and only demonstrated things that she already knew. In high school, she also said the experiments were not useful because there were often issues with the experimental equipment that required students to alter their experiments. Student 1 notes that when changing the procedures, she had to think critically about what data she was collecting, which indicates that she approached the laboratory with a high-level approach in high school. This high-level approach carries through to her experiences with the college laboratory.

Student 22 reported that the laboratory in high school was not useful because she performed experiments infrequently. She also found the laboratory not useful in college. In her interview, she indicated that she found the laboratory experiments in college to be boring. This perception affected the way in which she approached the laboratory experiments. Because she did not think the laboratory experiments were useful or engaging, she adopted a surface-level approach.

Both Student 1 and Student 22 state that the midterms are where they focus their energy and studying. This is likely because the midterms consist of the majority of the course grade. Because Student 1 perceives the laboratory as being related to the midterms, she finds the laboratory useful in learning chemistry. Student 22 does not see any relationship between the laboratory experiments and the midterms, and she thinks that the laboratory is not useful.

Conclusions

Students take a variety of approaches to learning in the laboratory. These approaches can be described by the Laboratory Approaches Framework, and span from surface-level approaches (Level 1) to deep-level (Level 3). This framework categorizes students' approaches in four different areas: beliefs about the purpose of the laboratory, working with experimental procedures, evaluating data and results, and questioning peers/instructor. The Laboratory Approaches Framework is useful in analyzing student behaviors in the laboratory environment.

Comparison of Approach Levels

The Laboratory Approaches Framework outlines the ways in which students approach learning in the undergraduate chemistry laboratory. Students coded as taking a Level 1 approach are passive learners who do not see the value of the laboratory. These students do not believe that the laboratory is an important part of learning chemistry, and as a result, do not engage in meaning-making when completing experiments. Students coded as Level 2 believe that the laboratory adds some value to learning chemistry, and understand that there are connections between the laboratory experiments and the chemistry concepts that they have learned. These students believe that the laboratory adds value to their learning because it provides increased time to explore the concepts, or because it provides a visual aid. The critical difference between the Level 2 student and the Level 3 student is that the Level 3 student believes that the laboratory is an integral part of learning chemistry. Because of this, the Level 3 student seeks to understand why he or she is performing the procedures, and actively connects experimental procedures and observations to the underlying chemical concepts. While the Level 2 student may engage with the procedure to

the point of wondering why he or she is performing a technique a certain way, the Level 3 student takes the additional step of making connections to the course material themselves.

The approaches described in the Laboratory Approaches Framework are consistent with other studies describing learning approaches in different classroom contexts. In a study of middle-school science students, Chin and Brown (2000) found that students' approaches could be explained as deep-level or surface-level in different categories.

The higher-level approaches adopted by Level 3 students are also consistent with curricular modifications designed to promote conceptual understanding. In the MORE thinking frame (Model-Observe-Reflect-Explain), students are prompted to first think about their initial ideas (model), observe what happens in the laboratory (observe), reflect on how their laboratory observations fit with or challenge their initial model (reflect), and then use the laboratory-generated data to explain the scientific phenomenon being studied (explain) (Tien, Teichert, & Rickey, 2007). The MORE thinking frame encourages behaviors that are similar to the Level 3 approach. Students adopting Level 3 approaches described reading through the procedure, making predictions about what they thought they would observe, and engaging in the process of explaining their results to their group members.

The approaches students take when learning in the laboratory can be affected by the way in which laboratory activities are structured. Chin and Brown (2000) found that some of the students in their study did not think about what they were doing when they performed experiments, but these students did engage in critical thinking afterwards when reflecting on the experiments that they performed. This suggests that scaffolding the laboratory activity can promote deeper approaches to learning.

The laboratory activities in this study are the same as described in Chapter 2. The procedures are provided to the students in a laboratory manual, and the students are instructed to record their data and observations in laboratory notebooks. Laboratory procedures had 'checkpoints' throughout to encourage students to consider the reasons for performing the procedures, although these were not graded or handed in. For more information regarding the structure of the course, refer to the section Context of the Study in Chapter 2.

In Tien, Teichert, and Rickey's (2007) work with the MORE model, experimental work is scaffolded so that students are prompted to engage in deeper approaches. Since students are required to reflect on what they have learned and generate explanations using their data, they engage in using deeper learning strategies. In a study of high school physics students in a constructivist-guided classroom, Roth (1994) found that students were able to successfully frame research questions and design experiments to explore these questions. In this study, the students were successful in engaging with inquiry laboratories due to the unique nature of their classroom environment. The classroom culture was such that students were responsible for constructing their own learning. Students were also introduced to new experimental techniques through demonstrations so that they were familiar with the equipment. This allowed students to focus on the experimental design during laboratory work, rather than having to learn new techniques and process what they were learning from the experiment at the same time. These same students

reported completing their chemistry laboratory exercises without understanding why they were performing the steps specified in the laboratory manual. The fact that the same students adopted different approaches in different learning contexts demonstrates the large effect the learning environment has on how students approach learning.

Implications

The case studies of Student 1 and Student 22 present two students who take very different approaches to learning in the laboratory, but are assessed similarly in terms of grades. This highlights the importance of having laboratory assessments that accurately reflect the learning goals of the laboratory. In the past, when the goal of the laboratory was learning laboratory techniques, students were assessed on the precision and accuracy of their results. In today's educational laboratories, where the focus has moved away from skill-building, it may be possible for students to take a surface-level approach and still be assessed highly. Depending on how the laboratory activities are structured and how students are assessed, it may be possible for students to complete the laboratory procedures without thinking about the meaning of the experiment. If students are able to successfully complete the laboratory experiment and any post-laboratory assignments without making deeper connections to the chemistry concepts, many students will adopt these low-level approaches.

It is possible for the laboratory program to accomplish many learning goals. These goals include learning laboratory skills and techniques, learning chemistry concepts, improving student attitudes toward chemistry, and developing skills related to scientific inquiry. Examining both Student 1 and Student 22 shows that both students had different goals for the laboratory, despite earning the same grades. Student 1 reported learning skills and techniques, although these were not assessed. She also states that the laboratory helped her learn and remember the course content, and in her interviews she indicated that she enjoyed performing laboratory experiments. Student 22 also reported learning skills and techniques, though these were not assessed. She did not indicate that the laboratory helped her learn chemistry content, improved her attitude toward science, or helped her develop skills related to the process of scientific inquiry.

It is clear that the laboratory has great potential to enhance chemical education. In the case of Student 1, the laboratory was a valuable tool that provided a way to make connections between the classroom content and the laboratory experiments. The laboratory presents a great opportunity for students to engage in metacognitive activity if students are encouraged to reflect on their ideas.

Study Limitations

While the case studies demonstrate associations between students' beliefs about the purpose of the laboratory and their approaches to learning, these do not account for other factors that may influence learning approaches.

I did know once, only I've sort of forgotten.

-A.A. Milne, Winnie-the-Pooh, 1926

Chapter 4: Examining the Effects of a Metacognitive Intervention on Laboratory Exam Performance

Introduction

To answer the third research question “Does metacognitive questioning improve student performance in laboratory assessments?” a metacognitive intervention for the chemistry laboratory was designed and its effects were measured. This chapter describes the intervention and its effect on student performance.

Rationale

Metacognition refers to the knowledge of and regulation of cognitive processes (Brown, 1987). Various frameworks have been used to characterize metacognitive activity. Flavell (1979) describes metacognition as having three components: knowledge about person, knowledge about task, and knowledge about strategy. Kipnis and Hofstein (2008) use a framework based on Schraw’s 1998 model that divides metacognition into knowledge of cognition, which includes declarative, procedural, and conditional knowledge, and regulation of cognition, which includes planning, monitoring, and evaluating.

Metacognition in the Chemistry Laboratory

Nakhleh, Polles, and Malina (2002) identify the development of metacognitive skills as one potential benefit of laboratory instruction. There are many areas in the laboratory where students can act metacognitively. When performing laboratory experiments, students have the opportunity to reflect on what they are doing and why they are performing the steps that they are performing. Often in the laboratory, results are not as expected. Students who self-regulate have the ability to think about why a particular result is not consistent with earlier predictions. The metacognitive skill of planning is also important in the laboratory setting. Students who are able to plan their activities can manage their time wisely in the laboratory.

The way in which the laboratory activities are structured can also encourage students to think metacognitively. In the laboratory, students are often given written instructions from a laboratory manual or handout, and oral instructions from a teaching assistant. These instructions have the potential to encourage students to reflect on their own thinking.

One area in the laboratory in which students can act metacognitively is when working through procedures. Kipnis and Hofstein (2008) reported that students working together on an inquiry procedure became aware of procedural mistakes when talking through their hypothesis. By talking through the procedure, instead of simply following it, the students were able to understand the meaning behind the steps they were about to follow and were able to alter their procedure to align with the desired outcome.

The laboratory instructor can also facilitate metacognition in the laboratory. Bond-Robinson (2005) describes a study in which graduate teaching ability was rated by a faculty member and by the students. The majority of teaching assistants focused on the transmission of procedural knowledge rather than helping students to think through challenging problems. Since the graduate teaching assistants were quick to give students the answers without having them think through the problems themselves, students missed out on prime opportunities to develop and practice metacognitive skills.

Metacognitive Interventions

Several interventions have been described that attempt to increase students' metacognitive activity in the classroom. Interventions aimed at encouraging reflection and self-assessment have led to increased student performance (White & Frederiksen, 1998; Zan, 2000). Metacognitive interventions have also been used in the laboratory setting. Many of these strategies aim to help students make connections between their laboratory observations and chemistry concepts. Because students have a great deal of information to process during the laboratory, encouraging reflection can help students understand the purpose of the laboratory experiments.

In a study of university students in South Africa, Davidowitz and Rollnick (2003) describe what they term the Competency Tripod, in which students engage with an analogy to help provide awareness of their thought processes. Students imagine a laboratory tripod having three legs that represent declarative knowledge, procedural knowledge, and communicative competence. These legs are linked together by social interactions in the laboratory. A case study analysis revealed that using this analogy helped some of the students think deeply about the laboratory experiments.

