ABSTRACT

EXPLORING THE UNDERGRADUATE CHEMISTRY LABORATORY CURRICULUM:
FACULTY PERSPECTIVES

By Michael E. Fay

Effectiveness of the undergraduate chemistry laboratory has been the subject of research for several decades. However, it has proven difficult to measure the effectiveness of the chemistry laboratory curriculum without an extensive understanding of its purpose. This research investigated the goals of chemistry faculty at all levels of the undergraduate curriculum via telephone interviews. The findings of this qualitative inquiry form the basis for future quantitative studies that will measure a more extensive understanding of the purpose for the chemistry laboratory.
EXPLORING THE UNDERGRADUATE CHEMISTRY LABORATORY CURRICULUM: FACULTY PERSPECTIVES

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Table of Contents

List of Tables .........................................................................................................................................................iv

List of Figures ..........................................................................................................................................................v

Acknowledgements ...............................................................................................................................................vi

Chapter One: Introduction to the Inquiry ...........................................................................................................1

  Research Question .............................................................................................................................................2

  Presence of Self ..................................................................................................................................................3

Chapter Two: Literature Related to the Inquiry ..................................................................................................5

  Theoretical Framework .....................................................................................................................................5

  History of the Teaching Laboratory in Chemistry ............................................................................................7

  Effectiveness of the Laboratory on Learning ....................................................................................................7

  Goals for Student Learning in the Laboratory ................................................................................................8

  Needed Areas of Research ...............................................................................................................................10

Chapter Three: Methodology .............................................................................................................................12

  Sampling Protocol ..........................................................................................................................................12

  Human Subjects ..............................................................................................................................................14

  Interview Protocol .........................................................................................................................................14

  Interview Analysis .........................................................................................................................................16

Chapter Four: Research Findings .......................................................................................................................17

  Interviews: Course Goals ...............................................................................................................................17

    General Chemistry – Faculty Innovators ......................................................................................................18
General Chemistry – Status Quo ................................................................. 22
Organic Chemistry – Faculty Innovators .................................................. 24
Organic Chemistry – Status Quo ............................................................... 25
Upper-level Chemistry – Faculty Innovators .............................................. 28
Upper-level Chemistry – Status Quo .......................................................... 30
Summary of Goals ....................................................................................... 33
Chapter Five: Analysis and Interpretation of Faculty Goals ....................... 34
Cognitive Faculty Goals .............................................................................. 37
Psychomotor Faculty Goals ......................................................................... 42
Affective Faculty Goals ............................................................................... 46
Intersection of Learning Goals ..................................................................... 50
Implications for Future Research ................................................................. 55
References ..................................................................................................... 57
Appendix 1 – A rubric to characterize inquiry in the undergraduate chemistry laboratory .......... 60
Appendix 2 – Structuring the Level of Inquiry in Your Classroom ................ 75
Appendix 3 – List of Laboratory Experiments Used to Establish Inter-rater Reliability ........ 87
Appendix 4 – Template for Innovator Email Invitation .................................. 89
Appendix 5 – Template for Status Quo Email Invitation ................................. 90
Appendix 6 – Informed Consent .................................................................... 92
Appendix 7 – Interview Protocol for Innovators ......................................... 94
Appendix 8 – Interview Protocol for Status Quo Participants .......................... 97
List of Tables

Table 1  Sampling Matrix for Innovative and Status Quo Participants………………..13
Table 2  Innovator Interview Analysis by Learning Domain………………………….35
Table 3  Status Quo Interview Analysis by Learning Domain……………………….36
Table 4  Cognitive Goal Summary…………………………………………………….41
Table 5  Psychomotor Goal Summary………………………………………………….46
Table 6  Affective Goal Summary……………………………………………………..50
List of Figures

Figure 1  Learning Domain Coding Frequency for Innovators...............................36
Figure 2  Learning Domain Coding Frequency for Status Quo Participants.............37
Figure 3  Venn Diagram of Faculty Goals by Learning Domain.............................53
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Chapter One: Introduction to the Inquiry

A photograph exists in two separate museums on the small island of Cyprus. In both locations, mere miles apart, the photo is framed and carries with it a caption. The accompanying caption at one museum gives a detailed account of the event captured in the image. It turns out that the image, as it exists in the second museum, carries with it a caption explaining the same event in entirely different terms.¹

How can it be that a single event is interpreted so differently by the people of the small island nation? As it stands, Cyprus is a nation divided by two cultures, two governments, and one very distinct line. The Turkish inhabitants maintain one portion of the island, while the other portion is under the control of Greek descended peoples. It is understandable that the two “sides” of this conflict/situation perceive any event with a very different perspective: that one understands any action on the part of the other to be a threat.¹

This current political tension is not as remote as geography would have us believe. In fact, one could argue that a similar conflict is looming in most chemistry laboratory classrooms. Teachers hold a set of expectations about how students should learn chemistry, and they structure their lectures, laboratory courses, and assessments according to these expectations. At the same time, students have their own set of expectations about what the laboratory experience will entail for them.² Grove and Bretz³ designed an instrument to measure such expectations. They compared the faculty expectations to those of undergraduates at various levels of the chemistry curriculum, finding that large, statistically significant gaps in expectations existed between students and teachers of chemistry. It is only as students continue in upper level courses that these expectations begin to become more homogeneous with those of chemistry teachers.³

Edmondson notes that, despite these initially disparate expectations, students very quickly learn to achieve success in their chemistry classes. They consider themselves successful on the basis that they are subsequently allowed to move on to the next course in the sequence.² Unfortunately, many students do not meaningfully incorporate many chemical concepts into their conceptual frameworks.⁴ Instead, they memorize algorithms and mnemonic devices to earn good grades in lecture, and they feel obliged to change their laboratory data in order to achieve better
accuracy and precision. Furthermore, students find it difficult to connect their laboratory experiences with topics discussed in lecture.

Many chemists believe that the laboratory is the place that students should learn the process of doing science. The scientific community has a strong belief in the inherent value of laboratory work because it offers direct experience with collecting and analyzing data from the physical world. As Tobin wrote in 1990, “Laboratory appeals as a way of allowing students to learn with understanding and, at the same time, engage in the process of constructing knowledge by doing science.”

However, studies have shown that in the undergraduate laboratory most students gain little insight into key concepts and that laboratory has little to no effect on achievement, reasoning, critical thinking, or scientific thinking. Nakhleh summarized the research on student learning in the chemistry laboratory stating that students often complete the assigned activities through memorization techniques (e.g. mnemonic devices), thus engaging in little meaningful learning. She adds that such tactics are often implemented due to the existence of broad, vague goals for the laboratory activities.

The state of affairs in the traditional chemistry teaching laboratory brings to bear several issues. There is little in the research literature to examine the student’s perspective on laboratory work and its correspondence (or the lack thereof) with the faculty’s perspective. In a review of the literature on work in the chemistry laboratory, Nakhleh points out that researchers have not fully investigated precisely what goals faculty members and students do have for laboratory work. In the absence of clearly defined goals and expectations, it is difficult to make any assertions about the value of laboratory as a learning environment let alone measure the degree to which the teaching laboratory meets its goals.

**Research Question**

The study described here is part of a larger investigation funded by the National Science Foundation – Course, Curriculum, and Laboratory Improvement (CCLI) program (Award No. 0536776). The primary objective of the overall investigation is to develop a rich understanding of both student and faculty goals for the laboratory, and to quantify the gap between these two
perspectives. The portion of the larger project that is reported in this document concerns itself
with exploring the expectations college chemistry faculty have for student learning in the
laboratory.

The following research question framed this study: What are the important learning
outcomes that faculty intend for students in the undergraduate chemistry laboratory? This
primary research question was conceptualized to include:

- What are important concepts and/or techniques for students to learn?
- What is most useful for students’ future careers?

The answers to these questions will provide the chemistry community with a deeper
understanding of faculty expectations for learning in the undergraduate chemistry laboratory.

**Presence of Self**

Although many chemists think that the presence of the researcher does not influence the
outcomes of the investigation, the idea of a discreet distance between the observer and the
phenomenon observed in human research is rejected by many qualitative researchers. As
Lincoln and Guba put it, “observation not only *disturbs* and *shapes*, but is *shaped by* what is
observed”\(^{10}\) (p. 98, emphasis original). This concept echoes the Heisenberg Uncertainty
Principle, which states that as the observer’s certainty in the position of an electron increases, the
observer’s certainty in the momentum of the electron decreases.\(^{11}\) As an early scientific example
of what is now called the observer effect, this principle clearly demonstrates that the very act of
studying a system can perturb it. The implications of such disturbance, or uncertainty, are
devastating to the presupposition that the researcher can be separated from the observation of
reality. As Heisenberg himself\(^{11}\) stated, “[we] have to remember that what we observe is not
nature herself, but nature exposed to our method of questioning.” It is therefore important for
this researcher to offer the reader a brief description of the perspectives that he brought to the
inquiry and that have come to shape it as a result. The following summary affords the reader
insight into such events:
During my junior year of high school, like so many other teens in this country, I took a chemistry class. I had always been interested in the sciences, but for the first time ideas seemed to “click” for me very quickly. Never before had I been presented with a subject that sparked my interest and came naturally to me. Moreover, I thoroughly enjoyed teaching this subject to my classmates who struggled with the mathematical applications and the conceptual modeling. Whether a flaw or a gift, one of my more apparent attributes is the desire to convey the meaning I find in the world with others. It was at this time that my innate affinity for teaching became inextricably linked to the subject of chemistry.

I entered college with the express intent of teaching chemistry in high school. It was, and is, more than just a passive interest; it is a passion. However, with chemistry and education as my dual majors at a small liberal arts institution, I was quite alone in my chosen fields. I was the only education major whose content area was chemistry. Fortunately, I had three fellow chemistry majors to share my interests and my time. As a result, I focused my primary energies on the study of chemistry, while the theories and practices of education took a back seat. I read about research-based teaching methods that were completely abstracted from chemistry, and as such I struggled to incorporate them coherently into my teaching philosophy. During my student-teaching placement, I attempted to implement a research-driven curriculum centered around the inclusion of inquiry-based activities. While my intentions were good, I did not understand fully how to teach using such methods.

As John Steinbeck wrote, “the best laid plans of mice and men often go awry.” Due to such a frustrating student-teaching experience, I decided to postpone my plans to begin teaching in my own classroom. I decided to seek further education in the theory of teaching chemistry. My graduate studies focused on inquiry in the classroom and practical methods for implementing such activities. During this time, I was afforded the opportunity to rediscover learning theories in the context of chemistry, especially Novak’s theory of human constructivism. I came to a deeper understanding of the process of learning, namely the construction of meaning within the learner. I discovered that knowledge cannot be conveyed from one person to another; it must be built by each individual, based on his or her experiences. It became apparent to me that the process by which I came to understand the theory of constructivism was evidence for the theory itself. In order to attribute meaning to this theory of learning, I needed to experience such learning in action. It was by this route that I built the concept of constructivism for myself.

As a result of these experiences, I have come to be very interested in the purposes, or goals, behind the curricula and pedagogies of chemistry teaching. My personal teaching goal for chemistry in secondary education is to build a scientifically literate society. I want my students to be critical analysts in all aspects of life and to construct personal meaning for a basic set of chemistry concepts that will be useful in their lives. Thus, it is a great benefit to me to understand the context of chemistry teaching goals at the undergraduate level, because I want to have a deep understanding of the setting in which my students will learn once in college. By recognizing that such experiences have had some bearing on this inquiry, I hope to convey the important role the knowledge of my own learning plays in understanding the context of this study.
Chapter Two: Literature Related to the Inquiry

Theoretical Framework

In the epigraph to *Educational Psychology: A Cognitive View*, philosopher David Ausubel writes:

“The most important single factor influencing learning is what the learner already knows. Ascertain this and teach him accordingly.”

This short statement grounds all of Ausubel’s work on education. The foundation of his *assimilation theory* is rooted in the idea that “reasoning capacity is primarily a function of the adequacy of the relevant conceptual framework a person has in a specific domain of knowledge.” (Novak 1998, cited from Bretz 2001) To put it another way, a chemistry student maintains a mental structure of existing knowledge that is necessarily utilized to incorporate new concepts encountered in chemistry courses and, ideally, in daily life. Ausubel calls\(^\text{13}\) the process of making these “non-arbitrary” connections between old and new ideas *meaningful learning*. As Bretz summarizes\(^\text{14}\), there are three criteria that must be met in order for meaningful learning to occur:

“i) [A] student must have some relevant prior knowledge to which the new information can be related in a non-arbitrary manner, ii) the material to be learned must be meaningful in and of itself; that is, it must contain important concepts and propositions relatable to existing knowledge, and iii) a student must consciously choose to non-arbitrarily incorporate this meaningful material into his/her existing knowledge, a disposition which Ausubel labels as the meaningful learning set.”\(^\text{14}\) (emphasis original)

It is important to notice that there is another form of learning to which students often become accustomed. This is called rote learning, in which case the student merely memorizes concepts, instead of connecting them purposefully to prior knowledge. Herron\(^\text{15}\) claims that the alacrity with which students pursue this strategy is due to a desire to put forth the “least cognitive effort.”
In other words, students typically do not want to expend the effort needed for meaningful learning, at least not without proper motivation. Rote learning and meaningful learning are at odds with each other.