Another intervention that has been used in the laboratory setting is concept mapping. When concept mapping, students construct diagrams that involve relationships between concepts. In a study involving students in a first year chemistry course, students reported concept maps to be helpful, but a group who constructed concept maps did not show any difference on an exam from a group who wrote essays about their experiments (Markow & Lonning, 1998). Another study involving high school students revealed no difference in test scores between a group of students who constructed concept maps and a group of students who did not (Stensvold & Wilson, 1992).

The MORE (Model-Observe-Reflect-Explain) model is another way of scaffolding metacognitive thought during the laboratory (Tien, Rickey, & Stacy, 1999). In the MORE framework, students first model their ideas about the whole experimental system. This requires students to consider the entire experiment, rather than isolated procedural outcomes. After performing experiments and making observations, students engage in refining their initial model, and using their experimental data to explain their models. This type of laboratory structure has been shown to improve student comprehension and performance on exams (Tien, Rickey, & Stacy, 1999; Rickey, 1999).

The primary goal of the intervention designed in this study was to encourage students to think critically about the procedures they were performing. Students taking a deeper approach (Chapter 2) used metacognitive strategies to understand rationale behind performing procedural steps in laboratory experiments. The intervention described in this chapter aims to encourage students to take a Level 3 approach, in which students connect laboratory procedures to chemical concepts and ideas. Students were prompted to provide explanations for procedures at critical steps in the

procedure (e.g. before heating the mixture, after stirring). The goal was to encourage students to understand what they were doing, as opposed to simply following the stated procedures.

This study aims to understand the effects of a metacognitive intervention designed to increase students' metacognition during the laboratory. Specifically, this chapter will address the research question, "Does metacognitive questioning improve student performance on laboratory assessments?"

Context of the Study

This study was conducted in the same introductory chemistry class described in Chapter 2. Data was collected during the Fall 2012 semester, in which the course had been restructured. During this semester, the lecture course and the laboratory course were separated into different courses. Students could either enroll in the laboratory course concurrently with the lecture, or could enroll in the laboratory course after successful completion of the lecture course. The majority of students (99%) were enrolled in the lecture and laboratory courses concurrently.

The laboratory course consisted of one one-hour lecture per week, taught by a lecturer in Chemistry, and one three-hour lab section, taught by a graduate student instructor. Lecture sections were held three different times during the week so that students could attend lecture prior to attending lab. Laboratory sections were three hours long and met once per week. In the laboratory sections, students worked in the same group of three for the entire semester.

The laboratory experiments performed during this semester were identical to the ones described in Chapter 2. Students also completed the same library research project as described in Chapter 2.

Students were required to submit notebook pages, post-lab worksheets, and two formal written laboratory reports. During this semester, an additional requirement of preparing the laboratory notebook with a flowchart of the procedure was introduced. Students were required to complete online homework assignments related to laboratory skills. Students also were assessed by a written laboratory exam, given at the end of the semester. The written exam consisted of short answer and multiple choice questions related to laboratory concepts.

Methods

Students enrolled in an introductory chemistry laboratory course at a large public university were chosen to participate in an intervention group or a control group. The assignment of control or intervention group was based on enrollment into different laboratory sections, each section being assigned as control or intervention. The intervention group consisted of four laboratory sections taught by four different graduate student instructors. The control group consisted of four laboratory sections taught by the same four graduate student instructor. This ensured that each instructor had both a control group and an intervention group. In the intervention group, students were instructed to complete additional worksheets during two laboratory experiments: one during the middle of the semester, and one at the end of the semester. The worksheets prompted

students to think critically about what they were observing in the laboratory, and also to think about the reasons for completing the procedures in the laboratory manual. Students were instructed to complete the worksheets while they were performing the laboratory experiments. Complete worksheets can be found in Appendix C. Students in the control group performed the same experiments but did not complete these worksheets.

Participants

Participants were students enrolled in first-year chemistry at a large public university. This course is intended primarily for non-chemistry majors who need to take chemistry as a pre-medical or major requirement. Course enrollment is typically around 1300 students in the fall semester.

Data Collection

During the second week of the semester, a survey was sent out to the entire class through the course website. The survey was accessed through an online survey tool (surveymonkey.com). The survey contained questions about students' prior experiences in chemistry as well as questions regarding student demographics.

Students in the experimental section completed additional worksheets during Laboratory Experiment 6, Depolymerization of Poly(lactic acid) Cups to Lactic Acid, and during Laboratory Experiment 10, Solubility and Spontaneity.

Table 22 outlines the demographic make-up of students in the experimental and control groups who responded to the survey and consented to have their responses used in the research. These groups were similar along all demographic variables.

Table 22

Demographic summary of experimental and control groups.

Variable	Category	Control Group		Experimental Group	
		N	%	N	%
Major	Life Science/Biology*	41	48.8	51	58.6
	Engineering	25	29.8	13	14.9
	Other	18	21.4	23	26.4
SES	Wealthy/Upper-middle or professional-middle	40	47.6	30	34.4
	Middle-class*	26	31.0	39	44.8
	Working-class/Low-income or poor	18	21.4	18	20.6
Ethnicity	Asian	40	47.6	51	58.6
	White*	27	32.1	17	19.5
	Other	17	20.2	19	21.8
Gender	Female*	49	58.3	55	63.2
	Male	35	41.7	32	37.6
Previous Semesters of Chemistry	0 -2	56	66.7	45	51.7
	3 or more	28	33.3	42	48.2
Total		84		87	

*used as reference category in regression analysis and includes responses of "Decline to State"

Description of the Intervention

The two experiments chosen for the intervention were Experiment 6, Depolymerization of Poly(lactic acid) Cups to Lactic Acid, and Experiment 10, Solubility and Spontaneity. Experiments toward the middle and end of the semester were chosen so that students had some familiarity with the laboratory environment. The two experiments were also stand-alone experiments that were not part of larger laboratory modules. These experiments were assessed via a worksheet that students completed in groups and turned in during the next laboratory period.

In Experiment 6, Depolymerization of Poly(lactic acid) Cups to Lactic Acid, students cut up plastic cups made from PLA and performed a depolymerization reaction. After the depolymerization, students performed a titration to quantify the amount of lactic acid monomer present in their sample. The goals of this experiment were for students to learn about polymers, and also to practice creating and interpreting pH curves. This experiment also demonstrated several principles of Green Chemistry, such as using safer solvents, design for energy efficiency, and high atom economy. Students also were able to draw real-world connections, as the PLA samples came from cups used in campus dining facilities.

For this experiment, the goal of the worksheet was to encourage students to think about the reasons for performing the experimental steps. In the interviews from Fall 2011 (Chapter 3), students who adopted high-level approaches spent time discussing chemical concepts with their groups and trying to make sense of the purpose for each experimental step. The worksheet questions also prompted students to engage in self-explanations.

In Experiment 10, Solubility and Spontaneity, students created saturated solutions of Borax (sodium tetraborate). Different groups prepared solutions at different temperatures. After preparing the saturated solutions, students performed a titration to determine the amount of borax that was dissolved. The class shared data with each other, and as part of the analysis, students constructed a van't Hoff plot to determine the standard change in free energy, standard enthalpy change, and standard entropy change for the dissolution of Borax.

In this experiment, students often have difficulty drawing connections between what they are measuring and what they are calculating. Students titrate to determine the concentration of hydroxide ion, which they then must connect back to the original concentration of dissolved Borax. Again, for this experiment, the worksheet prompts were aimed to encourage students to think critically about the reasons for performing the experimental steps. Students were asked to state in their own words why it was important to use different temperatures, what data they will record, and what that data will help them determine. The complete worksheets for both Experiment 6, Depolymerization of Poly(lactic acid) Cups to Lactic Acid, and Experiment 10, Solubility and Spontaneity, can be found in Appendix C.

Analytic Plan

Multiple regression was conducted to determine if the experimental group performed better on the laboratory exam than the control group while accounting for differences between the two groups.

Variables Created

Table 23 (below) describes the variables created from the Fall 2012 survey data.

Table 23

Summary of variables used for analysis of Fall 2012 survey data.

<u>Variable</u>	<u>Used as</u>	<u>Type</u>	<u>Scale</u>
labexam	Response	Continuous	0-100
Exp	Explanatory	Dichotomous	0/1
Male	Explanatory	Dichotomous	0/1
3 dummies for major	Explanatory	Dichotomous	0/1
3 dummies for SES	Explanatory	Dichotomous	0/1
3 dummies for ethnicity	Explanatory	Dichotomous	0/1
2 dummies for prior experience	Explanatory	Dichotomous	0/1

Response Variable

labexam represents the student's score on the laboratory exam given at the end of the quarter, scaled to 100%.

Explanatory Variables

Exp represents whether or not the student was in the experimental group or control group (experimental group = 1, control group = 0).

Student major, socio-economic status (SES), ethnicity, gender and prior experience in chemistry data were collected by self-report from the options presented on the survey.

- Dummy variables created to represent gender are: **male** ("Male"=1), ("Female" or "Decline to state" = 0).
- Dummy variables created to represent major are: **engineering, othermajor** (combination of Physical Science, Mathematics, Humanities, Undeclared, and Other), with Life Science/Biology as the reference category.
- Dummy variables created to represent SES are: **seslow** (combination of "Low-income or poor" and "Working-class"), **seshigh** (combination of "Wealthy" and "Upper-middle or professional-middle"), with **sesmed** ("Middle-class" and "Decline to state") as reference.

- Dummy variables created to represent ethnicity are: **asian** (combination of “Chinese/Chinese American,” “Japanese/Japanese-American,” “Korean/Korean-American,” “Filipino/Filipino-American,” “South East Asian,” “Other Asian,” and “East Indian/Pakistani”), **otherrace** (combination of “American Indian/Alaska Native,” “Pacific Islander,” “African-American/Black,” “Mexican/Mexican American/Chicano,” “Spanish-American/Latino/Latina,” “Middle Eastern,” and “International Student”), with **white** (“White”) as reference. Students who declined to state their ethnicity were grouped with the reference category.

Students who indicated more than one ethnic category were grouped with **otherrace**, unless they indicated multiple races categorized as **asian**.

- Dummy variables created to represent prior experience in chemistry are: **sem012** (“I have never taken chemistry,” “1,” or “2”), with **sem345** (“3,” “4,” or “More than 4”) as reference.

Results

Descriptive Statistics

Descriptive statistics for the laboratory exam are shown in Table 24 (below).

Table 24

Descriptive statistics for laboratory exam.