What can be done to bring students to learn chemistry in a meaningful way? A problem arises if an attempt is made to address all three of these criteria from the perspective of the teacher. Only one variable lies in the power of the teacher to control, namely making the chemistry content available to the students “in such a manner that it can be connected to students’ prior knowledge and be of sufficient interest that they might choose to do so.” The other two variables are under the control of the student; the student brings prior knowledge to the learning environment, and the student decides whether to learn meaningfully. A more effective effort is described by Bodner. He states that “[this model] requires a subtle shift in perspective for [teachers]; a shift from someone who “teaches” to someone who tries to facilitate learning; a shift from teaching by imposition to teaching by negotiation.” For Bodner, the crux of the issue lies in active learning. Knowledge cannot be passed verbally from teacher to student; therefore, students should be active participants in the learning process so they might construct knowledge within their own minds.

Novak’s theory of education, human constructivism, becomes a valuable resource for chemistry teachers to guide students toward meaningful learning. Therefore, human constructivism and Ausubel’s meaningful learning are valuable as a framework for this research, which seeks to understand faculty goals for student learning in the chemistry laboratory. According to Novak’s theory, knowledge is a human construction, and as such, it is incumbent upon the educational system to support learners as they construct knowledge. Furthermore, “meaningful learning underlies the constructive integration of thinking, feeling, and acting, leading to human empowerment for commitment and responsibility.” It has been asserted that students must be provided with experiences in each of the three learning domains (cognitive, affective, and psychomotor). Thus, this framework provides a basis to understand the faculty intentions explored.
History of the Teaching Laboratory in Chemistry

John Maclean, Professor of chemistry at Princeton beginning in 1795, argued that “I am of opinion it is impossible for one to require even a slight knowledge of chemistry without either making experiments or seeing them performed, and that to become proficient in the science it will require much practice as well as extensive reading”.6

Nakhleh et al. claim that the laboratory has held a high place in science education due, in part, to advocates such as Maclean.6 Other contributors include the requirement by Harvard University that entering students have experience in the laboratory and intentions similar to Maclean’s, expressed by early chemistry textbooks. According to Nakhleh et al., laboratory instruction is currently regarded as “desirable, if not essential” by nearly the entire community.6 It is fortunate that periodic reviews of this literature have been done, making it easier to see where such lines of inquiry have led and are leading.

When Hofstein reviewed the history of the laboratory in 1982,7 he found the following points worthy of comment. Many research studies conducted prior to 1980 found no significant differences between learning in the laboratory and other modes of instruction, in terms of attitudes, scientific method, and critical thinking. He was not surprised that one area in which the laboratory showed an advantage was the development of manipulative skills. It is apparent to almost anyone who observes learning in such a setting that students often are required to function merely as technicians; they are required to use very little scientific ingenuity.7

Effectiveness of the Laboratory on Learning

The theory that frames the research herein proposes that active engagement of the learner in doing science (experiences in the psychomotor domain) is one of three requisites for meaningful learning. However, Spencer17 and Domin18 claim that a flaw exists with the approach most often taken toward teaching chemistry in the laboratory. Domin states that the laboratory as it currently exists “[is] an environment in which very little meaningful learning takes place.”18 Of course, most of the critics concede that laboratory instruction is beneficial and important to student learning,18 but they caution that care should be taken to structure this
experience in such a way that all three of the learning domains (cognitive, affective, and psychomotor) are employed.

The situation in which chemistry teachers find themselves can be explained in the following way. Suppose a young man attended a fairly large university, where many students had to be “gotten through” the general chemistry curriculum. His professors taught the laboratory portion of the course according to what could rightly be called a “high-throughput” method: lectures are large and impersonal; experiments are merely performed by following a strict procedure; data analysis consists of calculating answers to equations given in the lab manual; and no conclusions beyond those calculations are required. In fact, suppose his entire undergraduate laboratory experience consisted of these methods. This is not a very far-fetched idea. In fact, it is a common experience.\(^{19}\)

As stated previously, the National Research Council (NRC) strongly recommends teaching chemistry through inquiry.\(^{20}\) This is a call for teachers to expect their students to collect and analyze data relevant to the problem and to develop and use critical thinking skills when drawing conclusions.\(^{19,21}\) (Manuscripts included in Appendix 1 & 2) In light of this call by the NRC, it is apparent that the teacher in the example above is not being very scientific in the search for appropriate teaching methods. He uses only his own experiences as data and thus comes to a flawed conclusion. Of course, this teacher should not be judged too harshly. He is teaching the way he was taught, and he has no other learning experiences in chemistry upon which he can draw.\(^{17}\)

In an attempt to provide support to teachers in this situation, Yang\(^ {22}\) provides a thorough explanation of the process he goes through to develop a new laboratory activity. He takes the reader through this process, step-by-step, answering questions about logistics. Many of the topics discussed are often skipped over by faculty less-experienced with developing new laboratory experiments. Unfortunately, this plan is not fail-safe. Often, when implementing a new experiment or course, faculty and teaching assistants feel discouraged by the additional work load placed upon them, and they become frustrated.\(^ {23}\) Buckley reported that teachers found difficulty in achieving certain learning outcomes, including “the development of students’ ability to plan and design experiments”.\(^ {24}\) It is important that those who intend to implement such new activities into the laboratory curriculum understand the potential pitfalls that await them.
Otherwise, they may become so discouraged that they renounce their prior efforts as not worth the energy.

**Goals for Student Learning in the Laboratory**

Both Lunetta and Tamir\textsuperscript{25} and Fay, *et al.*\textsuperscript{19} came to similar conclusions about the typical student experience in the laboratory. According to Lunetta and Tamir,\textsuperscript{25} students

> “are commonly asked to make observations and measurements, record results, manipulate apparatus, and draw conclusions…Thus, in spite of the curricular reform of the past 20 years, students still commonly work as technicians.”\textsuperscript{25}

Furthermore, Garratt\textsuperscript{26} makes the following declaration:

> “I contend that in our teaching we over-emphasize laboratory work at the expense of planning and interpretation, and consequently we devise laboratory exercises that encourage a ‘stamp collecting’ approach to science.”\textsuperscript{26}

Therefore, it is imperative that any discussion of the laboratory curriculum address the goals that are meant to be achieved. One of the earliest comprehensive reviews of the aims of practical work came from Buckley.\textsuperscript{24} The aims set forth by him were:

1. “To encourage accurate observations and careful recording;
2. to promote simple, commonsense, scientific methods of thought;
3. to develop manipulative skills;
4. to give training in problem solving;
5. to fit the requirements of practical exams;
6. to elucidate theoretical work so as to aid comprehension;
7. to verify facts and principles already taught;
8. to be an integral part of the process of finding facts by investigating and arriving at principles;
9. to arouse and maintain interest in the subject; and
10. to make phenomena more real through actual experience.”

Some years later, Shulman and Tamir\textsuperscript{27} proposed a more concise set of goals for laboratory instruction:
1. “To arouse and maintain interest, attitude, satisfaction, open-mindedness, and curiosity in science;
2. to develop creative thinking and problem-solving ability;
3. to promote aspects of scientific thinking and the scientific method (e.g. formulating hypotheses and making assumptions);
4. to develop conceptual understanding and intellectual ability; and
5. to develop practical abilities (e.g. designing and executing investigations, observations, recording data, and analyzing and interpreting results).”

Others have consolidated or expounded upon this set of goals over the years. Summaries and revisions can be found in Hofstein,7 Pavelich and Abraham,28 and Johnstone and Al-Shuaili.29 In each case, it should be noted that each of these lists of goals center around all three of Novak’s learning domains. Students are expected to make connections to concepts discussed in other venues (cognitive), to acquire a certain skill set useful for scientific investigations (psychomotor), and to maintain interest in the subject of study (affective).

**Needed Areas of Research**

In a critical analysis of research on learning in the laboratory, Hofstein7 outlined the common weaknesses of research studies. Included in his summation is a discussion of the laboratory manual. He observed that “[T]he laboratory manual plays a major role for most teachers and students in defining goals and procedures for laboratory activities.”7 He adds a call to include an analysis of the laboratory manual in studies of the effects of teaching and learning in the laboratory. This call is also made by Tamir and Lunetta30 who advise that

“laboratory activities must be written to provide higher levels of initiative and conceptualization… in order to make better use of the potential of laboratory activities in the learning of science.”30

The research described herein is a first step toward characterizing the goals and expectations teachers have for learning in the laboratory. This work can then be extended to map out the social and educational context in which the teaching laboratory resides.

Where Hofstein leaves off, Nakhleh et al.6 pick up the call for research. They claim that “researchers have focused on understanding of chemical concepts as the most desired outcome of engaging in laboratory work.”6 One area that they claim might be the “key to all successful
“learning” is the attitudinal response students have toward science and self-confidence. The affective domain is one area in which little research has been conducted.\textsuperscript{6}

Nakhleh \textit{et al.}\textsuperscript{6} go on to describe the possible importance of distributed cognition in future research. Distributed cognition functions on the precept that worthwhile knowledge does reside solely within the learner’s mind. Instead, this framework “recognizes that knowledge can be \textit{distributed} over the environment and the individuals”.\textsuperscript{6} (emphasis mine) While Moore\textsuperscript{31} cautions that the distribution of such knowledge does not necessarily lead to the better functioning of the system (here, the educational system), there are multiple implications of this idea.

The primary implication for the research described herein is that investigators are required to consider the entire context of the learning environment investigated. According to Lincoln and Guba\textsuperscript{10} it can be assumed that a single construction (\textit{i.e.} conceptual understanding) exists for the phenomenon that occurs upon the addition of a particular acid to a particular base. However, when investigating social contexts

> “it seems better to assume the existence of multiple social realities as constructed by the several participants (not to mention yet another such reality constructed by the investigator him- or herself).”\textsuperscript{10}

Qualitative research methods are well-suited to characterizing such contexts, due to the rich data that are obtained from the participants.

Nakhleh \textit{et al.}\textsuperscript{6} call for research to investigate the students’ goals. They ask, \textit{are the goals of faculty and students in any kind of alignment}? They suggest that this alignment with faculty goals (or lack thereof) influences the students’ perceptions, and in return, this influences learning in the laboratory.\textsuperscript{6} Therein lies the need for this investigation into faculty goals for learning in the chemistry laboratory. Without a qualitative understanding of the entire context of learning in the laboratory, there can be little progress toward understanding the complexities of student learning. This investigation into faculty perspectives of learning in the laboratory will ultimately provide: (1) student perspectives on learning in the laboratory; and (2) the development of an instrument to quantify differences between student and faculty goals for the laboratory.
Chapter Three: Methodology

Sampling Protocol

A data collection matrix (Table 1) was constructed to organize the population of faculty members to be sampled, thus ensuring diversity of respondents for the project. Faculty participants were sampled from two sub-populations: chemistry departments labeled as Innovative or Status Quo (defined below). An innovator was defined in this research as a chemistry department that has received a National Science Foundation (NSF) grant from the Course, Curriculum, and Laboratory Improvement (CCLI) program. Using the NSF FastLane database, a search was conducted for all chemistry CCLI grant recipients since 1995. These faculty members were considered to be innovative because they sought to make changes in laboratory teaching techniques or curriculum design at their institutions. Both the innovative and status quo populations were organized by the same stratification system. Institutions were categorized by mission (Research 1, Comprehensive, Liberal Arts, and Community College), type (public or private), and size (student population). This ensured the full spectrum of institution types and laboratory courses was represented in the sample. Only institutions with American Chemical Society (ACS) approved four-year programs were included in the sampling. As community colleges are ineligible for such approval, membership in the Two Year College Chemistry Consortium (2YC3) was used as an alternative criterion. These stipulations ensured that all of the participants were members of departments whose undergraduate chemistry curriculum had the approval of its primary professional society.
Table 1. Sampling Matrix for Innovative and Status Quo Participants.

<table>
<thead>
<tr>
<th>Innovation</th>
<th>Comm. College</th>
<th>Lib. Arts College</th>
<th>Comp. University</th>
<th>PhD University</th>
</tr>
</thead>
<tbody>
<tr>
<td>Status Quo</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>General Chemistry</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Organic Chemistry</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Upper-Level Courses</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

The abstracts of the CCLI grants identified through the sampling protocol were carefully read to make purposeful selections for participation in the study from within the innovator population. Two tenured/tenure-track faculty members were selected to represent each type of institution and each laboratory course level (general chemistry, organic chemistry, or upper division courses), as depicted in Table 1. According to Patton,\textsuperscript{35} intentionally selecting “information-rich cases” for investigation is necessary for the success of purposeful sampling. “Information-rich cases are those from which one can learn a great deal about issues of central importance to the purpose of the research, thus the term purposeful sampling.”\textsuperscript{35} Given that the purpose of this research is to investigate the laboratory learning goals that chemistry faculty intend for undergraduates, it is more advantageous to focus on understanding the professional ideals of a small number of carefully selected faculty members who have demonstrated efforts to implement such goals rather than to collect data from a large, random sample of all chemistry faculty.

The status quo sample consisted of chemistry departments with ACS approved programs that were not included in the innovator population. These potential research subjects were considered to represent the “status quo” for undergraduate chemistry laboratory teaching because their departments had not received funding via the CCLI program to modify the laboratory
curriculum in more than ten years. Thus, they were expected to have courses closely structured to the national norms. Status quo institutions were chosen for each of the categories in Table 1, using a random number generator. Participants from land grant institutions and historically black colleges and universities (HBCU) were intentionally included in both the innovator and status quo samples.

**Human Subjects**

As per requirements of the Office for the Advancement of Research and Scholarship at Miami University, this research project was reviewed by the Institutional Review Board (IRB) and was approved. All researchers completed the ethics training necessary for involvement in this research. Selected subjects, both innovators and status quo, were contacted initially via email (Appendix 4 & 5). All participants were provided with an informed consent waiver (Appendix 6) that explained the purposes of the study and provided information regarding their rights as human subjects. Faculty members were requested to provide laboratory course syllabi, student manuals, and notes used by the instructor(s). The interview protocol (Appendix 7 & 8) was also available for participant perusal, upon request. Faculty members who did not respond were contacted again via email approximately three weeks after the initial request. Upon rejection, or failure to respond to the second email request, invitations were sent to newly-sampled faculty members as replacements. The same methods of sampling were used for these replacement departments as for the original innovator and status quo chemistry departments.

**Interview Protocol**

This project sought to explore intentions, or goals, of faculty members, and as such, there is no direct observational data available. Consequently, faculty members were interviewed in order to procure the necessary data. The interview is a powerful tool for qualitative research because it allows the researcher a glimpse into someone else’s mind. It is an especially valuable alternative to direct observational data when the target information is the intention of the subject.35
A semi-structured interview allowed the researchers to probe the individual faculty members’ goals, expectations, and their general beliefs about teaching college chemistry laboratory courses. Semi-structured interviews include “prompts for the interviewer to request elaboration of additional details and examples in response to the personal views offered by the interviewee.” In other words, questions are planned in advance and sufficiently open-ended to permit the interviewee the freedom to respond. Open-ended questions lend credibility to the responses obtained in the interview, as explained by Patton:

“The basic thrust of qualitative interviewing is to minimize the imposition of predetermined responses when gathering data. When using qualitative interviewing strategies for data collection, it is critical that questions be asked in a truly open-ended fashion. This means that the questions should permit respondents to respond in their own terms.”

Telephone interviews were conducted by either a chemistry faculty member or a graduate student. Permission to digitally record each interview was granted by each interviewee immediately prior to conducting the interview. Lines of inquiry were explored with innovators according to one interview protocol (Appendix 7) and with status quo participants according to a modified protocol (Appendix 8). Innovators were asked specifically about the modifications they planned for the curriculum, while status quo participants were asked to characterize the curriculum at the course-level with which they are most familiar, as well as any changes in the laboratory curriculum. For example, a department may be moving its physical chemistry curriculum toward a focus on spectroscopy and away from thermodynamics. This variation on the interview protocol offered the informant the opportunity to explain such changes, with minimal influence of the interviewer’s expectations for a change.

It should be noted that the chemistry professors interviewed in this study represented their respective departments when responding to some of the questions, and a portion of the information they provided was not unique to their own persons. Data concerning institutional (and departmental) demographics and laboratory staffing procedures were collected from the participants during the interviews. At the conclusion of each interview, the participants were reminded of the request for laboratory materials (syllabus, manuals, etc.) detailed in the informed consent waiver. Finally, the participants were asked for permission to be contacted again, should the need arise, and were offered the chance to receive reports generated through this project.
Interview Analysis

After each interview was completed, the digital record was downloaded to a password-protected computer for transcription and analysis, and a copy of this record was stored on a CD-RW as a back-up. Interviews were transcribed using Dragon Naturally Speaking and analyzed with the assistance of the NVivo qualitative data coding software. The data were analyzed to find themes or patterns in the faculty perspectives. This is called cross-case analysis, because responses from different informants to common questions from the interview guide are grouped together. This method of analysis follows an inductive path, because the themes and patterns examined later in this document emerge out of the data rather than being imposed on them prior to data collection. This idea comes from the work of Glaser and Strauss, who developed “grounded theory.” The heart of this theory of evaluation within qualitative research states that findings are grounded in specific contexts; theories that result from the findings will be grounded in real-world patterns.
Chapter Four: Research Findings

The purpose of this research was to understand the perspectives of college chemistry laboratory professors in regard to student learning. The research questions shaping this study were:

What are the important learning outcomes that faculty intend for students in the undergraduate chemistry laboratory?
   a. What are important concepts and/or techniques for students to learn?
   b. What is most useful for students’ future careers?

The answers to these research questions are discussed in the next two chapters.

Interviews: Course Goals

Semi-structured interviews were conducted with eighteen college chemistry faculty members with some degree of responsibility for the structure of the curriculum within various undergraduate chemistry laboratory courses. Nine of these faculty members were classified as innovators, while the other nine work at institutions that were considered to be maintaining the status quo (due to the absence of any NSF funding for laboratory reform). The institutions and courses in which these faculty members work were classified according to the stratification system discussed previously (see Table 1, Chapter 3).

This qualitative study was designed in order to inform future quantitative research. The sample discussed here consists of eighteen faculty members, and the project collaborators have a similar sample size. Therefore, there is no intention of making generalizations across the population of chemistry faculty members. These qualitative findings will be used to generate a survey and to subsequently develop a quantitative profile of faculty goals using a large, random sample.

During the interviews, faculty members were asked to describe their institution. Next, they were asked to provide demographic information about the chemistry department, particularly regarding the student population and course enrollment at various levels (general
chemistry, organic chemistry, etc.). Innovators were then asked to discuss recent changes in the chemistry laboratory curriculum brought about by the funding received from their NSF grant(s).

When the professors had finished describing the course of interest, they were asked to discuss the goals that they had in mind when designing or modifying the laboratory experiments included in the course. Descriptions of goals or intentions articulated by the professors comprise the majority of this chapter. In keeping with human subjects research protocols, all names below are pseudonyms. Each quote is annotated with information labeling the participant by sample (innovator or status quo), institution type (e.g. liberal arts), and the course level discussed (e.g. general chemistry). Chapter 5 presents analysis and interpretation of these findings in light of the theoretical framework grounding this research.

**General Chemistry – Faculty Innovators**

Six professors in the innovator sample and three professors in the status quo sample discussed the introductory, or freshman-level, chemistry course at their institution. Clare was an innovator who teaches and does research in chemistry education at a research I university. As an innovator, she discussed a project funded by NSF to involve research experiences in undergraduate laboratory courses. The following account describes the goals she considered when changing the design of the general chemistry lab curriculum:

“Well the main goal is to expose students to a research experience, and do it as part of their courses. So, in other words, not requiring them to go outside of their normal course work to try and work with somebody in the lab. So exposing them to the research experience, um...in terms of what that will result in, or outcomes, what I'm hoping is that: number one we would have increased retention within the science majors, so have students stay in the sciences. If we could get somebody to switch over to chemistry, that would be icing on the cake. That's not necessarily a primary goal, as long as we can retain people in the sciences. Number two: increase people's interest in science, and doing science research. So one of the things that we're looking at is to see what fraction of the students go through [our program], and then go on and do some other kind of research experience, compared to those who don't have a [our program] experience. And through the research experience we are having them involved in, we'd like to see if we can get students involved in more of the scientific process skills. So the actually thinking about how you design a scientific experiment, um, carrying out an experiment and having the opportunity to revise it, change it, you know, basically make mistakes, and learning how to really
make claims from data. So be able to look at data that is collected and determine what is a valid claim and what is not, which is pedagogically a really different exercise than ‘did I get the right answer, when I collected this data’.” (Clare, research I, innovator, general chemistry)

Clare highlighted the opportunity to engage in scientific thinking as the primary goal. She called it a “research experience” in the beginning, but by the end of this excerpt she explained the idea more thoroughly. Clare wanted her students to be engaged in the entire scientific process, from planning the experiments to drawing conclusions. Furthermore, she expressed two related goals: 1) to keep students studying science and 2) to catch and hold the students’ interest.

Angela was a community college professor responsible for the general chemistry lab course. During her interview, she expressed the same goal as Clare, namely, to include research experiences in the curriculum of the general chemistry lab course. She explained her reasons for this goal:

“One of our – one of our goals – is what we had in, uh, in [our] program, and that’s to give students experiences more like what chemists really do – or what scientists do. So, you know, give them sort of a flavor for, um, what it means to do science. ‘Cause we don’t really do that real well; I mean they don’t – most of our labs have more laid out procedures, and they’re not really asking questions themselves, and there’s not much of their own design in the experiment. So, it’s, it’s very much more – I mean they don’t have data pages; we don’t do that. It’s not a canned sort of lab from that perspective. And there is – in like the one – in the antacid lab for instance, they’re analyzing a product; they tend to like that one a lot, because they’re analyzing something that they utilize. But most of them are pretty well spelled out, in terms of a procedure; and they certainly don’t have the freedom to ask their own questions; at least in the general chemistry they don’t. And so, we want to have more, more um, labs that simulate more authentic research type experiences, where they’ll be more involved in asking the question or designing the procedure to answer the questions. But we haven’t fully implemented – I mean this is still very much in the early stages. […] we’re going to be developing experiments, and we have this idea in mind that they’re more project based, and application type – you know, real-life application sort of project based where the students are involved in, if not designing the experiments because obviously they won’t know how to use the NMR, but certainly in interpreting the results, where there’s not necessarily a canned answer that we’re expecting them to get.” (Angela, community college, innovator, general chemistry)
Angela indicated that giving students the opportunity to act as researchers in the laboratory is a goal for general chemistry. She explained that experiments planned for the future would be projects that have “real life applications.”

Andrew was a teacher at a liberal arts college. He expressed his primary goal to be student conceptual understanding:

“The overriding goal for most of [the experiments] is a conceptual understanding. Because many of them are inquiry-based, discovery based, or explicitly then applying things that they have, that were done in class or from prior labs, or tying together strings that were particularly from the introductory course... the – probably the major goal is then conceptual understanding of what is going on. And then again, this is broken down into the macroscopic, microscopic, and molecular nano scale, and symbolic representations... integrate those representations... since this course is preparatory for the future courses, there is a secondary goal of learning techniques, learning how to use equipment of various sorts. A sort of introduction to the different types of tools available to chemists. Some of them are manipulative: diode array spectrometers, we use NMR and IR, we also use GC. And we also do things where you make up an experiment and try it out... And then within that there is some sense of experimental design; so in terms of a more practical or applied aspects, there are techniques, there are instruments, there are elements of experimental design.” (Andrew, liberal arts, innovator, general chemistry)

It is important to notice that in addition to conceptual understanding, Andrew also expressed the goals of learning laboratory techniques and experimental design as important in general chemistry.

Jacob was a comprehensive university professor and recently joined a consortium of colleges working to improve the undergraduate laboratory experience. He stated his goals for the general chemistry lab clearly and concisely, emphasizing the reinforcement of topics covered in lecture and the opportunity to physically work with those concepts. Unfortunately, due to a faulty connection with the recorder, this interview could not be transcribed with the same degree of fidelity as the others. The following is not a direct quote, but the interviewer’s best approximation of what was said during the interview:

The first goal is the reinforcement of topics covered in lecture. Secondly, the students need to put their hands on something to see science happen, because they’re doing it (causing it to happen) and talked about it in lecture. They are cultivating many corporate contacts for internship opportunities. What level of kid do you want:
quant, organic, or general chemistry? This is very selfish, but folks in organic don’t want it to be the first time a student sees something. This is a creature comfort. They want students to be comfortable at the bench before so they don’t get hurt. (Jacob, comprehensive, innovator, general chemistry)

John was an innovator teaching at a research I university. He expressed a strong effort to connect chemistry to other disciplines, using the laboratory as the medium for that connection:

“I try hard to make a combination of things happen, so that it bounces back and forth between Physics, Chemistry, and Biology.” (John, research I, innovator, general chemistry)

He also mentioned the importance of safety in the laboratory:

“Well, well, first of all it needs to be safe, right? The next thing is it needs – it needs to have a true hands-on experience which is not cookbook, but is rather an - involves inquiry and is more open-ended as to what it does. But it also has to have structure to it, uh enough structure that the student is not just lost. And it needs supervision which is surely what we have… We like labs to have aspects which are very clearly defined as to what to do, and other aspects which are open-ended and are unclear as to what the outcomes will be.” (John, research I, innovator, general chemistry)

John also described the laboratory as a place for students to experience chemistry “hands-on.” However, he stressed that the experiments performed by the students should include elements of inquiry, which for him meant that the outcome of the experiment was “unclear” to the student.