Mean(M) and standard deviation (SD) for the laboratory exam are shown for the experimental group and control group.

<u>Experimental Group</u>		<u>Control Group</u>	
Mean	SD	Mean	SD
78.2	14.5	71.8	16.6

Relationship between experimental group, student demographics, and laboratory exam performance

The multiple regression model estimated the effects of the experimental group on laboratory exam performance. Because the experimental group and the control group consisted of different students, demographic factors were included in the analysis to account for these differences. College major, gender, and ethnicity were not significant predictors of laboratory exam performance, and these variables were dropped from the final model. The multiple regression statistics for the final model are shown in Table 25.

Table 25

Estimates for Experimental Group and Demographic Factors on Laboratory Exam Performance.

Standard Errors (SE) are shown for computed estimated coefficients. Demographic variables are used in the model for control.

<u>Variable</u>	<u>β</u>	<u>SE</u>
Exp	5.35*	2.35
seslow	-7.96*	3.23
seshigh	0.34	2.61
sem012	-6.37*	2.37

*significant at 5% level

The analysis shows that the experimental section had a higher laboratory exam average than the control section. This result was significant at the 5% level. Two demographic variables were found to be significant in the model. Students who self-identified as low SES had a lower laboratory exam average than students who self-identified as medium or high SES. Students who had 0-2 previous semesters of chemistry had a lower laboratory exam average than students who had 3 or more previous semesters of chemistry.

Discussion and Conclusions

Students in the experimental section performed better on the laboratory section than students in the control section. This result was significant at the 5% level when controlling for demographic differences between the sections.

There are several potential explanations for this difference. One possibility is that students who used the worksheets took deeper approaches to learning. Even though the worksheets were only used in two laboratory sessions, it is possible that students were periodically encouraged to reflect, and continued to do so in other weeks when they did not have the additional worksheets.

Another possibility is that students in the experimental section spent more time on the laboratory experiments since they had the additional worksheets to complete. Based on discussions with the laboratory instructors, this seems unlikely. The worksheets were carefully designed so that students would have time to answer the questions when waiting for parts of the procedure to finish.

These findings are consistent with other metacognitive interventions, in which the intervention group showed gains on exam scores (White & Frederiksen, 1998; Tien, Rickey, & Stacy, 1999). These findings are also consistent with literature that suggests students benefit from engaging in self-explanations (Chi, de Leeuw, Chiu, & Lavancher, 1994).

After discussions with the laboratory instructors, it became apparent that not all instructors implemented the worksheets in the same manner. Some groups of students completed the worksheets as directed, during the laboratory, while other students completed these worksheets at the end of the laboratory period. It is interesting to note that the students in the experimental group showed improvement despite the different levels of implementation. This suggests that the

act of reflecting on the experiment is critical, rather than the time period at which students engage in this reflection.

Even though the intervention described in the study was small, gains were observed in exam performance. This type of intervention could be easily adapted in a number of classroom settings. Future work is needed to assess how to best implement these types of interventions, and to further understand the reasons why students showed improvement.

As the true method of knowledge is experiment,
the true faculty of knowing must be the faculty which experiences.

-William Blake, All Religions are One, 1788

Chapter 5: Conclusion

The goal of this dissertation study was to gain an understanding of the way students approach learning in the laboratory. Since learning approaches affect learning outcomes, understanding student learning approaches in the laboratory can help educators assess whether or not the laboratory program is effective in meeting its goals. Students' learning approaches are influenced by their perceptions of the learning environment. This study is broken into three main parts. The first part of this dissertation study examines students' beliefs about the usefulness of the chemistry laboratory, and how these beliefs relate to students' previous experiences in chemistry. The second part of this dissertation characterizes student learning approaches in the chemistry laboratory. The third part of this dissertation examines the effect of an intervention aimed at encouraging students to adopt deeper learning approaches in the laboratory.

Students' prior experiences in chemistry shape their views regarding the role of the laboratory in learning chemistry. The survey described in Chapter 2 showed that students who performed experiments more frequently in high school and who had the opportunity to engage in experimental design were more likely to enter college with the belief that the laboratory is a valuable part of learning chemistry. These beliefs may affect the way in which students approach learning in the laboratory.

The interview study described in Chapter 3 revealed that when conducting experiments in the laboratory, students take a variety of learning approaches. The Laboratory Approaches Framework characterizes these approaches, which range from surface-level (Level 1) to deep-level (Level 3). Students using surface-level approaches self-report performing experimental procedures without actively connecting them to chemistry concepts learned in class. Students using deep-level approaches self-report linking the experiment with theory, asking conceptual questions, and reflecting on their observations during the laboratory period.

In order to foster deep approaches to learning in the laboratory, similar to Level 3 students, a metacognitive intervention was designed. This intervention is described in Chapter 4. Students in the intervention group completed worksheets with questions to encourage them to reflect on the experiment. The worksheet questions highlighted specific steps in the laboratory experiment and prompted the students to make connections between chemical principles and laboratory procedures. Students who completed these worksheets had a higher average on the laboratory exam compared with the control group who did not complete the worksheets.

The laboratory has great potential to enhance students' learning experiences in chemistry. In the laboratory, students are able to visualize chemical reactions, and engage in the process of conducting experiments. Interviews with students taking deep approaches showed that these

students are using the laboratory to help them learn chemistry. These students view the laboratory as central to learning science and self-report benefiting greatly from discussions with their instructors and peers about their laboratory observations. However, students taking shallower approaches are not gaining as much from the laboratory. These students view the laboratory as merely a requirement, and are missing many of the opportunities that the laboratory offers for conceptual development. Understanding what factors influence students' approaches to learning can help educators to foster deep-level approaches in the laboratory.

In order for students to gain deeper conceptual understanding from the laboratory, it is important that students not approach the laboratory exercises as cookbook. Adding components of experimental design can engage students and encourage them to think critically about the limitations of experimental procedures and equipment. Students should also have opportunities to reflect on their understanding during the laboratory and explain their observations. When students engage deeply with the laboratory, the laboratory can provide a valuable experience in helping students understand chemistry.

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Appendix A: Interview Protocols

Appendix A.1. Interview Protocol used in Framework Development

This protocol describes a semi-structured interview. The main points and questions are outlined below. Follow-up questions will be asked when appropriate based on student responses.

Part 1: Questions regarding student perceptions of the laboratory.

Question 1: Describe your experiences in the laboratory until this point in the semester.

Question 2: What do you think you are learning from the laboratory?

Question 3: Do you think the laboratory is valuable? Why or why not?

Question 4: What skills, if any, do you think you have gained from the laboratory?

Question 5: Describe your experiences working in groups in the laboratory and discussion section.

Part 2: Self-report of laboratory approach.

Hand student copy of experimental procedure just completed.

Describe to me your thought process as you were completing the procedure.

Follow-up questions: Why did you do that step? What is happening during that step? What sort of questions did you ask your group members? What questions did you ask your GSI?

What would you do if you were working in the laboratory and you calculated a heat of combustion that was very different from your theoretical value?

Hand student copy of experimental procedure for the following week's lab.

Read through the following experimental procedure. You will complete this in the laboratory next week.

As you read through, think aloud about what you expect to see. What do you think you should pay attention to in this lab?

Appendix A.2. Interview Protocols used in Case Studies

Interview 1

Question 1: Your survey indicates you took ____ class. How was your chemistry class in high school similar to or different from Chem 1A? Was it taught differently? Explain. (If student did not take chem., other science class will be substituted)

Question 2: Tell me about your experiences with the laboratory in high school. On your survey you indicated [comments about frequency of laboratory activities or experience in laboratory]. Tell me more about [comments about frequency of laboratory activities or experience in laboratory]. Is this the same in Chem 1A?

Question 3: What type of lab activities did you do in high school?

Question 4: Was the lab useful? Why or why not?

Question 5: What did you learn from lab activities in high school? What was their purpose? How is this similar to or different from Chem 1A?

Question 6: Tell me about your lab experience in Chem 1A.

Question 7: What do you think the purpose of the lab is?

Question 8: What types of things do you think the instructors want you to learn from the lab in Chem 1A?

Question 9: Do you think this is what is you are getting out of the lab?

Question 10: Do you like the lab? What do you like/dislike about it?

Question 11: On your survey, you indicated you are (very confident/confident/not very confident/not at all confident) in your ability to perform experiments. Why is this?

Question 12: Is there anything else you would like to add about your experience in the laboratory?

Interview 3

The following questions are for a semi-structured interview. The main points are outlined below. Follow-up questions will be asked based on student responses.

Question 1: Describe your experiences in the laboratory throughout the semester.

Question 2: What do you think that you learned from the laboratory?

Question 3: Do you think the laboratory is valuable? Why or why not?

Question 4: What skills, if any, do you think you have gained from the laboratory?

Question 5: Describe your experiences working in groups in the laboratory and discussion section.

Question 6: Describe your experiences conducting the research project. What do you think the purpose of this was? What did you learn?

Question 7: During the semester some of the experiments you conducted had a focus on 'green chemistry.' Did you like these experiments? Why or why not? What did you learn about chemistry from these experiments? What does green chemistry mean to you?

Question 8: In the light inquiry lab, you were instructed to make an extraction. Describe to me how you extracted your dye.

Follow up questions: How did you decide which solvent to use? Why did you choose that solvent? How did you decide when to stop your extraction?

Question 9: During the semester, you have completed several experiments. Which lab was the most useful in helping you understand chemistry?

Follow up questions: What did it help you learn? What about that particular lab made it useful? Why was this important?

Appendix B: Case Study Transcripts

Appendix B.1. Student 1, Interview 1

[00:00:06.20] Interviewer: So I'm going to ask you some questions about your survey, so your survey indicates that you did not take chemistry

[00:00:18.11] Student 1: Yes.

[00:00:18.11] Interviewer: But you took, um, lots of lab science classes.

[00:00:23.08] Student 1: Yes, and lots and lots of basically our higher level bio was sort of biochemistry, so I had a little bit of chemistry in there.

[00:00:33.26] Interviewer: So how were your science classes in high school taught similar to or different from Chem 1A?