The final innovator who talked about the general chemistry laboratory was Carl. He was also a teacher and researcher at a research I university. Carl had been collaborating with several faculty members from different departments to produce new experiments for the general chemistry lab using problem-based learning (embedding concepts into “real-life” situations):

“We had some interest in getting labs that would hit different kinds of general chemistry content. So, I’m trying to think – there were a couple of cases where there were ideas that came up that were associated with spectrophotometry that we set aside, because we already had a couple of spectrophotometry groups. So that was the only – there was an idea of covering multiple parts of the general – traditional general chemistry lab content. That was the only – I think it is fair to say that was the only constraint that we had as chemists. We wanted it to be part of the content, but we also didn’t want too many on a particular part of the content. So as a result,
there were things that—scenarios that we didn’t use, but there were also—there are
parts of the content in which it was difficult to find a particular application, at least
among the faculty that we were working with… One of the things we knew we were
going to look like we were doing, but we weren’t trying to do, was to be vocational.
Um, we’re trying to use these scenarios, the contexts, as a way of embedding
learning within another context that exists in the real world— if you don’t mind the
phrase. And we were not looking to say, ’Ok somebody is going to come out of our
course and be ready to do medical laboratory science based on this particular test for
albumin’. Although, in fact, the student who did that lab, would be pretty well-
prepared for that kind of job. So we weren’t looking to prepare anybody for a
particular kind of job; we just wanted job-related scenarios to be part of what they
were learning.” (Carl, research I, innovator, general chemistry)

Carl made a point of clarifying the intent of his program. He stressed that his goal was not to
train students for certain, explicit career paths, but to prepare them for future experiences in the
“real world” and to explore a wide range of content.

These general chemistry laboratory innovators shared some goals in common. Andrew
and John expected students to learn techniques and have the experience of working with their
hands. Clare and Angela went further, expecting those experiences to mimic the role of a
researcher. Making connections while in the laboratory was also a common goal. Angela and
Carl wanted the students to connect the laboratory with ideas and experiences in the students’
lives, while John expressed interest in connecting the laboratory to other fields in the sciences.
Finally, Clare stated that she intended to increase the students’ interest in science.

**General Chemistry – Status Quo**

The previous section explored the goals that innovative chemistry faculty members had
for general chemistry laboratory courses. This section, in turn, explores the general chemistry
goals of the professors in the status quo sample. To begin, Sarah was the department chair at a
liberal arts college. She had been leading her colleagues through a curriculum review, prompted
by their regional accreditation body. She indicated that the faculty had recently reviewed the
goals for all levels of chemistry lab courses. In this context, she articulated the following goals:

“Um, I personally am pushing my, an agenda here, where at the very least, we
should have practicums for, uh, the students in the laboratory setting – where we’re
not just testing them by, on paper; we actually have them to go through, um, a mini experiment to see if they have learned specific techniques. Um, the students will have – in other words we would want them, for example, in general chemistry basically to know how to use an analytical balance, how to do a titration, how to use the spectrophotometer, things like that. Certain techniques we would want, and expect, them to know how to do by the end of that sequence, first year sequence.”  
(Sarah, liberal arts, status quo, general chemistry)

Sarah stated that she wanted students to take practical exams so that their ability to perform techniques and use laboratory equipment could be tested.

Ryan taught at a much larger, comprehensive university, and he expressed a similar goal of having students learn techniques to illustrate concepts. He went on to emphasize that the underlying reason for this was to prepare students for future courses, such as organic chemistry:

“Well, the number one goal is to illustrate the concepts, the chemistry. Um and you know chemistry is an experimental science... Now, I’m aware that there are multiple options as far as lab simulations go, as far as you want to go in wet-work and micro-scale, and such. And so those would serve quite adequately to help out with the concepts, but then you got this second reason, which is yeah an awful lot of students, they’re either chemistry majors – so they need to be trained up for their organic labs, analytical labs, and so on – or they’re biology majors, slash pre-med, slash prepharmacy students and so on – who again will go on, first of all, into organic labs. And the idea of walking into an organic chemistry lab with no lab background at all is ridiculous. But secondly, so many of these people are going to go into some form of lab work as a career. And so, while we could get away with not having them in the labs with all the other safety- and waste-related problems, as far as fulfilling the conceptual part of the course, the practicality of it and what many of our kids are going to end up doing means that they gotta have some kind of lab training – real hands on lab training. And I think, I think you do – you appreciate things more anyway when you do it, rather than just watch it on a computer.”  
(Ryan, comprehensive, status quo, general chemistry)

Ryan strongly asserted that the act of physically working in the laboratory to “illustrate concepts” was a goal of the laboratory learning experience.

Joan taught at a community college that is spread across several campuses. Each campus has a chemistry department that is considered to be autonomous, but there was some sharing back and forth between faculty members concerning the curriculum. Joan was another professor who also stated the desire to make connections between the laboratory and lecture courses:
“Well, mostly I want it to be supportive of what we’re doing in the lecture. So when we’re working problems in the lecture, then they have done something similar in the laboratory, but of course messier. It makes it – and I mean messier in that the numbers are not just there for them. They’ve got to sift through all the information to pull out what’s needed, instead of having a neat little two or three sentences, like a problem is at the end of the chapter. Now, I have to say – and probably down deep I know – the majority of them never see the connection. But my goal is that, by what they do in the laboratory, they see how people get this sort of information in order to use and to learn something from it. I often think, when they come in to us they can do well in a math class… and then they come in to our chemistry and it’s like they have no math skills, because the two things to them are independent. They must store it separately. And I think they also walk into our labs and don’t see the connection either very well, from our lecture into our laboratory. And that’s what I wish we could do better.” (Joan, community college, status quo, general chemistry)

Joan made some skeptical comments about how infrequently the students saw connections between lecture and lab and between chemistry and math. However, she pointed out that it was her intention for them to make these kinds of connections.

Sarah and Ryan articulated that working in the laboratory setting, learning certain techniques, and using laboratory equipment were the important goals that they considered when planning a general chemistry course. However, Joan claimed that the primary goal in general chemistry was to take those experiences of working in the laboratory and connect them to the concepts taught in the lecture portion of the course.

The innovators and status quo participants who were interviewed regarding the general chemistry laboratory shared a common interest in expecting students to learn to perform certain techniques. Joan (status quo), John (innovator) and Carl (innovator) focused on learning concepts. Several of the innovators (none of the status quo participants) expressed goals of incorporating real world experiences of the students into the learning experience. Such were the learning goals that these chemistry faculty members considered important for the students in the general chemistry laboratory.

*Organic Chemistry – Faculty Innovators*

Four professors were interviewed regarding the organic chemistry curriculum. One was an innovator, and three others were classified as status quo. Chris was an organic chemist
teaching at a liberal arts college and was classified as an innovator. He expressed the intention of making the chemistry lab course interesting for his students:

“So, I guess my thinking at that point was to do something interesting – that’s why I chose the chemiluminescence. I think it has a natural um – there’s a natural interest in that. If you make this, synthesize this stuff in the lab and then we actually go into a little dark room where, you know, there’s no windows and, you know, the ultimate test is that we mix the things together – uh it either glows or it doesn’t glow. Um, that um, there would be that element of interest in it. But probably the most importantly, there’s a – third week was meant to sort of build on some of the skills they learned in the two previous weeks. So, I guess overall goals would be to um, to uh teach appropriate techniques, um also to in general learn how – or to have the students learn something about how the whole process of a synthesis works. I mean, that’s really what that module’s supposed to be about. Essentially, chemists do two things: they either make stuff, or they analyze it. And, so the synthesis module has the goal of helping people to see, ‘What are the factors that would be important in thinking about making something?’ And of course, it’s not just a matter of ‘have you made it or haven’t you made it’, but ‘how do you get it to be pure, how do you, you know, get it away from side-products, etc.’ Um, so I think that’s sort of the overall picture of what we’re trying to uh do. It has the secondary goals of learning something about the chemical literature, um how to – you know, beginning writing scientifically appropriate reports, admittedly somewhat artificial at this point because they’re all doing um for the most part the same thing… this is their first lab experience and so we want to just introduce them to these lab techniques and what it’s like to work in a lab. Of course, we cover safety issues. That’s a part of the first um, first day’s lecture: how do you work safely in the lab. I guess that covers the main things that we’re thinking about.” (Chris, liberal arts, innovator, organic chemistry)

In addition to making the laboratory interesting for the students, Chris focused on a skills-based approach, holding laboratory techniques and science reasoning skills as “overall goals.” He claimed to have “secondary” goals for communicating scientifically and making the laboratory a safe environment.

Organic Chemistry – Status Quo

David was also an organic chemistry teacher at a liberal arts college, but he was classified as a status quo participant. He began the discussion of second semester goals by recognizing that students were expected to have learned many techniques during the previous semester of organic
chemistry. He went on to describe these techniques in detail, including references to the operation of several instruments. David ended this discussion by explaining that he expected students to develop some degree of autonomy in the lab during the second semester of organic chemistry:

“So in organic chemistry, my colleague [name omitted] is in charge of the first semester, I’m in charge of the second semester. In the first semester, um [...] is a very heavy sort of techniques semester. Uh, um that is that [he] has constructed a series of preparations and other kind of activities, but we want to make sure they’re exposed to distillation, recrystallization, GC Mass Spec, NMR, chromatography, um so I think that would give you a good idea about how we just don’t have chromatography and how boring that is. I mean he tries to roll that into a real experiment, but, but you know, when he’s doing his lab lectures, it’s all about the technique. Then in the second semester, what I try to do is to give sort of more, you know, kind of multi-week preparations of things where they have to make something, but they have to get a good-enough yield because then they gotta use that in the next step to try to give them the feeling of what it would be like to be in, let’s say a synthetic lab. Um, and I kind of assume that they’ll bring the techniques from the first semester into the second semester. Uh, I’m therefore not particularly descriptive when I tell them ‘you’re gonna go do this’. I don’t say ‘take a 100 mL flask and do this’. I mean, they have to start to make choices as to what it would mean to actually try to do this on a one mill mole scale. Um, and that would be an example of where we’re trying to step these students up to where if they had a journal article and they were finally trying to follow a journal article, that would not be all that direct of could they take educated guesses as to what these kinds of experiments meant, and you know, could they follow experimental and those kinds of things. So, I would say our goal at the end of the first semester of organic lab is just precisely that; you know, could they just be given some sort of experimental description and really kind of understand what that meant and translate it into, in regards to going in the lab and trying it out, or doing it.” (David, liberal arts, status quo, organic chemistry)

David claimed that the first semester of organic chemistry was primarily focused on learning techniques and understanding the procedures used. Then, in the second semester, the students started making decisions regarding the procedures and relied on the techniques from the previous semester.

Jessica was a professor at a comprehensive university, and she also stated that students should have learned techniques during the first semester at her institution. On the other hand, she emphasized the connection of laboratory experiment topics to the concepts taught in the lecture course:
“Right, well it’s, it’s really um – it’s different in different courses. For example, in organic chemistry the first semester is really about introducing them to a lot of techniques. So it doesn’t have as much um, uh as much direct application of the lecture material in that course, but it does have the concepts that they need for organic chemistry applied. And we focus a lot there on um on, on trying to see where these techniques might be used later on. Then, when they get to the second semester, it’s much more tied to the lecture; they do a lot more of the same uh reactions that they’re seeing in the lecture. So we tie a little bit more theory in from the lecture in to that semester, but we also talk about um the different variables that are in the lab. And so we want them to, to not only have the skills that we teach them in the first semester, but then we want to apply those skills um, just as a matter of routine um to one particular reaction. And they need to know what are the important variables in that reaction and, for example just what temperature would you run the reaction, what are the safety precautions – so we definitely emphasize that they have to consider all the safety precautions. […] Um, so we develop kind of skill set first, then we go to uh the actually analysis of um of how to run an experiment that’s directly applied from a reaction they learned in lecture.” (Jessica, comprehensive, status quo, organic chemistry)

Jessica provided specific details about the concepts that students needed to connect between the lab and the lecture. She also placed emphasis on learning how to run experiments.

Similarly, Alex articulated that his primary intention was to incorporate techniques learned in the laboratory with the theory learned in the lecture. He further emphasized a personal opinion regarding virtual laboratory activities. He asserted that being physically present in the lab and interacting with the materials and ideas was necessary in order to teach “instinct at the bench.”

“Well, mastery – we were talking about the laboratory curriculum, and so the question I guess can be focused on that for the time being, what an A is in the laboratory? And, the A goes to exceptional mastery of technique and theory. That a student is able to analyze, to execute properly, and to understand what happens, and furthermore, to understand what did not happen. So mastery is very comprehensive. It speaks to, not only intellectual understanding, but also hand-eye coordination and manipulative skills that come only from experience. You cannot teach a virtual laboratory; you cannot teach instinct at the bench by watching movies. So, if a student suddenly is getting a discoloration in the product, when the product is supposed to be a white solid and it’s coming out to be green slime. Can the student then figure out what may have gone wrong? If I were to repeat this, could I get the correct result? Do I know what – do I even know how to ask the right questions, what possibly went wrong? Well, that’s mastery.” (Alex, community college, status quo, organic chemistry)
Alex indicated that a connection existed between active participation in the laboratory and the ability of a student to “figure out” problems that arose. He called this ability “mastery” of the subject.