[00:00:40.28] Student 1: I would say that it was very different in that you could just go to a book and read chapter 3 and you know that you're going to do well on the test because there was a decent amount of memorization, you did have to analyze things, but I could just, I knew that if the night before a test I read the entire chapter and comprehended it I would be fine. Chem 1A, it seems to be more of like, because you don't have this book that you can look at it seems to encourage this if I don't understand something I need to go talk to other people and see how they thought of this and see what they did for this problem, it really encourages the exchange of information and how to do things because I know that I never sought other people's help before this, I would just read the book, and now I'm in like four study groups.

[00:01:27.11] Interviewer: Oh wow, so you really are changing your approach.

[00:01:31.16] Student 1: Oh yeah, you really need to, it's just so much more time effective and I think that I'm learning things a lot better because I'm getting the basic ideas and instead of learning a bunch of specific when this happens you do this, when this happens you do this, I think about well I have an electron here, and I don't have an electron here, so this will probably happen, that's kind of how things have switched, and it's not that bad of a transition.

[00:01:57.21] Interviewer: OK, so you didn't take chemistry in high school, obviously, but you took other lab classes.

[00:02:03.25] Student 1: Physics and Bio.

[00:02:09.01] Interviewer: How is your experience with the lab previously? You indicated something was always broken, missing...

[00:02:17.24] Student 1: It was supposed to have something that was pH 9 and our teacher would be like well it was actually pH 6, and we were like this drastically affects this experiment, this is moderately dysfunctional, we had to submit labs for IB, we would have error paragraphs that were like this long, they were just massive, and then our results and conclusions were always this is what should have happened, it didn't, and this is why this happened, so, we did all right with grading but things were definitely not the best, scales were always unbalanced

[00:02:55.17] Interviewer: How did that affect your learning in the lab?

[00:02:59.23] Student 1: It made it a lot more difficult because you knew what you were supposed to be seeing but you never saw it, you never saw how something worked, you never really, because I know that like again I'll compare it to this chem lab, in this chem lab the experiments are pretty simple which I'm pretty happy with, I don't want to be doing anything complicated, my lab experience has not been the best, but they always work, you can always think about them, you can always think them through, you have to do your calculations and think about how your calculations are going to work and it's always functional, I think that with our other lab they tried to do, we had gel electrophoresis things that they tried to do and they just went horrible because our teacher put in too much dye, she was like you should put in 10 drops, and you needed like half of one, so I think that you just couldn't see what it needed to see, and it just made the learning, like this lab was supposed to be illustrating this concept and it's not, so I am slightly confused was basically my lab experience.

[00:03:58.13] Interviewer: Do you think it was useful?

[00:03:58.13] Student 1: The labs...were not entirely useful as far as learning the concepts but I would say that we got very creative as far as how we approached and analyzed our data so that was good and sometimes we would get creative about trying to change our apparatus or change the experiment to fit what we had because it's like well, if we do this experiment it's not going to work so why don't we just switch it to this experiment so you do have to kind of shift the parameters of what you were trying to do sometimes, so I guess that that was a good exercise in creativity and experimental design, but on the bright side.

[00:04:38.25] Interviewer: So talking more about the lab in Chem 1A, what do you think the purpose of the lab is?

[00:04:42.11] Student 1: The purpose of the lab, well I think that first of all, since this is basically everyone's first science class, it seems like a lot of it right now is learning how to use in the lab and good laboratory procedure and safety and it seems like we're getting experiments that are decently simple so that we have the time to sit down and think, like this is what I need to do and just develop that thinking process of I'm going to test this, I'm going to try and figure out why this works, I want to observe this, so that's what I think the purpose is. I think that as far as illustrating the concepts I do that more out of lab just because I want to be prepared for lab but I

think that sometimes, that was really like stoichiometry, that lab helped me a lot with that just because I got to see it, I got to see oh, I put in this much baking soda and this much vinegar and nothing happened because I didn't have enough vinegar

[00:05:37.29] Interviewer: So you said you do stuff ahead to prepare, what do you do to prepare?

[00:05:43.07] Student 1: I just try and like, I'll look at the lab, obviously, read the lab before, and then the concepts that I don't understand because I haven't been in chemistry before, I'll google, Wikipedia, look at my OWL textbook, I brought another chemistry textbook that my dad has from home just so that if the OWL one isn't sufficient I can look at another one, usually I'll talk to my friend Connor about it because he was in a national institute of health laboratory so I'll be like Connor, what's going on with this and just try and prepare what should I expect to see in this lab so that when I go in I have some idea of what should be happening so if it's not I can re-evaluate what I'm doing

[00:06:21.19] Interviewer: So how did that baking soda lab help you with stoichiometry?

[00:06:22.04] Student 1: The baking soda lab helped because it like never really made sense to me, the calculations I could kind of see how things canceled because I did that a lot in physics, but I just had a lot of trouble with the concept of a mole, it just kind of, I think I lost it somewhere so for me it just really like helped to see, basically the limiting reagent was the concept that I missed somewhere in translation, so for me that was like oh, that's what they mean kind of moment, so that was just like a quick example back in the time when I was like holy crap, this is chemistry, I have never taken it before

[00:07:06.02] Interviewer: Do you like the lab?

[00:07:06.03] Student 1: I do, I used to be really worried about the lab because I thought it was going to be really really stressful, but our GSI is really nice and so that helped a lot the first day, it's fine, chill out guys, and we always have enough time, and everything works, so I do enjoy the lab. It's long, once you get to three and a half hours in you're like I'm kinda hungry, but other than that I do actually enjoy my lab.

[00:07:35.12] Interviewer: What do you like about it?

[00:07:35.12] Student 1: Um, I would say that I definitely enjoy interactive things, I do like having things that illustrate what we're learning because especially on tests, demos in lectures being the same thing, I need to have that physical example to draw back on and think about so if I can't remember how does this work I can have a mental image of it working, and so that can help me just a little bit if I need a little kick in the right direction, and then I think that definitely the lab, like you need to have lab skills, and I think that this lab has been very good so far with being didactic in that area of we're going to slow down and teach you how to use the lab which

has been really useful for me because coming from a high school lab it was haphazard, I needed to learn like the order of this lab.

[00:08:21.16] Interviewer: So why do you need to have lab skills?

[00:08:24.02] Student 1: Because I think I might want to go into science and science would definitely require you to be able to use the laboratory, and also it's just useful in every day to be able to do things precisely and to be able to measure things out precisely and to have that focus and that precision that it takes to be able to get accuracy and precision as we learned in our last lab.

[00:08:45.21] Interviewer: OK, so on your survey, you said that you are not very confident in your ability to perform experiments in the laboratory. So, why is that?

[00:08:56.08] Student 1: That's definitely changed

[00:08:57.24] Interviewer: Tell me about it.

[00:08:58.20] Student 1: Because, before I was really not confident about that just because of the fact that my laboratory experience had been so weird and I assumed that everyone else had had laboratory experiences that were a lot better than mine or maybe a lot more chem oriented, especially since of course one of the first people I talked to about Chemistry was the guy who worked in the NIH lab, a little bit of a divide there so I was pretty, like I said I was pretty scared coming in and I've definitely gotten a lot more calm now that I've settled into the routine of I need to do this, I need to figure this out before, need to read the experiment, make sure I understand it, so I've definitely gotten a lot more calm, I would say that my confidence level in the laboratory has like tripled since that survey.

[00:09:41.21] Interviewer: So if you were to answer it now, if the choices were not at all confident, not very confident,

[00:09:48.23] Student 1: I would say pretty confident, not the most confident, but I would say pretty confident, when I go in there I'm like, I can do this, a lot better.

[00:10:02.21] Interviewer: And then on your survey, it says describe three key features of a good scientific experiment. You said it is an exploration, it is not something where one follows a cut and dry procedure but it's more interaction, where the procedure and critical thinking are interwoven, I'm just going to go one at a time and maybe you can tell me more about what you meant by that.

[00:10:20.14] Student 1: So that one again, that was filled out pretty much in reaction to my old lab, where it was like do this, get this, et cetera, I like it where you have to think about it and like figure out, maybe change the procedure a little bit, or maybe the lab we just did, the titration lab,

if you added in five drops at a time once you get towards the end it's not going to work, they don't exactly tell you that, it's something that you have to figure out. So these haven't been quite as critical thinking involved as I would like them to get eventually where you really have to consider what is this procedure doing, what should I be doing better to make this work better, because they are very simple, right now I'm fine with the simple lab, I'm not going to complain about that right now. But I do think that I would like something that is a little bit more, you have to think about what's going on here and adjust what you're doing to account for this, so that would be an improvement that I can see, but then again at the same time for people like me who are just coming into lab and just having that experience, that may be slightly scary, but later down the road maybe.

[00:11:33.15] Interviewer: So then 2, you said that it addresses a problem, arguable concept, or area where experimentation could broaden one's understanding of the concept. So why is that important?

[00:11:41.09] Student 1: Because if you're just repeating something that's been repeated 5 million times and you already know, something that you can already visualize, like I've already seen this happen.

[00:11:52.13] Interviewer: What would be an example of that?

[00:11:53.04] Student 1: I'm not sure, I just always think of my physics labs where it's like, hey, the block dropped, like, gravity is working, we actually had experiences where we're like, we're going to drop a block and figure out that gravity works, and for me those were just kind of a little bit too boring and illustrated, this could have easily been a class demo where we dropped a block, and it fell, like, our results table was like it fell, it fell, it fell

[00:12:26.12] Interviewer: So that did not enhance your understanding of gravity?

[00:12:28.01] Student 1: No, it didn't

[00:12:29.24] Interviewer: In the same way that the stoichiometric lab...

[00:12:34.16] Student 1: I think that yeah, just going back to the stoichiometric one, because it was done in a more exploratory manner, it was a competition, it was like let's see who can make the biggest airbag. You couldn't just say when I put in this many moles and this many moles they all react, it was, I need to figure out how to maximize my volume so I need to figure out both like, which one is going to make the height raise because that is really what changes my volume the most and then like does it really matter compared to the volume of the bag, I mean the mass of the bag, how should we maximize that, should we try and go for more mass, or less mass, so there was a little bit more critical thinking involved in there just in the fact that it was a competition, they didn't say use 0.75 grams of this and 10 grams of this, you had to figure that out.

So that made it a little bit better. It's still simple, but you just have that little extra step that makes it not boring, because you're like oh, I want to win, I want to make this work, I want to make my solution turn green, like for the titration one it wasn't you should add this much and then add in this many drops because they would tell you your results sometimes, they would say add in this many drops and record your color change instead of this is the color change you want, how many drops should you add

[00:13:48.13] Interviewer: So the way it was presented?

[00:13:49.27] Student 1: It does make a little bit of a difference.

[00:13:54.23] Interviewer: The third one you said, it can be tested with a certain degree of precision. Variables shouldn't be selected at random, and then I think you got cutoff, it says the method of measurement, and I don't know what was after that.

[00:14:06.26] Student 1: OK so that would probably be talking about how a lot of things, like I'm not a big fan of qualitative labs that are grossly like oh, just kind of look at this and sort of like, just pure observational labs, I do like to have something that can be measured, just because for me with the qualitative it's really hard to describe things that well which may get better in this lab, but it's not just that, it's that some experiments you just can't be precise about and the experiment itself seems kind of flawed and I guess that that just came from high school again where it's like...

[00:14:49.00] Interviewer: Do you have an example of one of those?

[00:14:51.01] Student 1: Um, let me think back to my bio lab, I would say again things like, kind of a combination of mistakes in the design where your teacher would have to be like well, we're not going to do this part because we can't measure it because we don't have the equipment, so you're just kind of guesstimating, I don't like guesstimating in lab, you just don't feel right, like I'm doing a lab, this should require some degree of accuracy and/or precision and/or this, and we're not doing this, it just doesn't make you feel very good about your results, and I like to feel good about my results, I think like I got these results for a reason, there's a reason why this is happening, it's not just that I had to guesstimate something. So that kind of bothers me, this survey was basically like what bothered you about your high school lab? Lots of things.

[00:15:47.17] Interviewer: Anything else you want to add about your experience in the lab so far?

[00:15:50.05] Student 1: Um, I'm not sure, well yes, there actually are a few things, so going back to working with people, that has carried over into lab as well which I like because I'm used to, in high school I was the one that always had to figure things out and be like no guys, we should do this because this isn't going to work, so there was a little bit of discussion between me

and the teacher in high school I guess, from the student doing the lab to the teacher, hey, this isn't working, I think we should do this and we would usually change it or do something else so I was the one that always had to freak out and try and do things at the last second, so no, we shouldn't do this, but here it's much more like we usually work in groups of two or three and everyone can bring something to the table, it's not just two people watching standing around while I do the experiment, it's two people saying, no, you should do it like this because, and I have a because and that because is very important because that's where, you know, the lab expands, you don't have just, I'm just going to look at this as, again, like stoichiometry, I'm going to look at this, I'm going to look at this as an exchange of how to like maximize something, you always have this because, because of like, because this is an acid, or because this is a base, and you learn something else outside of just the experiment, because someone's explaining your thinking to you of why they think you should do this. So that's been really helpful, so that would be another thing, is that the labs do encourage, if you do them properly and want a good grade and aren't just sitting there like I want to get done and go to my de-cal, but there is that option to have scientific conversation even if it is very simple, you feel like it's happening and it's enhancing your understanding, and it does make, I've noticed in the post-lab that those are usually a little bit easier for me than other people, just because I try and have those conversations during the lab, with like why is this happening.

[00:17:47.25] Interviewer: Ok, so now the second part is going to be some chemistry content questions

[00:22:37.17] Interviewer: Describe a laboratory experiment that you could perform to determine the molarity of a sample of acid. What steps would you take, what data would you gather, and how would this data allow you to determine the molarity?

[00:22:56.00] Student 1: OK, so molarity of an unknown acid. So I would use titration, like we did earlier in lab, and I would get my acid, and hopefully not burn myself in the process, very carefully I would set it up under a buret is how you say it? OK, so I would basically do the same thing that we did in titration, I would get a base and I would probably dilute that base to not very strong because I wouldn't want it to be like one drop of base turns the whole solution to whatever color and I would use an indicator of some sort, probably either the blue-green one or the pink-purple one, whichever one I had on hand, and I would basically add drops of base of a known molarity until the known volume of acid changed, so basically I would have, yeah, so I would have like

[00:00:14.00] Student 1: So that's basically what I would do, I would add drops, so I want to determine the molarity of the acid, what I would do is I would put the base and then I would have some sort of base down here in a beaker or a flask, and I would have the acid of unknown concentration, I may dilute the concentration of the acid if it seems that it's too strong so that one drop is just turning the entire base, so I would have that and then I would just add it a little bit at a time and see when the base changed, like when the indicator and the base changed colors because that would tell me when the solution went from acid to basic, so if I knew the molarity

of the base and how many moles are there to react with, which I could know if I measure it and I prepare it, like I would measure out a certain amount and then put it in there, and then I would obviously know how many moles of whatever was making my solution basic were in there, and then I would know how many moles of whatever I had that was acidic that went in there, and provided that I know the chemical formulas of each, if I have moles and moles and I have maybe a 2 to 1 or a 1 to 1, then you can just use stoichiometry to figure out how much of each is reacting.

[00:01:47.29] Interviewer: So what data would you need to record from this experiment?

[00:01:51.24] Student 1: I would need to record how much of the base I have, not necessarily, obviously I would have to have either one that I mixed from a powder into like a solution, but I would need to know the number of moles of whatever my base is, and then I would need to know, for the acid, since I can't really know, I can't record the moles, I would have to record the change in volume, so I would have to record how many milliliters I put in, so that's

[00:02:25.26] Interviewer: And then how would you determine the molarity?

[00:02:26.18] Student 1: Because if I know the moles of base, and I know how much acid I put in, then I would know how many moles of acid I put in because once the base changes, once the color would change it means that all of the moles of whatever I have in the base have reacted with all of the moles or most of the moles, it's probably not going to be perfect, whatever I have in the acid. So I would know the number of moles of whatever acid I have, and I would know the volume of whatever acid I have and the molarity is moles per volume, so then I could do that.

[00:03:01.10] Interviewer: How would you decide what indicator to put in?

[00:03:06.04] Student 1: I'm not sure, I would probably just use the one that I was familiar with, probably the one that I used in lab just because I'm no expert on indicators, and I would certainly want one that I think would show, I've heard that some indicators just show, it wouldn't change color when it was an acid, it doesn't indicate base, neutral and acid it just indicates one side of the spectrum or the other, so I would want something that shows base, so when I'm looking at it I'm like, this is a base, it's showing basic color, so that I can see that color change and see ok, it's turning slightly more green, like again, that experiment it went blue, green, yellow, so just like see the gradient of how it's changing

Appendix B.2. Student 1, Interview 3

[00:00:04.04] Interviewer: OK, so tell me about your experiences in the laboratory throughout the semester.

[00:00:20.07] Student 1: OK, so my experience in the laboratory has been pretty good so far, I would have to say, they generally connect pretty well to the chem concepts which help me, um, especially the last one was interesting, because we looked through the spectroscope, because I missed lecture I didn't really understand what the lines that we were supposed to be seeing were and then I saw them and I was like oh, breaking the light apart into the different spectrum, anyway, so my GSI has been amazing, I have to say, she's been really good with giving us guiding questions that lead us towards the answer and that's been really helpful rather than just telling us the answer because then like, I always have to come up with the answers to my questions in lab so that just helps solidify things a little bit more, so overall I think that lab has been a pretty good experience.

[00:01:12.09] Interviewer: So you said something about connecting, do you have an example?

[00:01:18.07] Student 1: Um, like I would say the one example would be, let me think back, so, or I'll just go with the most recent one, the light one, like when we were looking through the mass spectrometer, like the absorption spectra you can see this is the peak, I can see where this peak is and compare it to like the other peaks, the peaks of a certain wavelength of absorption, so you can kind of see, and then we did a Beer's law plot, so you can actually physically see with increasing concentration how less light passes through the solution that you have, like we had beta carotene as a dye for example, so we actually had like, you could demonstrate a linear relationship, our graphs were perfectly stacked on top of each other of how more concentration lets less light through even though me looking at the solutions I remember me and my partner were looking at the solutions going these all look exactly the same color, we are in so much trouble, so just things like that.

[00:02:24.16] Interviewer: So what do you think that you have learned from the laboratory?

[00:02:28.02] Student 1: I think that the laboratory has reinforced the practical applications of the concepts, I don't think that the laboratory has really taught me the new concepts because that's what lecture is for, but it's definitely reinforced them and it's made it so that, really, I think the most useful thing about laboratory is when I am sitting down and taking a midterm or having to think about a chemistry problem in any sort of way, I have something tangible where if I don't remember which way things usually go or if I don't remember how to calculate things or if I don't remember whether my ΔH should be positive or negative, I can think back on lab and on what I've seen in lab and it helps me remember. So for me it's more of like a memory device, this honestly helped me remember the concepts, and even though it demonstrates pretty basic concepts, you know, we're not going into exciting electrons in a Chem 1A lab and observing the energies, well you sort of are with the color thing, but you know, we're not like doing the really, I

would say that we aren't doing advanced concepts, we are more reinforcing basic concepts, sometimes you need that picture that you can go back and draw on and that picture in addition to that concept can help you answer questions in general.

[00:03:41.14] Interviewer: OK. So do you think that the laboratory is valuable?

[00:03:44.06] Student 1: Yes.

[00:03:45.15] Interviewer: Why is that?

[00:03:47.16] Student 1: Because it does reinforce those concepts, you do need a laboratory, because I know, especially coming into college this is going to be the first lab class that a lot of people take in college, there's like 1200 kids taking it or something, and I think it's really important to have this experience in lab where they teach you not just concepts but they also teach you a little bit about lab, like, I didn't know the difference between a beaker and a flask, I mean, that's a good thing to know, I didn't know how to pipet, I didn't know how to titrate, so I would say that learning those basic concepts is a really vital and important part of this lab because otherwise when you go into other labs and they just say titrate this you're not going what do you mean? so I would say that that's really valuable and then again just having that picture that you can attach on to when you're sitting on that midterm and kind of freaking out a little bit has been really useful, having some sort of tangible picture, because they can talk about the absorption spectra and they can talk about how you would make a Beer's law plot but until you really apply it yourself it's kinda hard to figure out whether you know it or not.

[00:05:00.12] Interviewer: So what skills, if any, do you think you have gained from the laboratory?

[00:05:05.07] Student 1: Skills as far as laboratory skills?

[00:05:09.02] Interviewer: Anything.