David, Jessica, and Alex articulated goals pertaining to techniques in the laboratory. They all expected students to learn appropriate techniques, but only David expressed the intent for the students to be able to plan aspects of the experimental procedures by the second semester of organic chemistry. Jessica and Alex, on the other hand, focused on making connections to the concepts and theory taught in the lecture.

These chemistry faculty members indicated that the most important goal for students in the organic chemistry laboratory was to learn techniques. All of these professors described the need for students to think about their actions in the laboratory. Chris (innovator) and David (status quo) thought that students should think critically and understand what happened in the activities they performed, while Jessica and Alex (both status quo) stated that students should connect the activities to the lecture topics. Only Chris (innovator) expressed the goal that laboratory activities should maintain the students’ interest.

_Upper-level Chemistry – Faculty Innovators_  

Finally, two innovative and three status quo participants discussed primarily upper-level courses during their interviews. Jason was an innovator who teaches a spectroscopy course at a liberal arts college. His intentions for this course were that the students have a chance to work together and study together. He also mentioned that the students are told, for one experiment, that they must develop a procedure on their own. That is, they were required to use their prior experience to come up with an experiment that was not just a protocol from the literature:

“[T]o get them together and working together, because this is - from this point on they will be together for all of their courses […] But in general we want them to be working together and getting to know each other – study together, and this is the first lab that really gets them doing that.” (Jason, liberal arts, innovator, upper level chemistry)
“I tell them, in fact, don't go looking for a literature prep or a literature example of [Nucleophilic aromatic substitution]; I want you to do this on your own and I want to know what works for you. You know this is all you.” (Jason, liberal arts, innovator, upper level chemistry)

“I go in every morning that I have lecture - the class has two lectures a week in addition to the lab - I go in and tell them that it's their favorite class [...] 'This is your favorite class' - and then by the end of the semester, they know that I think that they should think that it's their favorite class. And most of them end up thinking that way.” (Jason, liberal arts, innovator, upper level chemistry)

Jason proudly claimed that the students considered this course to be their favorite. He believed this to be a result of his attitude and comments that the course should be their favorite.

Neil was a physical chemistry teacher and researcher at a large university. He claimed that the most fundamental goal for the laboratory was to teach concepts born from current research and to connect them to the lecture course and the “everyday lives” of the students:

“So, one of the goals – one of them was to bring current research – is to teach the fundamentals of physical chemistry, make sure the students understand that, and complement what they get in the lecture classes. Um, that’s the most fundamental – the most important. At the same time, doing that in terms of some of the experiments that have relevance to current things that the students know about in other chemistry – and outside of chemistry – topics, such as relationships to biology, medicine, things that they see in their current everyday lives. So to bring some relevance to – current relevance to - the experiments in addition to covering the fundamentals. And the course also has a – and also the way I teach the class, since it has a fair amount of instrumentation involved, so the students feel comfortable using the instrumentation and don’t have sort of a fear of it, and treat it as a black box. And so the course has some component of it in which the students learn about the instrumentation – although that’s not the focus because it’s not an analytical chemistry course. So and then the fourth goal that’s tied with this writing intensive – to give the students experience doing scientific writing, and being able to convey their results in a written format – in a logical and coherent and concise manner. So they learn scientific writing. (significant pause) Though, I think the main focus of it is to get them to appreciate and understand – in addition to those things, in with all of them – is to get the to appreciate and understand physical chemistry and its broad relevance to other areas of chemistry and other disciplines. And that’s one of the things that the feedback always conveys from the students, that they do have – gain that appreciation.” (Neil, research I, innovator, upper level chemistry)
Neil went on to delineate several other goals which included learning about instrumentation and how to write scientifically. At the end of this discussion, he paused for a significant amount of time, and then he added another goal as the “main focus” of the course. He stated his intent to have the students appreciate and understand the relevance of physical chemistry “to other areas of chemistry and other disciplines”.

Jason and Neil have very few goals in common, because Jason spoke about a spectroscopy course and Neil discussed a physical chemistry course. However, they both stated goals for student learning that involved understanding the concepts taught in the laboratory course. Jason indicated that students were expected to plan their own experimental procedures from topics discussed in the course, and Neil wanted students to connect ideas to the lecture course and other areas of science. Additionally, Jason articulated a goal for students to be interested in the course.

*Upper-level Chemistry – Status Quo*

Kelly was a status quo participant who taught physical chemistry at a liberal arts college. She articulated the goal to have students do error analysis, specifically propagation of error, in order to justify their results. She focused on learning the technique of performing these calculations:

“We have the goal that they should be able to do error analysis to justify the results, the measurement is right in terms of accuracy and precision. Also they can do, I mean, error propagation for initial measurements, which has of course uncertainty. Results can – I mean by doing – I mean error propagation can justify how good, I mean how much a – how much uncertainty for your final results. For example, I mean determine heat of combustion for naphthalene; that is the classic thermochemistry experiment. Okay? For measurement attempts using that thermometer which has uncertainty – finally they can I mean find out what is uncertainty for heat of combustion so they can calculate form this data. This is a technique they have to learn. So p-chem is quantitative; it’s very reliant on this technique, uh this capability. This is another goal – I mean of course writing, that is how to convey the result to uh the faculty member – I mean how to, how to – that is how they do it by writing a report. In a report they have to be able to do analysis: data analysis, error analysis. Also, they have to know how to do kind of uh justify what’s wrong with that uh data, I mean. Why? They have to answer that kind of question.” (Kelly, liberal arts, status quo, upper level chemistry)
In addition to focusing on error analysis, Kelly also expressed her intent to teach students to write about their experiment and report on their data.

Matthew was a faculty member at a research institution who taught physical chemistry. He identified three levels of goals: broad goals of education, hopes for the course he taught, and a third which he didn’t discuss. He explained the main goal for his course as a hope that it “emulated real life:”

“Yes, well I think one can identify goals on three levels. I could wax poetic about the broad goals of education, and liberal education in particular, that would be not particularly characteristic of any single course. And let me skip over that if I can. […] My hope for the course is that – and I think I’ve gotten more clear on this over the years – that it emulate life in the real world. Now, it certainly does that better than the lecture course. Nobody is ever going to get paid to sit down and take multiple choice tests. Whereas what they do in this lab course is pretty much what they might do in the real world, certainly related to what they will do as a graduate student, if they do grad student research, somewhat related to what they would do in a technical job. And this means not so much the manipulation of a little glassware, but the point of – they will need to do some library research in some way or other. They will need to make written reports one way or another. They will need to have oral reports, one way or another – both in informal one-on-one interviews and in presentation with – well it used to be transparencies; it’s becoming power points. They will need to figure out in many cases how some instruments work. So those things – they will need to, you know, face some difficulties. They’ll need to figure out what’s going on. So, those things I think are useful partly just so that they’re familiar when the students do go on, and partly because in the course of doing those things they are learning things about themselves and about the world that don’t show up in lecture courses very much. It always seems a little strange to me that the lab course, which ought to be physical manipulation, is also the place where we teach writing. In fact, we teach everything that doesn’t have a home somewhere else. It all gets thrown into the objectives of the lab course; and that’s somewhat true of all the lab courses, but I think it’s particularly true of this one. So, my hope is that it emulate real life. The major reason it doesn’t emulate at least what they would do as a grad student or even an undergraduate researcher is that we put a lot of effort into seeing that they don’t get, and remain, frustrated very long. I mean we try very hard to see that things will work for them. […] On the other hand, we do try to give them the feeling that they’re figuring out things on their own, and that it’s not a cookbook where they come in and they have complete instructions and you just “do this”. Now, in the end, they come close to that, but we try to – you know we try to say, “well you’re gonna have to go to the library and look this up, and then come back and do it”; or “we’d like you to read these instructions and try to figure out how to use the instrument”. In the end, if they keep asking questions, we’ll give them more
and more help. But that’s not a bad lesson about the real world.” (Matthew, research I, status quo, upper level chemistry)

Matthew expressed his objectives for this course as the ones that don’t “have a home anywhere else.” He later clarified his purpose for making this comment by saying that students should learn things about the world that don’t show up in the lecture course. While he strongly emphasized his goal that the laboratory experience should relate to the real world, he listed several tasks that this goal was incumbent upon. One involved communicating scientifically by completing oral reports, written reports, and library/literature research. Another task was working with instruments, to the extent that students were able to “figure out” how to use them. Finally, Matthew expressed his concern that the laboratory fails to model the real world, because the students were not permitted to be frustrated for a long time. He indicated that in the real world of science, the researcher may remain frustrated over failed experiments for long periods of time.

Sean taught physical chemistry at a comprehensive university, and he expressed an intention to coordinate the laboratory with the lecture. However, the majority of the discussion of his goals revolved around the use of computational software. This made it clear that it was his primary goal for the physical chemistry students:

“I guess that’s a lot different from – yeah, large universities usually do it now. But yeah, I try to coordinate the lecture and the lab very much so. Since I start out teaching quantum, we start out doing some experiments dealing with, you know, dealing with quantum things. One of the other kind of things I really try to stress in that course is I try to get the students exposed to using computational software. So things like Hyperchem. And um, that’s sort of a challenge because you’ve got these students coming in who really don’t know much of anything about quantum and you know what’s going on behind the scenes when you do like a Hyperchem calculation, or some type of semi-empirical calculation. You know it’s pretty complicated, sophisticated stuff. So um you know probably about two months into the semester I will have them up to that point where they understand, you know, the idea of describing molecular orbitals as a linear combination of atomic orbitals, and can go into that software and actually do something, and at least conceptually know what’s going on.” (Sean, comprehensive, status quo, upper level chemistry)
By the end of this discussion, Sean articulated an underlying goal for working with the computational software. That is, he intended for his students to conceptually understand what they were actually doing in the experiments.

These physical chemistry laboratory professors expressed the goal for students to use equipment and to learn techniques, although Matthew considered that to be minor, stating that the laboratory was supposed to be more than simply manipulating glassware. Sean claimed that understanding concepts was important, while Kelly emphasized communicating to the scientific community. Finally, Matthew stated that the most important goal for the laboratory was to model experiences that the students would have in the real world.

**Summary of Goals**

Most of the participants, innovator and status quo alike, expressed an interest in making conceptual connections to the lecture course associated with the lab course they discussed. Several of them also indicated that they intended the students to make connections to other courses, disciplines, and even to the “real world.” The terms “conceptual understanding”, “cookbook” labs, “inquiry”, and “real world” came up as goals in many interviews without any prompting from the interviewer. These words, along with several other recurring phrases, were used as common links between the interviews in order to analyze and extrapolate meaning from the data. That analysis is included in the next chapter.
Chapter Five: Analysis and Interpretation of Faculty Goals

The question guiding this research probed college chemistry faculty members’ intentions for student learning in the undergraduate laboratory. While this researcher expected to investigate the professors’ intentions for the undergraduate curriculum as a whole, the rich data presented in the previous chapter suggested that redirecting the investigation toward the professors’ specific course goals would be an important first step toward the investigation of curriculum outcomes. This change in direction demonstrates a beneficial attribute of qualitative research and grounded theory. The researcher is permitted to follow the data where it leads, rather than imposing a hypothesis upon the data.

The theoretical framework that guides this inquiry asserts that, in order for meaningful learning to take place, the student must experience the integration of their own thinking, doing, and feeling. In the language of cognitive psychology, these three sets of experiences are called learning domains; they represent the cognitive, psychomotor, and affective domains, respectively. *NVivo* qualitative analysis software was used to code, organize, and analyze the interview data. Participant comments were coded according to their own words (each instance is called a “node”) in the first iteration of the analysis. Next, the nodes were analyzed and grouped according to their alignment with the cognitive, affective, and psychomotor learning domains. Finally, each node was explored to find differences among the underlying intentions of the faculty.

When the interviews were coded across these learning domains, frequency counts were tabulated for participant statements of goals in each domain. Such analysis was done in order to determine the distribution of goals from both the status quo and innovative groups across the learning domains. Charts depicting this analysis of the data are presented in Figures 1 and 2, and Tables 2 and 3. Table 2 shows that, among the innovators, Jason did not express any cognitive goals and Carl did not express any psychomotor goals. Among the status quo participants, Kelly and Sean omitted affective goals, and Joan omitted psychomotor goals. This observation led to a comparison of the goals articulated by each participant across the learning domains. Figures 1 and 2 were constructed with the expectation that a trend would emerge among either the
innovators or the status quo participants. It was observed from Figure 1 that a few of the innovators expressed goals evenly across the domains. Figure 2 shows that fewer status quo professors expressed goals evenly.

Furthermore, by comparing Figure 1 to Figure 2, innovators were observed to articulate goals in the affective domain more frequently than status quo participants. Analysis of such frequencies suggested additional lines of inquiry to investigate qualitatively through the rich interview data.