[00:05:09.02] Student 1: OK, you know, I didn't really have lab skills before this, I knew how, I knew basic, ok, well you need to measure precisely in a general way, I knew how to use a graduated cylinder but other than that I basically had to learn everything about lab from Chem lab, which has been good because now when I go into other labs I'll have a decent standard set of lab skills that I can apply, so that has been good.

[00:05:43.11] Interviewer: What has it been like working in groups in lab?

[00:05:44.23] Student 1: I like working in groups, me and Gwen, my lab partner, still talk to each other, we still meet, we still see each other, and we still discuss chemistry concepts, so I kind of like, I know some people moved around a bit more and talked to other people during lab but I kind of after a few weeks me and Gwen realized that we got along well together and we tried to

work together, and sometimes our lab GSI would break us out of the group and have us work with other people which makes sense because you should meet other people in your lab, but I would say that the most valuable part of the groups for me has just been finding someone that I can talk to about the concepts and when you're working in a group you can't just guess and like kind of do your own experiment and get out of there because it's not just you that has to rely on the experiment, it's your partner, so there's a little bit of quality control with peer pressure, like no, we need to do this, we need to understand this, because both of us are going to leave and when we leave we have the data that we did here so we need to make sure that we understand this while we're here, before we go home. because if we go home and we didn't understand it, and we realize that we did something wrong, then you're already at home, you've already left the laboratory where you would have a chance to correct any mistakes and your lab write-up is probably not going to be the best thing ever, so I would say that it just forces you to discuss chemistry concepts, and even though you should be doing that sometimes you don't so it just gives you an environment where you have to discuss them, otherwise it's going to make your life a lot harder.

[00:07:15.04] Interviewer: So when you are discussing, what kind of questions are you asking, or what kind of things do you talk about?

[00:07:18.18] Student 1: A lot of times it's like why is this happening, or a lot of it is before we do the lab, like what are we going to expect to see, because we do the pre-lab so usually like with my lab partner, sometimes my lab partner likes to rush a little bit more, just wants to get out of there but usually it's what are we going to expect to see, what are we going to have to be careful of in this lab like especially things that are timed, we need something carried out at a hotter temperature, that's something that you talk about before like all right we're going to have to move over here and do this because if this cools the Borax is going to dissolve out of the solution and you know things like that because it's supersaturated, just those are the conversations that you have before. So a lot of it is just discussing concepts like with the solubility one discussing solubility, what is solubility, how is this going to affect it, why do we have to rinse the buret out with the hot water before we pipet more Borax solution, that's just an example from one of the labs, but a lot of it is addressing the procedure and going over the why of each step which inevitably involves the chem concepts that we did the previous week or two weeks ago in lecture.

[00:08:39.22] Interviewer: Tell me about your research project.

[00:08:41.03] Student 1: The research project, we did the difference between baking soda and baking powder, which ended up being a very nice and easy one to do because it was just tidy, you didn't have any hanging loose ends, so it was rather...the only problem I had with the research project is it could be hard to find academic sources, like for example sometimes we could find academic sources about like what is baking soda, what is baking powder, but we needed like an academic source as to what ingredients they're usually used with, and we have cookbooks, like we know what ingredients they're used with just from looking around and seeing

that this is always used with this ingredient, this is always used with this ingredient, but you're not going to find a scholarly article that's like baking soda in cooking is usually used with ingredients that are more...it was just, you know, we just couldn't find one that said that. so that was a little bit frustrating at times, in general I don't know, maybe if we had a different, less home-based or something project we wouldn't have had that problem, but as far as the chemistry concepts went, those were really easy to find, it was easy to find things about like basically just an acid-base reaction, and stoichiometry, and thermodynamics, it's slightly endothermic and that's why you need an oven, things like that, so that stuff was easy to find and/or calculate but the more practical things like what is this used with, you know, you feel kind of like an idiot citing Betty Crocker sometimes, but overall I thought it was really interesting because we picked one that we were honestly interested in because I love to cook so for me I've always wondered why and it actually helps me in the kitchen because now when I'm adjusting recipes and I'm using like a slightly less acidic ingredient, I know, I actually put in slightly more baking powder if I adjust a recipe and it actually works, you get a better rise if you do that, so for me I've been able to take my research project and make my cooking better which has been kind of cool.

[00:10:56.15] Interviewer: So what do you think the purpose of the research project was?

[00:10:57.21] Student 1: I think that there's a few purposes. Because, one, you need to know how to research, you need to know how to be able to research, it's almost like the lab thing, like teaching basic skills, you need basic research skills, and so that's been really helpful because we went to the chem e-brary, the online library which was really helpful because you can do key word searches which are your best friend when it's really early in the morning, you know we had to go to the library and look through books, I know for us, to determine whether the reaction would be endothermic or exothermic we had to use the table of standard enthalpies and find one of those that had everything we needed, so it was really like, it's almost like doing a lab but you don't have the introduction in the front that tells you everything you need to know, you essentially have to write that introduction yourself, and so I would say that research skills are important, and then, just going through and connecting chem to all aspects of life and seeing how, especially since we had to go around and listen to other people's, it was really useful to reinforce things because we had someone whose project dealt largely with pressure, so you had $PV = nRT$ and you were just kind of, as like a review for the final, you were reminded of a lot of concepts and you know you explicitly had to identify the useful physical properties of molecules and that was really helpful because you remember oh there's a lot of hydrogens attached to oxygens here, this one may be an acid, oh this one's probably going to be the one that breaks off because of the electronegativity is clustering the electrons over here, so just reviewing things like that definitely helped just to go over the concepts and to have to investigate a concept in depth yourself and apply it to a more real-world example that's more complicated than one that you would normally pick, like a spray can like an aerosol can, little bit more complicated with the pressure than just a normal like gas cylinder being compressed, so definitely just taking it to another level and seeing how you would take it to another level.

[00:13:04.00] Interviewer: So some of the experiments had a focus on green chemistry, what did you learn about green chemistry from those experiments?

[00:13:09.09] Student 1: Um, mostly just, I feel like a lot of green chemistry is common sense, just like looking at it and I feel like it's just chemistry with we're going to try and you know find ways to ok look at this chemical, this chemical is dangerous, kind of how can we get away from that chemical, like looking at what a certain chemical does in a reaction and finding a greener way to do it is what I took away from that, in the biofuel one you realize that hey, this biofuel actually works, why aren't we using this more and things like that, to me, the green chemistry thing just sort of demonstrated like the viability of certain, like, and kind of made me wonder why we're still using some of the things that we're still using, and I think that it also just shows perhaps just setting you up in terms of lab skills, well, ok, I know that I'm not going to need an entire beaker full of this, maybe I should just get the amount that I need so that I don't have to waste it because I know now that whenever you dispose of chemicals there's a risk there there's a hazard there, and it's just wasteful and you shouldn't do that. so I think that it just forces you to be a little bit more conscientious in lab perhaps about what you're doing, even though it's just NaOH or something but still, what if this were a different chemical that would explode if it got into the ocean, you know, so I would say that that is what the green chemistry is, it's just like a little nagging thing in the back of your mind. I would not call Green Chemistry a focus of the lab course because it was just always something that you had to address, I mean even in the first lab just with the model airbag, you don't really think that there's anything to do with Green Chemistry but then you realize ok stoichiometry, we don't want to be wasteful here so I'm going to try and balance the stoichiometric ratio so that I don't have any reactants left over that are unreacted because that's not good, or do I actually need to use this much and just, I feel like with most of the labs there was a question at least where you had to think about the environment and something larger just than chemical principles which I think is good

[00:15:28.26] Interviewer: So there was a question on the survey about how confident you are in your ability to do experiments, so how confident would you say you are and why?

[00:15:35.21] Student 1: I would say I am very confident now, especially compared to where I was before just because I obviously have more experience in lab now and it's just become a lot less scary, like before lab to me was scary like ooh, college lab, and now it's definitely less scary because I've just had more practice with it. it's really just that simple, I've carried out labs, I've realized that I know how to do the techniques, and really all it takes is focus, understanding what you're doing, and precision and accuracy, trying to carry things out as best as you can, pipetting, that can be really annoying sometimes when your bulb doesn't quite fit on but you know, just like figuring out things like that so it's just the basic skills, the confidence, and the understanding, and I feel that I have definitely acquired those through this lab.

[00:16:33.27] Interviewer: So I'm going to ask you some questions about the dye lab, so I'm going to give you a copy of the procedure to remind yourself of what you did. So you were

instructed to come up with a procedure for making an extraction, so tell me about how you designed your procedure.

[00:16:51.14] Student 1: Um, we just thought about there's dye molecules attached in some form to this organic matter over here, so we figured first of all we should try to break it up into smaller pieces to increase the surface area that's exposed, so we just mashed it up with a mortar and pestle which seemed like a better idea than anything else because first of all we had them in the lab so that was a little hint that we should use them, and second of all it just seems easier than chopping it up with a knife. So first we ground it up, well we used a carrot, I'll just do the carrot one for an example, and so that basically increases the surface area that you can have to basically react with, and then we put it in ethanol instead of water, because we were looking at it and if I remember correctly it was polar, like it had some polar and some nonpolar parts, we should use ethanol because like dissolves like, water is polar, there are some nonpolar parts so we wanted to use ethanol, so we put it in ethanol and since we weren't necessarily looking for the most effective way to remove it, like it was basically just design an extraction procedure and you know we didn't want to adjust temperature because I personally do not like using hot plates so that was more of a personal decision so we put it in room temperature ethanol and then we stirred it, agitated each solution for 5, 10, and 15 minutes respectively because the variable we were testing is how time affects it so we did it basically because we didn't want to do temperature, so we did how time affected it so we would just stir it for 5 minute and then we would filter out the solution because we didn't want any of the big carrot particles or any sort of particle other than dye getting into the solution because that would affect the way that the light would travel through it because if you have a giant hunk of orange carrot in there the light's not going to go through because all of a sudden you have something solid in your solution, so we filtered it to make sure that we got everything out and I would say that's what we did.

[00:18:57.10] Interviewer: So what was it like designing your own procedure?

[00:18:59.09] Student 1: Um, I had done it before with IB so it wasn't the scariest thing ever and especially one that was, it was decently obvious what you needed to do with this one but it was like slightly interesting just because you had that little moment of uncertainty, as I no longer have a procedure that I can look at and ask why this is happening, I have to come up with my own procedure and then look at the steps and make sure that I'm like getting everything and that I have some form of something that is going to work, so I think that it was nice that it was a small portion of the experiment, it was just extracting the dye so it wasn't exactly rocket science, you know, how can I turn the water orange or the ethanol orange, not that hard, but so it was, you know, not the most stressful thing but you still had to think about it more than just the usual mindless follow the steps and do the experiment.

[00:20:01.15] Interviewer: So there have been a lot of labs during the semester, is there one that stands out as being the most useful in helping you understand chemistry?

[00:20:10.13] Student 1: Um, I would say, every time I think about it I think about a different one.

[00:20:18.23] Interviewer: OK

[00:20:18.23] Student 1: So just one, um, I think that the solubility one certainly helped because for me I always forget how to calculate solubility because i get like the K and the K_{sp} confused and I never know, sometimes you do like the s squared times, or it ends up being like 2 s squared times s or something and I always forget like when you carry down the exponent, and just having something that illustrated a concept that I would get moderately confused on would probably highlight that one as being the most useful.

[00:20:59.22] Interviewer: What about that particular lab made it useful?

[00:21:03.08] Student 1: Well first of all it was like the Borax one, that was the solubility one, just to clarify, and I think that it was just useful because to me it really solidified the Q and the K because I could like see it happen, and again that really helps me, just having that visual thing to attach onto, especially when you could see it re-solidifying inside of your pipette, things like that, um, but it was just like, it just really helped to be like the Q is greater than the K which means that there is too much in here which means that if it goes back to room temperature it's going to solidify which means that we need to rinse it out with hot water, so when I'm sitting on a test and I have one of those little graph things, I just pretend, whatever it is, it becomes Borax and I just think about it that way and it helps me become less confused and that is a good thing.

Appendix B.3. Student 22, Interview 1

[00:00:03.09] Interviewer: OK, so first I have a few questions about your survey responses, so your survey indicates that you took Chemistry in high school. So how was your Chemistry class in high school similar to or different from Chem 1A?

[00:00:15.21] Student 22: Um, I really liked Chemistry in high school, like it was, it was fun, because the teacher was really like, you know, like, like he made it fun because he had a lot of like demonstrations and fun ways to help us remember, and um I like the Chem lectures too, it was a lot more demonstrations in like Chem 1A now, so they're both good in their own ways.

[00:00:43.19] Interviewer: What about the focus of the class, or how it was taught, or the approach, was that similar or different?

[00:00:50.28] Student 22: I don't know, like I think like for Chem 1A, so I'm in a study group, I think that that's more helpful than the lecture itself.

[00:01:06.01] Interviewer: Why is that more helpful?

[00:01:07.07] Student 22: Like, cuz, for the study group like we actually go over stuff that would be on the midterm, where I feel like from the lectures like I understand it, but when I go over midterm practice like review, like it doesn't help as much as the study groups did.

[00:01:23.08] Interviewer: So tell me a little bit about your experiences with the lab in high school, so you said that you did lab about once a month, and you followed a given procedure, and you said that you would calculate the molarity of solutions, and you said that all of the chemistry labs were just all right, so tell me what you mean by that.

[00:01:45.20] Student 22: Um, I think, cuz I was in regular Chemistry, I wasn't AP, so we didn't do as many labs as the AP class, so a lot of them were pretty simple and um I don't know, I think like for Chem here, like, I feel more stressed to do lab because they're actually graded more critically than it was in high school, so the one in high school wasn't as stressful as the one here.

[00:02:14.19] Interviewer: So why is the one here more stressful?

[00:02:16.28] Student 22: Cuz like, the grading, yeah.

[00:02:25.05] Interviewer: There was a question on the survey that asked you to rank how useful the lab was in high school and you said it was not very useful, and you said you didn't really remember them, you mostly focused on completion for the grade, so tell me more about that.

[00:02:38.19] Student 22: Wait, what was the question?

[00:02:41.20] Interviewer: The question on the survey asked you to rank how useful the lab was in helping you learn Chemistry, and you said it was not very useful.

[00:02:49.03] Student 22: I think part of it was that I had it in 10th grade so it was a long time ago so I don't remember it now, but, um, yeah, I think that's like the main factor, and also like we didn't go over that many labs because it was just regular Chemistry.

[00:03:07.20] Interviewer: So would you say the lab in Chem 1A is different?

[00:03:10.19] Student 22: Um, I guess it's different, also, because there's more resources too than there was in high school, so we actually get to like explore more and actually learn.

[00:03:27.15] Interviewer: So do you think the lab in Chem 1A is more useful in helping you understand the chemistry, or not useful?

[00:03:38.14] Student 22: It's related to what we're learning but it doesn't really, I feel like it doesn't help me as much, like for the midterm.

[00:03:50.24] Interviewer: So what do you think is the most helpful part of the class?

[00:03:52.17] Student 22: For midterms?

[00:03:57.13] Interviewer: Sure.

[00:04:00.05] Student 22: Um, at least it goes over what we need to know and stuff.

[00:04:15.22] Interviewer: What does?

[00:04:15.22] Student 22: The lectures, like she talks about, but again I feel like the study groups are more helpful.

[00:04:21.22] Interviewer: So you feel like you get the most out of the study group.

[00:04:27.15] Student 22: Yeah.

[00:04:27.15] Interviewer: So what do you think the purpose of the lab is?

[00:04:30.02] Student 22: Um, I guess like to get the hands-on experience of how we use chemistry in real-life.

[00:04:38.26] Interviewer: So why is that important?

[00:04:39.27] Student 22: Um, I guess it's just like the application of everything, I don't know.

[00:04:51.28] Interviewer: Why do you think it's important to have the application?

[00:04:55.01] Student 22: Um, it affects us like, I guess you don't really realize like how much like you need chemistry, for example, to make nylon requires like chemistry

[00:05:16.16] Interviewer: So on the survey you indicated that you are not very confident in your ability to perform experiments, so why is that?

[00:05:23.23] Student 22: Cuz like when I read the labs, it's kind of like, in a way, dense, and, cuz like even if you read over it, during lab again I have to read over it as I'm doing it and like I get kind of confused so I have to ask my lab partner for guidance.

[00:05:49.15] Interviewer: Has that changed since you've been in Chem 1A?

[00:05:54.02] Student 22: Kind of the same, it's kind of like once I read it I have a general idea of it but when I'm actually doing it I have to ask questions to be sure of what I'm doing.

[00:06:09.11] Interviewer: There was another question on the survey that asked you to describe three key features of a good scientific experiment, and the first one you said was accurate measurement. So why is that important?

[00:06:20.14] Student 22: Um, if you don't have accurate measurement then you won't get the right results

[00:06:34.25] Interviewer: The next one you said was preparedness, so why is that important?

[00:06:36.22] Student 22: Like again, like, if you read the lab and if you're prepared then it makes it easier to do the lab instead of being stuck all the time and trying to ask questions like oh, is this right, is this right

[00:06:51.10] Interviewer: And the last one you said was knowledge, so what did you mean by that?

[00:06:54.24] Student 22: I guess like, cuz some of them ask you to do the calculations so if you have knowledge, like how to calculate molarity, then it makes it easier, and you'll understand the lab better, like why it's being performed

[00:07:10.25] Interviewer: Is there anything else you want to add about your experiences in the lab in Chem 1A so far?

[00:07:16.03] Student 22: Um, it wasn't what I expected, you know how in college you have more resources so I thought we would do really cool experiments but I guess they're OK

[00:07:30.07] Interviewer: What did you expect?

[00:07:32.23] Student 22: You know like in those movies you see all this bubbling and fire and all that kind of stuff, here it's just kind of like really safe which I guess is good for us, it's just like, that was my expectations.

[00:07:47.29] Interviewer: Do you like the lab in Chem 1A?

[00:07:49.24] Student 22: Um, it's ok

[00:07:51.28] Interviewer: What do you like or dislike about it?

[00:07:53.20] Student 22: Um, I guess, sometimes they're kind of boring, like the titration lab, that was really long, and, just like the length of it, it takes a long time to do, and I guess the good part about it is, um, our GSI, she's pretty nice about it and she helps out, so.

Appendix B.4. Student 22, Interview 3

[00:00:02.08] Interviewer: OK, so tell me about your experiences in the laboratory throughout the semester. How has the lab been?

[00:00:08.21] Student 22: Um, it got a little easier, like not as complicated as the first few, or the middle labs.

[00:00:20.26] Interviewer: Why do you think that is?

[00:00:21.29] Student 22: Um, I don't know, maybe, well, I don't know if it's related, but like Stacy said that the later units are easier than the previous ones so maybe that's why, it might be kind of like, maybe not, I don't know.

[00:00:42.12] Interviewer: Which labs were easier?

[00:00:45.26] Student 22: Like, for example, the last one with the dye extraction, that one wasn't so bad.

[00:00:59.23] Interviewer: Which ones were difficult?

[00:01:00.17] Student 22: Um, the titrations just because like you have to be really like precise and accurate, and like, you add too much and it changes color

[00:01:14.17] Interviewer: When you say difficult, do you mean completing them, or thinking about them...how are they difficult?

[00:01:18.10] Student 22: Difficult in terms of like, um, getting the results that you want and the time to complete it because some of them are really long, or like, um, like just sometimes the instructions I guess.

[00:01:39.06] Interviewer: So what do you think that you have learned from the laboratory?

[00:01:42.25] Student 22: I definitely learned what the equipment are called, um, how to write better lab reports, um, and I guess just like some of the real-life applications that the labs are related to, like the biodiesel stuff, you know how for the pre-lab it has the information that you can read about it, for that chemical or whatever you're using, that kind of stuff.

[00:02:23.08] Interviewer: Can you give me an example?

[00:02:26.22] Student 22: Um, like the biodiesel one it's like a renewable source of like energy, cause like I never knew that much about oil, and how you can reuse like the plants and how you can like extract that out of a plant-based source.

[00:02:50.02] Interviewer: Do you think the laboratory is valuable?

[00:02:52.27] Student 22: Um, I think it is but I guess for me on a scale of 1 to 10 I would say a 7 to me.

[00:03:04.24] Interviewer: Why is that?