Table 2. Innovator Interview Analysis by Learning Domain.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Identifier for Figure Below</th>
<th>Institution Type</th>
<th>Course Level</th>
<th>Cognitive</th>
<th>Psychomotor</th>
<th>Affective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clare</td>
<td>P1</td>
<td>Research 1</td>
<td>Gen Chem</td>
<td>5</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Andrew</td>
<td>P2</td>
<td>Lib Arts</td>
<td>Gen Chem</td>
<td>4</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Angela</td>
<td>P3</td>
<td>Comm Coll</td>
<td>Gen Chem</td>
<td>3</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Jason</td>
<td>P4</td>
<td>Lib Arts</td>
<td>All levels</td>
<td>1</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Jacob</td>
<td>P5</td>
<td>Comprehen.</td>
<td>Gen Chem</td>
<td>3</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>John</td>
<td>P6</td>
<td>Research 1</td>
<td>General/upper</td>
<td>1</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Carl</td>
<td>P7</td>
<td>Research 1</td>
<td>Gen Chem</td>
<td>2</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Chris</td>
<td>P8</td>
<td>Lib Arts</td>
<td>Organic</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Neil</td>
<td>P9</td>
<td>Research 1</td>
<td>Upper</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>
Table 3. Status Quo Interview Analysis by Learning Domain.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Identifier for Figure Below</th>
<th>Type</th>
<th>Course Level</th>
<th>Cognitive</th>
<th>Psychomotor</th>
<th>Affective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sarah</td>
<td>PS1</td>
<td>Lib Arts</td>
<td>Gen Chem</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>David</td>
<td>PS2</td>
<td>Lib Arts</td>
<td>Organic/upper</td>
<td>3</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>Jessica</td>
<td>PS3</td>
<td>Comprehen.</td>
<td>Organic/upper</td>
<td>4</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Ryan</td>
<td>PS4</td>
<td>Comprehen.</td>
<td>Gen Chem</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Kelly</td>
<td>PS5</td>
<td>Lib Arts</td>
<td>Upper</td>
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<td></td>
</tr>
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<td>Matthew</td>
<td>PS6</td>
<td>Research 1</td>
<td>Upper</td>
<td>2</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Joan</td>
<td>PS7</td>
<td>Comm Coll</td>
<td>Gen Chem</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Alex</td>
<td>PS8</td>
<td>Comm Coll</td>
<td>Organic</td>
<td>5</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Sean</td>
<td>PS9</td>
<td>Comprehen.</td>
<td>Upper</td>
<td>1</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>
Cognitive Faculty Goals

All but one participant (N=17) articulated goals closely aligned with the cognitive domain of learning. Many faculty (N=16) claimed that connecting laboratory experiences to concepts taught in lecture was important to them. For example, one professor at a liberal arts college explained this importance in terms of conceptual understanding in the laboratory:

“The overriding goal for most of [the laboratory experiments] is a conceptual understanding. […] Probably the major goal is then conceptual understanding of what is going on.” (Andrew, liberal arts, innovator, general chemistry)

Another professor from a community college clearly articulated her intent to connect the thinking that students did in lecture with the actions they performed in lab:
“I want them to see connections between – or make connections between – concepts we’re talking about in class and what they’re doing in the lab. I want – in some cases, lab activities that they do are meant to give them a hands-on work with the concepts talked about in class.” (Angela, community college, innovator, general)

This concise quote from a professor of physical chemistry at a large, research I university coincided with this theme:

“We are also interested in um making real what they learn in p-chem lecture, and the students address that more than anything else.” (Matthew, research I, status quo, upper-level chemistry)

Here, Matthew stated very clearly his goal to make connections to the lecture. Comments like these were frequent among the interviews, regardless of course-level and institution type. Furthermore, all of the professors in the status quo sample and all but one innovator shared this common goal of connecting the laboratory activities to topics discussed in the lecture. One community college professor, though not optimistic that this goal was met, stressed the importance of making such connections:

“Well, mostly I want it to be supportive of what we’re doing in the lecture. So when we’re working problems in the lecture, then they have done something similar in the laboratory, but of course messier. Now, I have to say – and probably down deep I know – the majority of them never see the connection. But my goal is that, by what they do in the laboratory, they see how people get this sort of information in order to use and to learn something from it.” (Joan, community college, status quo, general chemistry)

As this common goal emerged from the interview data, another cognitive goal surfaced along with it. Faculty at all levels of chemistry not only intended for students to make connections between the laboratory experiments and the lecture course associated with it, but students were also meant to connect the ideas learned in the chemistry lab with other science and math courses. Consider the following remarks:

“Um a little more than ten years ago we got a Howard Hughes uh grant, in order to create what we call the ChemBio lab, and this was meant to sort of to integrate the disciplines. The modules – two modules focused on chemistry; two focused on biology […] So this was a way that the students could sort of integrate together and
see the connectivity between the two disciplines.” (Chris, liberal arts, innovator, organic chemistry)

“And we’re trying to figure out ways of having students to realize that concepts should not be compartmentalized within a given, uh, context of a given course, that these are used all the way through their time at the college. And that’s particularly true in chemistry: what you learn in g-chem you’re going to revisit in organic, in p-chem, in biochem, and, and organic; you carry these concepts maybe with a slight differentiation from one class to another, but what – we’re finding that students do not always retain.” (Sarah, liberal arts, innovator, general chemistry)

“I try hard to make a combination of things happen, so that it bounces back and forth between Physics, Chemistry, and Biology. […] And I’ll add to that Engineering and Mathematics as being important as well.” (John, research I, innovator, general chemistry)

Nearly all of the faculty members articulated their intention of involving some sort of interconnectedness between the laboratory activities and other areas of the students’ education.

Many of the goals that pertained to the cognitive domain were common among the sample of professors. Initially, it did not appear that any of the stratifications used in the methodological framework could discriminate among these cognitive goals. However, upon closer analysis of the interview data, a pattern emerged that innovators more often discussed these goals from a holistic perspective, while status quo participants focused more intently on the details of concepts. Consider the following comment by a research I innovator:

“And through the research experience we are having them involved in, we'd like to see if we can get students involved in more of the scientific process skills. So the actually thinking about how you design a scientific experiment, um, carrying out an experiment and having the opportunity to revise it, change it, you know, basically make mistakes, and learning how to really make claims from data. So be able to look at data that is collected and determine what is a valid claim and what is not, which is pedagogically a really different exercise than “did I get the right answer, when I collected this data”. (Clare, research I, innovator, general chemistry)

Now consider this comment by a community college professor in the status quo sample:

“In other words, how to handle what they collect and what’s a reasonable answer. Or even just – if they’re doing a molecular weight by freezing point depression, they don’t always think about “Is this a reasonable answer or not?” I mean when you think hydrogen, H₂, with a molecular weight of two, and then on a
freezing point depression they get a molecular weight of like .05, shouldn’t they be a little surprised? Or if they got a negative number, shouldn’t they be surprised and question what they got?” (Joan, community college, status quo, general chemistry)

The goals of both of these professors were coded as “critical analysis” by the researcher. However, Clare expressed this goal differently than Joan. Clare (innovator) discussed the scientific process and described the experience a student-researcher would have, while Joan (status quo) went into great detail about specific concepts she expected the students to be able to critically analyze. Thus, Clare was interested in the whole laboratory experience, and Joan focused on the finer details that comprise the experience.

Further evidence of this dichotomy between a holistic view and a focus on details is evidenced by the following quote by a professor at a comprehensive university:

“[Staying] current – with, uh, trends in, in our local community has been a driving force there and trying to get experience with um, with various concepts. […] But things like that, that are current trends in the field, we will just introduce them as one lab concept.” (Jessica, comprehensive, status quo, organic chemistry)

Jessica was focused, here, on the actual concepts that are included in the laboratory course, whereas Chris (below) focused more generally on learning about the synthetic process:

“Also to in general learn how – or to have the students learn something about how the whole process of a synthesis works. I mean, that’s really what that module’s supposed to be about […] And, so the synthesis module has the goal of helping people to see, ‘What are the factors that would be important in thinking about making something?’” (Chris, liberal arts, innovator, organic chemistry)

This analysis does not suggest that all status quo participants were intent on the minute details of the concepts presented in the laboratory; likewise, neither did all innovators embrace a holistic view of the course. Consider the thoughts of Matthew, a status quo participant:

“They will need to figure out in many cases how some instruments work. So those things – they will need to, you know, face some difficulties. They’ll need to figure out what’s going on. So, those things I think are useful partly just so that they’re familiar when the students do go on, and partly because in the course of doing those things they are learning things about themselves and about the world that
don’t show up in lecture courses very much.” (Matthew, research I, status quo, upper-level chemistry)

Here, Matthew expressed a view more similar to the innovators than to the other status quo professors. That is, he attended to several, general aspects of the students’ experience, rather than describe the minute details of the instruments with which the students work. There is a discrepancy between this status quo professor and the majority of the status quo sample. However, the trend was prominent among cognitive goals where innovators demonstrated a holistic view and status quo professors focused on the minute details involved with implementation of the course. These cognitive goals described above are summarized in Table 4.

Table 4. Cognitive Goal Summary

<table>
<thead>
<tr>
<th>Cognitive Goal Discussed</th>
<th>Faculty Participant</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conceptual understanding</td>
<td>Andrew</td>
<td>Liberal arts, innovator, general chemistry</td>
</tr>
<tr>
<td>Make connections to topics in lecture</td>
<td>Angela</td>
<td>Community college, innovator, general chemistry</td>
</tr>
<tr>
<td></td>
<td>Matthew</td>
<td>Research I, status quo, upper-level chemistry</td>
</tr>
<tr>
<td></td>
<td>Joan</td>
<td>Community college, status quo, general chemistry</td>
</tr>
<tr>
<td>Make connections to other fields</td>
<td>Chris</td>
<td>Liberal arts, innovative, organic chemistry</td>
</tr>
<tr>
<td></td>
<td>Sarah</td>
<td>Liberal arts, status quo, general chemistry</td>
</tr>
<tr>
<td></td>
<td>John</td>
<td>Research I, innovator, general chemistry</td>
</tr>
<tr>
<td>Critical analysis</td>
<td>Clare</td>
<td>Research I, innovator, general chemistry</td>
</tr>
<tr>
<td></td>
<td>Joan</td>
<td>Community college, status quo, general chemistry</td>
</tr>
<tr>
<td>Experience a range of content</td>
<td>Jessica</td>
<td>Comprehensive, status quo, organic chemistry</td>
</tr>
<tr>
<td></td>
<td>Chris</td>
<td>Liberal arts, innovative, organic chemistry</td>
</tr>
</tbody>
</table>
Psychomotor Faculty Goals

The goals of faculty members were also coded as characteristic of the psychomotor domain (Table 5). As with the cognitive goals, many psychomotor goals were common among both the innovator and status quo professors. These common goals included working with instrumentation, glassware, and other apparatus in the laboratory; learning techniques for experimental procedures; and communicating scientifically regarding the work students had completed in the laboratory.

However, the data demonstrated a correlation between the status quo professors that contrasts the mindset of the innovative professors. As with goals pertaining to the cognitive domain, the innovators demonstrated a holistic point of view, and the status quo participants gave very detailed explanations of student actions.

Angela’s goal, quoted below, illustrates the shared aims of the innovators. She described for this researcher the circumstances in which her general chemistry students found themselves:

“[I]t’s not just me telling them things or them reading things, but they’re experiencing by doing activities with chemicals, with lab apparatus, whatever. They get a hands-on and a visual perspective with the work.” (Angela, community college, innovator, general chemistry)

She clearly stated a desire to introduce the students to techniques and instrumentation that will be important later, yet she was not narrowly focused on specific techniques, such as learning how to use an analytical balance or to perform a titration. By contrast, other faculty cited very specific goals in the psychomotor domain:

“[W]e actually have them to go through, um, a mini experiment to see if they have learned specific techniques. Um, the students will have – in other words we would want them, for example, in general chemistry basically to know how to use an analytical balance, how to do a titration, how to use the spectrophotometer, things like that. Certain techniques we would want, and expect, them to know how to do by the end of that sequence, first year sequence.” (Sarah, liberal arts, status quo, general chemistry)

Sarah expressed the goal, common to status quo participants, for students in general chemistry to learn techniques, but her focus progressed to precise performance criteria that she expected the
students to meet. A trend existed where innovators were more general, and the status quo participants were highly-specific. This trend pervades all levels of chemistry teaching investigated. Consider Chris, an innovator and a teacher of organic chemistry. Chris stated

“But probably the most importantly, there’s a – third week was meant to sort of build on some of the skills they learned in the two previous weeks. So, I guess overall goals would be to um, to uh teach appropriate techniques, um also to in general learn how – or to have the students learn something about how the whole process of a synthesis works.” (Chris, liberal arts, innovator, organic chemistry)

Chris only claimed the goal that students learn “appropriate techniques”. He did not mention individual tasks the students learned to perform, but instead kept the focus on a broad range of actions. On the other hand, Alex, Sean, and David, all status quo professors, described the laboratory differently:

“In the lab, in terms of technique, you know I see physical chemistry as – since we’re using this open lab policy, it’s – you know, they’re really starting to develop some maturity in lab. You know, something that’s really going to kick in when they take analytical, where you know you’re responsible for reporting the percent iron, or something. And you’re going to be graded on the quality of your result, and it doesn’t matter how well you write your report, if you’re off by seven percent you’re going to get a bad grade. It’s uh – p-chem is sort of a step in that direction where, you know, you’re not going to be guided through the procedure all the way. You’re gonna have to start demonstrating that you can do some things on your own: use good technique.” (Sean, comprehensive, status quo, upper-level chemistry)

“So the point of the exercise is partly to learn how to do a fractional distillation, but the greater part of that exercise is to explain to others why it happens the way it happens. For that they have to go back to some general chemistry and review their Raoult law of partial pressures, mole fraction calculations.” (Alex, community college, status quo, organic chemistry)

“It’s to make sure that they’re all hands-on users of all the major equipment in the department. […] all my people who go through my advanced synthesis lab become user of the high-field NMR, users of the GC Mass Spec, any kind of equipment. […] As much as possible, I try to introduce, you know, experiments that will use that kind of instrumentation as well.” (David, liberal arts, status quo, upper-level chemistry)
While Chris (innovator) spoke broadly about learning “appropriate techniques”, the status quo professors specifically discussed certain procedures and instrumentation used. For them, the focus was on the basic details of activities that the students typically performed.

Probably the most compelling example of this dichotomy between innovators’ holistic goals and status quo professors’ detail-specific goals were found in the response of Kelly, a status quo professor from a liberal arts college. She explained her goals for the physical chemistry laboratory:

“We have the goal that they should be able to do error analysis to justify the results, the measurement is right in terms of accuracy and precision. Also they can do, I mean, error propagation for initial measurements, which has of course uncertainty. […] This is a technique they have to learn. So p-chem is quantitative; it’s very reliant on this technique, uh this capability […] but uh this course, the goal is the transition from like, uh, normally like g-chem to research. So, so that’s why they – for the research you have to justify your measurement is right. Right? To address – I mean how good your final result is – so convince people, say what is uncertain in your final results, so we know how you justify your work. Then you have to be able to deliver your uh findings, uh your results, into I mean people in the scientific community. That’s why these two techniques – these two capabilities – are important for students to get into a real world and working, or go to grad school.” (Kelly, liberal arts, status quo, upper-level chemistry)

Kelly articulated goals that were focused very specifically on activities that the students needed to be able to perform in the physical chemistry course. She indicated that the students are expected to analyze the uncertainty of their data, giving specific examples of the “capabilities” that she thought were important. The two capabilities she mentioned were doing error analysis and delivering findings to the scientific community.

Kelly discussed another goal that emerged as common across all of the participants, namely the development of writing and speaking skills. Many professors explicitly stated that they considered scientific communication skills to be very important:

“As opposed to just making – and also to be succinct and articulate in their writing, not necessarily succinct, but direct in their writing, and to be as specific as possible, to avoid saying things like ‘my numbers were off’, you know what does that mean? I want them to articulate their understanding of the concepts, what they learned in the lab, using appropriate language – you know, language of the field – you know, so and being as direct as possible and as focused as possible when they’re writing.” (Angela, community college, innovator, general chemistry)
“Uh, we emphasize such things as developing writing and, uh and, uh communication skills. [...] And we make people revise their writing; it’s very important to do that, or you don’t learn. We also have people give oral presentations to the class on topics that are related to the lab. [...] I believe that no matter what they do, if they go on in Chemistry, they will be involved in communication. And, and that their communication skills often differentiate them versus other people. So it’s very important to be able to write well, and to speak well.” (John, research I, innovator, upper-level chemistry)

“Mainly it is to write good uh lab reports [...] This is another goal – I mean of course writing, that is how to convey the result to uh the faculty member – I mean how to, how to – that is how they do it by writing a report.” (Kelly, liberal arts, status quo, upper)

“I guess that’s something that we take pretty seriously. Uh, we like to, you know, students to really work on their communication skills. So this – since the physical chemistry course is the first time we’re having them write scientific reports, you know kind of scientific writing, I typically start out kind of lenient.” (Sean, comprehensive, status quo, upper-level chemistry)

There was no feature of communicating to the scientific community that signified a difference among participants. This goal of writing and speaking effectively was common to both innovators and status quo participants at various levels, and no evidence was found to justify separating them, as with the previously discussed goals of learning techniques and concepts. Nevertheless, developing scientific communication skills is apparently a common goal for professors, transcending the boundaries of course level and institution type. The goals described above are summarized in Table 5.
Table 5. Psychomotor Goal Summary

<table>
<thead>
<tr>
<th>Psychomotor Goal Discussed</th>
<th>Faculty Participant</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Learning laboratory techniques</td>
<td>Angela</td>
<td>Community college, innovator, general chemistry</td>
</tr>
<tr>
<td></td>
<td>Sarah</td>
<td>Liberal arts, status quo, general chemistry</td>
</tr>
<tr>
<td></td>
<td>Chris</td>
<td>Liberal arts, innovative, organic chemistry</td>
</tr>
<tr>
<td></td>
<td>Sean</td>
<td>Comprehensive, status quo, upper-level chemistry</td>
</tr>
<tr>
<td></td>
<td>Alex</td>
<td>Community college, status quo, organic chemistry</td>
</tr>
<tr>
<td></td>
<td>David</td>
<td>Liberal arts, status quo, upper-level chemistry</td>
</tr>
<tr>
<td></td>
<td>Kelly</td>
<td>Liberal arts, status quo, upper-level chemistry</td>
</tr>
<tr>
<td>Use equipment (instruments, glassware, etc.)</td>
<td>Angela</td>
<td>Community college, innovator, general chemistry</td>
</tr>
<tr>
<td></td>
<td>Kelly</td>
<td>Liberal arts, status quo, upper-level chemistry</td>
</tr>
<tr>
<td>Communicating to the scientific community</td>
<td>Angela</td>
<td>Community college, innovator, general chemistry</td>
</tr>
<tr>
<td></td>
<td>John</td>
<td>Research I, innovator, general chemistry</td>
</tr>
<tr>
<td></td>
<td>Sean</td>
<td>Comprehensive, status quo, upper-level chemistry</td>
</tr>
</tbody>
</table>

Affective Faculty Goals

Finally, faculty goals regarding student feelings and attitudes were coded and analyzed as affective goals (Table 6). Overwhelmingly, both innovators and status quo professors asserted that they intended for chemistry to relate to the real world experiences of their students. Many stated that the chemistry laboratory needed to be “relevant” to the students’ lives:

“[Right] so these are chem majors and it is my objective to have them recognize at least organic chemistry in the real world. Rather than being a technician, have been the explorer.” (Jason, liberal arts, innovator, upper-level chemistry)
“I don’t want them just to go in there and it’s an independent event and their minds aren’t engaged. […] Relevance to what they’re doing.” (Joan, community college, status quo, general chemistry)

“Yeah, so just making them aware of the different, uh, different applications of the labs they do. So, for example, in the instrumental analysis class, we will have an inorganic example, an organic example, an um environmental chemistry example, a biochemistry example using various instruments, so they can see that, you know, they’re used in a lot of different applications. Um, so with analytical chemistry we definitely wanted to bring in some of the um, of the actual uses that the students would see out in the um, in the real world.” (Jessica, comprehensive, status quo, upper-level chemistry)

Jason (innovator) stated his objective for chemistry majors in the advanced organic course to recognize its relation to the real world and to explore the chemistry. Joan and Jessica (both status quo) also wanted students to be engaged in what they are doing and to realize the relevance of it to the real world.

Others indicated that the underlying goal was to prepare the students for future experiences, i.e. real world jobs that the students will have:

“One of our – one of our goals – is what we had in, uh, in [our] program, and that’s to give students experiences more like what chemists really do – or what scientists do. So, you know, give them sort of a flavor for, um, what it means to do science.” (Angela, community college, innovator, general chemistry)

“Um, we’re trying to use these scenarios, the contexts, as a way of embedding learning within another context that exists in the real world – if you don’t mind the phrase. […] So we weren’t looking to prepare anybody for a particular kind of job; we just wanted job-related scenarios to be part of what they were learning.” (Carl, research I, innovator, general chemistry)

“My hope for the course is that – and I think I’ve gotten more clear on this over the years – that it emulate life in the real world. Now, it certainly does that better than the lecture course. […] Whereas what they do in this lab course is pretty much what they might do in the real world.” (Matthew, research I, status quo, upper-level chemistry)

Angela (innovator) claimed to want her students to know what it means to “do science,” preparing them for their future job or courses. Carl (innovator) was more direct, saying that he wanted students to experience “job-related scenarios.” And Matthew (status quo) clearly stated
that the activities, in which the students were engaged, mimicked experiences from the real world. As such making the curriculum relevant to the student was a goal shared by chemistry these professors. As with the psychomotor goal for students to engage in scientific communication, no evidence was found to distinguish innovators from status quo professors. An approximately equal number of representatives from each sample claimed this goal, and the motivating factors were not significantly different among them.

The goal of promoting student collaboration and teamwork emerged in several interviews. Upon comparing the statements taken from two interviews (one status quo, one innovator), it was observed that the innovator had a different underlying goal than the status quo participant. Consider the following comments:

“[To] get them together and working together, because this is - from this point on they will be together for all of their courses […] But in general we want them to be working together and getting to know each other, study together, and this is the first lab that really gets them doing that.” (Jason, liberal arts, innovator, upper-level chemistry)

“So what I tend to do, then, is to pair people together, so that instead of having like ten different experiments going on, I might have five different experiments. Each student will do it; it’s actually not bad to have two identical runs of the same experiment. Students are always amazed to say, ‘but wait a second, we both did the same thing, and we’re getting two different NMRs. What’s going on here?’ Uh, and that helps me; then I’m talking to pairs of students.” (David, liberal arts, status quo, upper-level chemistry)

Jason, the innovator, asserted that he wanted students to work together with the underlying purpose of developing relationships from which they could all benefit. David, on the other hand, set this goal to meet his practical goal of overseeing and grading the students’ work. He claimed that working in pairs was intended to cut down on the number of experiments being run simultaneously. The intent was not the same in these two uses of group work.

Another goal that showed evidence of a discrepancy between the innovative and status quo professors was the desire to help the students achieve independence. Among the innovators, student independence to think, act, and feel motivated this goal. This resonated with Novak’s theory that meaningful learning requires the integration of thought, action, and feelings. Several of the status quo professors, on the other hand, were motivated by a desire to train
independent operators in the lab for the sake of ease of instruction. This was evident in the following explanation by David:

“I think in the introductory organic course, our major goal is that students have been exposed to the standard types of techniques that an organic chemist would use. And then ‘expose’ meaning we want ‘em, we want ‘em replicated. That is we want to teach ‘em the technique once and then we want them to do the technique again and be much less direct of – and have them really formulate what questions, really, or you know, they would need to know in order to use that technique. […] So I guess by knowing, we would really hope that they would need much less direction the third time they face this, which would be in their own laboratories, experience. So that would be the goal of that lab.” (David, liberal arts, status quo, organic chemistry)

David asserted that students should have **become competent workers in the lab** for the purpose of needing less direction in future courses. In contrast, Neil claimed to want students to understand the operation of instruments and to feel comfortable using them. In this way, Neil’s goal was **to gain independence** for the sake of comprehension, and thus future application:

“And the course also has a – and also the way I teach the class, since it has a fair amount of instrumentation involved, so the students feel comfortable using the instrumentation and don’t have sort of a fear of it, and treat it as a black box.” (Neil, research I, innovator, upper-level chemistry)

Through iterative rounds of coding, the analysis of the interviews revealed that innovative and status quo faculty shared many common learning goals for students in the laboratory. The goals associated with the cognitive domain were **connecting concepts to the lecture, connecting concepts to other fields**, and **critical analysis**. The goals associated with the psychomotor domains were **working with instrumentation and other equipment, learning techniques and procedures**, and **communicating to the scientific community**. These goals were often shared among innovators and status quo professors, but a difference in the underlying intent was discovered. However, fewer participants shared affective goals in common. Such goals included **making connections to the real world, engaging in collaboration,** and **gaining independence**. When the underlying motivations for the goals were analyzed, the motivation
behind the affective goals showed evidence of greater disparity than the goals of the both the cognitive and psychomotor domains. The goals described above are summarized in Table 6.