[00:03:04.24] Student 22: Well, like, it's not on the low end because it is valuable, you do learn stuff out of it, but it's not too valuable because, I don't know, I think, I don't know, I don't see it much on the higher end.

[00:03:26.02] Interviewer: What do you mean by that?

[00:03:26.02] Student 22: Like, I guess it's just like how you set your, I don't know, set your values I guess? Like, if I were to, if you had a test to study for or a lab to study for the night before I would probably study for the test instead of the lab, I would prioritize that kind of second or third.

[00:03:53.18] Interviewer: Why is that?

[00:03:54.19] Student 22: Um, I don't know, I don't see it as important I guess? Like maybe, um, like, I know it's important to read the lab beforehand so that you're well prepared and stuff, but that's something that you can do last minute and you'll do okay on it.

[00:04:26.09] Interviewer: So what skills, if any, do you think that you have gained from the laboratory?

[00:04:29.27] Student 22: Um, I guess like, what I've learned, like what kind of tools, what the equipment is called so then I can easily access it faster, and just like knowing, cuz like a lot of the procedures like kind of repeat throughout the labs so like if you see it then you automatically know what to do, like the first time you do it, if you first see it you ask around and you're kind of confused, so I guess doing it repeatedly helps you do it better the next lab, or like, um, yeah, I don't know.

[00:05:26.09] Interviewer: So tell me about your experiences working in groups in the lab and discussion section.

[00:05:31.06] Student 22: It's been pretty okay, cuz like most of the time I work with one of my friends but then on the, um, previous lab, I worked in a bigger group and I got kind of irritated because one of the guys was doing something that he wasn't supposed to with the extraction so it was kinda, what the heck are you doing, cuz this is wrong

[00:06:02.22] Interviewer: Was he goofing off or doing something...

[00:06:06.00] Student 22: No, you know if you're using the carrot it says to use ethanol, and like, cuz, you have to use ethanol or water, so it says to use ethanol, but then he was like, you know how you're supposed to mash up the carrot, he put water in it to make it more, I don't know why, so I guess that messed up the weight too, his reasoning was, I didn't want to get into a big argument about it, so I was kind of like whatever

[00:06:46.14] Interviewer: Do you think it's helpful to work in groups?

[00:06:49.13] Student 22: I think it's helpful to work in groups especially on labs because it can get confusing sometimes if you're kind of lost on a step then you have someone to ask.

[00:07:00.18] Interviewer: What kind of stuff do you ask your group members?

[00:07:02.22] Student 22: Um, like, um, is this what we're supposed to use or, it's kind of like, it's kind of like also makes it easier, someone can help you do the step and you can do it instead of you immediately going back and forth between the notebook and the actual experiment kind of thing, just to check like, oh, is this right or not.

[00:07:36.12] Interviewer: So tell me about your research project.

[00:07:38.15] Student 22: Um, we researched on hand sanitizer whether the alcohol based ones or non-alcohol based ones work better.

[00:07:52.16] Interviewer: What did you find out from that?

[00:07:54.21] Student 22: The alcohol-based sanitizer kill more bacteria than the non-alcohol ones because, like, the main ingredient in the alcohol one, there's two different ones, isopropanol and ethanol, and the non-alcohol based ones use this other one that I can't think of right now, the alcohol one uses more of the chemical in high concentrations, so I guess with that factor it helps it kill more, but also because alcohol's chemical properties kill the bacteria better than the non-alcohol one.

[00:08:40.04] Interviewer: What do you think the purpose of the research project was?

[00:08:43.13] Student 22: I guess just like maybe to get a feel of what it's like to do research, in the future cuz we'll probably have to do sometime later in our lives

[00:09:01.04] Interviewer: Did you like doing the research project?

[00:09:03.14] Student 22: Um, it was OK.

[00:09:08.29] Interviewer: Some of the experiments had a focus on Green Chemistry, what did you learn about Chemistry from those experiments? What does Green Chemistry mean to you?

[00:09:23.08] Student 22: Um, when you say Green Chemistry the first thing that I thought of was the biodiesel, cuz of like the whole renewable source of energy thing, and I guess also the lactic acid one, was it like what I learned from it?

[00:09:43.24] Interviewer: What you learned from it and also what did you gain of an understanding of Green Chemistry?

[00:09:51.28] Student 22: I never really dealt with Green Chemistry before, but I guess it's pretty cool, like, there's so many other topics in Chemistry, in Chem 1A in general, if it's possible to do this with biodiesel or with plastic cups then there's probably a lot more stuff you can do with Green Chemistry and make it more recyclable or reusable

[00:10:33.07] Interviewer: How would you define Green Chemistry?

[00:10:35.02] Student 22: Um, something that can be, um, like recycled, like more of like to benefit the environment, so if not wasting products or, um, just like to benefit the environment and the people in general.

[00:11:06.16] Interviewer: There were some questions on the survey about how confident you are in your ability to perform experiments, did this change over the course of the semester?

[00:11:15.13] Student 22: Um, I don't know, maybe a little, but like, in general, everyone is a new lab so you never really know if you'll be prepared for it so it can vary, I think it's, if anything, changed a little bit, like better.

[00:11:42.02] Interviewer: How confident would you say you are in your ability to do labs?

[00:11:46.05] Student 22: On a scale of 1 to 10, 10 being really confident, I would probably say 7 or 8

[00:11:50.19] Interviewer: Why is that?

[00:11:52.27] Student 22: Um, I guess, well, following the directions aren't that bad but it's more of like doing the lab reports that are hard, cuz like, it's like when you try to understand the concepts for the test it's different than trying to understand the concepts when you're doing the lab.

[00:12:15.21] Interviewer: Why is that different?

[00:12:15.21] Student 22: I guess like, I feel like, um, I don't know, it just seems kind of harder because, like, maybe cause it's the real-life application thing, like actually to your lab, I guess like you can understand what you're doing in the lab but you don't understand what's actually happening conceptually

[00:12:43.03] Interviewer: So how would you go about figuring that out?

[00:12:52.06] Student 22: Like trying to do the lab reports? I usually go to my GSI office hours to ask for help and she clears things up so it makes it easier to understand.

[00:13:00.21] Interviewer: What kind of questions do you ask your GSI?

[00:13:03.09] Student 22: Um, like, um, just going over some of the stuff, or like how would I go about solving this kind of problem, something like that.

[00:13:27.03] Interviewer: You said it was different with the lab and with the exam, the conceptual understanding, can you say more about that?

[00:13:34.11] Student 22: Like, um, I guess it's like, um, I'm not sure if it's because of the way it's worded or something or like, um, I don't know, I guess I'm having a harder time trying to finish the lab report than just trying to do actual chemistry problems.

[00:14:01.09] Interviewer: I'm going to ask you a few questions about the light lab, so I'm going to give you the procedure to remind you of what you did. You talked about this a little bit before, but you were instructed to do an extraction, so tell me how you decided to do your extraction.

[00:14:19.27] Student 22: OK so we used carrot and we decided to test the temperature factor, so after we mashed the carrot up and weighed it out we put it in like the ethanol solvent, or solution, in three different beakers, and one of them we put it in an ice bucket so it would be at equal temperature and the other one was at room temperature and the last one was at a higher temperature, I think it was 50, I can't remember the temperature, and after that we took it out and we just, we put it in these little rectangular tubes and put it in that machine that calculates the absorbance of the peaks and stuff.

[00:15:30.04] Interviewer: So how did you decide what solvent to use?

[00:15:32.00] Student 22: Um, because, um, cuz one is nonpolar and one is polar and we know that ethanol is a nonpolar one, so that would be able to extract the beta-carotene because the beta-carotene is nonpolar

[00:15:54.09] Interviewer: How did you decide when to stop your extraction?

[00:15:59.09] Student 22: It said to stop it after 10 minutes.

[00:16:09.23] Interviewer: Tell me about your experience designing your own procedure, did you like that, did you not like that...

[00:16:17.20] Student 22: At first I thought it would be something hard cuz like, it's not like how the others were, but it seemed to be pretty easy, so

[00:16:29.05] Interviewer: Did you like doing that?

[00:16:29.05] Student 22: Um, it was OK, I'm kind of neutral about it.

[00:16:41.18] Interviewer: You've done a lot of labs throughout the semester, is there one that stands out as being the most useful in helping you understand the chemistry?

[00:16:47.24] Student 22: Um, I don't know, like the biodiesel one is coming to my head, maybe because I don't remember the first few that we did, cuz it was so long ago, but, yeah, biodiesel

[00:17:03.27] Interviewer: What about that particular lab made it useful?

[00:17:08.21] Student 22: Just cuz that one, it was really emphasized with the whole green chemistry concept, how it was reusable, like, better for the environment

[00:17:30.16] Interviewer: What did you learn from that lab?

[00:17:32.09] Student 22: I think the reason I remember it more is because we did the lab report for it, but, um, so that one I learned also how to write a lab report better and I guess also like more of the concepts of Green Chemistry and like, just like more of why it's used as opposed to other fuel sources.

[00:18:10.25] Interviewer: You said the concepts of Green Chemistry, what concepts?

[00:18:13.23] Student 22: Like the whole reusable, renewable source.

Appendix C: Intervention Worksheets

Appendix C.1. Worksheet for Laboratory Experiment 6: Depolymerization of Poly(lactic acid) cups to lactic acid.

Answer the following questions before you begin the lab:

What is depolymerization? Discuss with your group.

Draw the reactants and products of the depolymerization reaction.

What will the titration help you determine?

After steps 1-5, while your mixture is cooling, answer the following question:

What did heating the mixture do?

Before moving on to step 6, answer the following question:

What does adding HCl do? Draw what you have in your flask after adding HCl.

Before titrating, answer the following question:

What data do you need to record? How will you use this in a calculation? What other information will you use in calculations? Set up a sample calculation.

Appendix C.2. Worksheet for Laboratory Experiment 10: Solubility and Spontaneity.

Before beginning the lab:

What are you trying to determine in this experiment?

Before Preparing the Borax Solution:

Why is it important to prepare Borax solutions at different temperatures?

Before Preparing for Titrations:

Why do you need to record the exact concentration of the standard HCl? How will you use this value in calculations?

Before Preparing Saturated Borax Solutions for Titration:

Why is bromocresol green indicator used for this titration?

Before Performing the Titrations:

What data will you record during the titration? What will you use this to calculate?