Table 6. Affective Goal Summary

<table>
<thead>
<tr>
<th>Affective Goal Discussed</th>
<th>Faculty Participant</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relate experiences to the real world / make it relevant to future jobs or courses</td>
<td>Jason</td>
<td>Liberal arts, innovator, upper-level chemistry</td>
</tr>
<tr>
<td></td>
<td>Joan</td>
<td>Community college, status quo, general chemistry</td>
</tr>
<tr>
<td></td>
<td>Jessica</td>
<td>Comprehensive, status quo, upper-level chemistry</td>
</tr>
<tr>
<td></td>
<td>Angela</td>
<td>Community college, innovator, general chemistry</td>
</tr>
<tr>
<td></td>
<td>Carl</td>
<td>Research I, innovator, general chemistry</td>
</tr>
<tr>
<td></td>
<td>Matthew</td>
<td>Research I, status quo, upper-level chemistry</td>
</tr>
<tr>
<td>Collaboration / team work</td>
<td>Jason</td>
<td>Liberal arts, innovator, upper-level chemistry</td>
</tr>
<tr>
<td></td>
<td>David</td>
<td>Liberal arts, status quo, upper-level chemistry</td>
</tr>
<tr>
<td>Independence in the laboratory</td>
<td>David</td>
<td>Liberal arts, status quo, upper-level chemistry</td>
</tr>
<tr>
<td></td>
<td>Neil</td>
<td>Research I, innovator, upper-level chemistry</td>
</tr>
</tbody>
</table>

**Intersection of Learning Goals**

Although analysis through the learning domains has been presented separately thus far, it is fundamental to Novak’s theory of human constructivism, and thus for meaningful learning to take place, that these domains become integrated within the learning experience. Therefore, the next level of analysis investigated the degree to which the participants integrated the learning domains across their goals for laboratory learning.
Three examples were included here to demonstrate the integration of cognitive and psychomotor goals. The following professors articulated the need for both thinking and acting to coexist in the laboratory setting:

“And so we want them to, to not only have the skills that we teach them in the first semester, but then we want to apply those skills um, just as a matter of routine um to one particular reaction. […] Um, so we develop kind of skill set first, then we go to uh the actually analysis of um of how to run an experiment that’s directly applied from a reaction they learned in lecture.” (Jessica, comprehensive, status quo, organic chemistry)

“So the point of the exercise is partly to learn how to do a fractional distillation, but the greater part of that exercise is to explain to others why it happens the way it happens. For that they have to go back to some general chemistry and review their Raoult law of partial pressures, mole fraction calculations. […] So mastery is very comprehensive. It speaks to, not only intellectual understanding, but also hand-eye coordination and manipulative skills that come only from experience.” (Alex, community college, status quo, organic chemistry)

“As opposed to just making – and also to be succinct and articulate in their writing […] I want them to articulate their understanding of the concepts, what they learned in the lab, using appropriate language – you know, language of the field – you know, so and being as direct as possible and as focused as possible when they’re writing.” (Angela, community college, innovator, general chemistry)

Jessica (status quo) made an important connection between learning skills and applying the laboratory to the lecture. She wanted the students to apply the skills learned in the laboratory to reactions learned in the lecture. Similarly, Alex (status quo) explained that his goal for students was to learn to do fractional distillation and also to understand the procedure well-enough to explain it to others. Finally, Angela (innovator) described her intention for students to be able to write well in terms of conceptual understanding, tying together both the psychomotor aspect of the writing with the cognitive aspect of understanding their writing.

Professors in both the innovative and status quo samples stated goals that exhibited integration of the cognitive and psychomotor domains. However, it was rare to find a professor who explicitly connected affective goals to either of the other two domains. This supports the assertion made in Chapter 2 that affective goals are the least often
incorporated into faculty members’ goals. Only two examples were found with explicit connections between affective goals and cognitive goals:

“Um, when we made the changes that were in that program, what we wanted to do was, um engage in a form of learning where we were embedding our instructions in scenarios. This is actually something which is current in higher education, usually under the name problem-based learning. So what we intended to do, was to take the principles that we were teaching in the laboratory, continue to teach them, and then turn around and have the students use what they have learned in a, uh solving or applying a scenario that we’re using, in which essentially they were role-playing.” (Carl, research I, innovator, general chemistry)

“My hope for the course is that – and I think I’ve gotten more clear on this over the years – that it emulate life in the real world. […] we do try to give them the feeling that they’re figuring out things on their own, and that it’s not a cookbook where they come in and they have complete instructions and you just ‘do this’.” (Matthew, research I, status quo, upper-level chemistry)

Carl (innovator) expressed his goal for students to learn concepts within the scenarios that are connected to the real world. As such, his intention was to “embed” the cognitive domain within the affective domain. Likewise, Matthew (status quo) hoped that his course connected to life in the real world, and at the same time he wanted students to solve problems, or to “figure out things on their own.”

None of the professors unambiguously articulated that they intended the integration of all three domains of thinking, doing, and feeling. Therefore, the extent to which each professor’s goals overlapped the cognitive, affective, and psychomotor domains was determined by examining the relative emphasis placed on each domain. For example, Carl (innovative) spoke mostly about problem-based learning and teaching principles (cognitive), but he emphasized that the problems provided to the students in these experiments were meant to help them connect chemistry to the “real world” (affective). While Carl emphasized thinking, he also recognized the need to connect the students’ thinking with their feelings and attitudes toward chemistry. A Venn diagram was used to visually represent Carl’s goals (Figure 3b). In his case, the circle representing the cognitive domain is the same size the circle representing the affective domain. As Carl did not include performance goals in his discussion, the circle that would represent the psychomotor domain is not present. The lack of goals pertaining to
the psychomotor domain was surprising, considering the inherently active nature of the laboratory.

Figure 3a-d. Venn diagram of faculty goals by learning domain.

Likewise, a similar diagram was constructed for each of the participants. Nine configurations for these diagrams were possible to make by changing the sizes and connections of the circles, though not all of them were represented by the participants. A
sample of several configurations is included in Figure 3. Clare (innovator) placed approximately equal emphasis on all three domains, citing such goals as **collaboration** (affective), **critical analysis** (cognitive), and **engaging in research experiences** (psychomotor). Thus, the diagram of her goals (Figure 3a) depicts all three circles intersecting with one another. The area where these circles intersect represents the experience of meaningful learning.

Sarah (status quo) gave much more emphasis and detail to physical activities than to thinking and reasoning, while omitting recognition of student feelings. She claimed that her goals were for students **to connect concepts between courses** (cognitive), **to analyze data** (cognitive), **to learn skills for future use** (psychomotor), and **to learn specific techniques** (psychomotor). The relative emphasis she placed on learning techniques and skills was greater than the emphasis on concepts and analysis. Accordingly, her diagram (Figure 3c) shows the presence of both the psychomotor and cognitive domains, the circle representing the psychomotor domain being larger.

Finally, Ryan (status quo) also greatly emphasized the importance of student performance, citing the goal that students should be trained for future courses. He gave limited recognition to the affective domain when he claimed that one goal is **to appreciate chemistry** more by physically interacting in the laboratory. He omitted the cognitive domain, altogether. As such, Ryan’s diagram (Figure 3d) reflects the connection of the psychomotor and affective domains, and the omission of the cognitive domain. The lack of goals pertaining to the cognitive domain was surprising, bearing in mind the relative emphasis placed upon such goals by other participants.

By analyzing the interview coding in this way, it was determined that the innovators demonstrated a greater degree of interconnectivity among the learning domains and gave higher priority to the affective domain than did the status quo participants. As stated in Chapter 3, this connectivity among the learning domains is required for meaningful learning to take place.
Implications for Future Research

Chapter 2 outlined the need for this research, namely that qualitative inquiries were needed regarding the context of the undergraduate laboratory curriculum. In particular, the call for research stressed a need to explore and characterize the goals of faculty members. The research described here responded to that gap in the literature by explaining the important goals that college chemistry professors have in mind when planning laboratory courses in the undergraduate curriculum. A thorough characterization of those goals was developed by applying Novak’s theory of human constructivism as a theoretical framework.12

Due to the nature of qualitative research, the conclusions asserted in this document cannot be generalized to the entire population of chemistry professors. Yet, this research provides an important foundation for designing quantitative research involving surveys of faculty, and ultimately student, perspectives of the laboratory curriculum. Such quantitative data can be useful for making generalizations across entire populations. Future research questions include:

1. To what extent do chemistry faculty integrate the cognitive, affective, and psychomotor learning domains into their goals for the undergraduate chemistry laboratory curriculum?

2. What effect does pedagogical content knowledge have on chemistry faculty members’ goals for student learning in the undergraduate chemistry laboratory?

3. What connection exists between goals for student learning in the undergraduate chemistry laboratory and the high school chemistry laboratory?

4. What are the learning goals that undergraduate chemistry students expect for their laboratory experiences?

The interview data collected using the interview guide (Appendices 7 & 8) was analyzed only with regard to faculty goals, due to the richness of the data and limited scope of this thesis research. Much more can be done in the way of analyzing additional faculty perspectives obtained here. Further analysis can be focused on the professors’ statements regarding the structure of experiments, the nature of assessments, and their
perceptions of the student response to the experience. All of these avenues are valid lines of inquiry, and the resulting conclusions would produce a substantial contribution to the chemistry education research literature.

It is projected that, upon conducting further research in these areas, a tool will be made available to college chemistry faculty that will enable them to compare experiments implemented in courses they teach. This will enable the professor to determine whether the laboratory experiments support the goals set. This instrument would prove useful for faculty members who are interested in understanding and improving the structure of their chemistry laboratory courses.
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Appendix 1 – A rubric to characterize inquiry in the undergraduate chemistry laboratory

The research discussed in this document seeks to understand the goals that chemistry faculty members have for the undergraduate chemistry laboratory. It is important to understand the nature of laboratory activities; therefore, it was necessary to develop an instrument to compare activities within the chemistry laboratory curriculum. The reprint of a peer-reviewed manuscript, regarding an inquiry rubric to make such comparisons, is included in this Appendix. The manuscript discusses the development of the inquiry rubric and assessed its validity and inter-rater reliability.


This paper has been published previously in Chemistry Education Research and Practice and is copyright, Royal Society of Chemistry. It has been reprinted with permission. Significant contributions were made by Nathaniel Grove toward establishing the inter-rater reliability of the rubric. He served as the second rater of the laboratory activities described herein, and he provided guidance and support throughout the manuscript preparation process.
A rubric to characterize inquiry in the undergraduate chemistry laboratory

Michael E. Fay, Nathaniel P. Grove, Marcy Hamby Towns, and Stacey Lowery Bretz

Abstract:
Consensus does not exist among chemists as to the essential characteristics of inquiry in the undergraduate laboratory. A rubric developed for elementary and secondary science classrooms to distinguish among levels of inquiry was modified for the undergraduate chemistry laboratory. Both peer-reviewed experiments in the literature and commercially available experiments were evaluated using the rubric, revealing a diversity of uses for the word inquiry. The modified rubric provides a valid and reliable standard of measure for chemists to examine their laboratory curriculum.

Introduction
For over 30 years, chemists have debated the appropriate uses of the laboratory in the undergraduate curriculum (Fuhrman et al., 1978; Pavelich and Abraham, 1979; Tamir and Lunetta, 1981; Furhman et al., 1982; Hofstein and Lunetta, 1982; Domin, 1999a, 1999b; Johnstone and Al-Shuaili, 2001; Garratt, 2002; Lederman, 2004; Jalil, 2006). Domin (1999b) discussed the relative merits of inductive vs. deductive laboratories and whether students should develop general principles from specific observations or vice versa. Garratt (2002) cautioned against defining chemistry as a laboratory-based science, but instead argued for the importance of ‘purposeful observations’. Jalil (2006) noted the opportunity that laboratory provides for students to make connections between theory and practice, but emphasized that such instruction should also support the cognitive development of students. Martin-Hansen (2002) claimed that the effectiveness of laboratory as a method of instruction stems from the opportunity that
students are given to ask questions, form hypotheses, collect and analyze data, and draw practical conclusions that can enable them to answer their questions.

**Constructivism and inquiry**

Constructivism as a theory of learning posits that “knowledge is constructed in the mind of the learner” (Bodner, 1986). Learning occurs when the student utilizes higher order thinking skills by connecting new knowledge to prior knowledge. Constructivism advocates instructional activities that encourage student-initiated and student-directed learning. Activities that engage students in scientific inquiry facilitate their construction of knowledge.

Martin-Hansen argued (2002) that students who participate in asking questions, forming hypotheses, collecting and analyzing data, etc. are engaged in scientific inquiry. However, many undergraduate chemistry experiments present students with directions for data collection and analysis to lead to a conclusion already known by students before even beginning the ‘experiment’. Classic examples of such pre-determined outcomes would be experimentally determining the value of the ideal gas constant, or using heats of reaction to determine the stoichiometry of a reaction. What do students learn from these laboratories? Can such experiences be considered inquiry?

What are the defining characteristics of inquiry in the undergraduate chemistry laboratory? There exists no operational definition of the term. Lack of consensus has lead to popularization of the term. Identifying and characterizing inquiry in undergraduate chemistry laboratory experiments requires a reliable and valid rubric to assess the level of inquiry. Since the 1960s, education researchers across the natural sciences have developed various iterations of three distinct instruments, each one designed to assess the level of inquiry at which students are

Fuhrman (1978) developed the Laboratory Structure and Task Analysis Inventory (LAI) to analyze science curricula. The LAI contains two sections: the first examines the organization of the laboratory by the instructor, while the second identifies laboratory tasks completed by the student; each of these sections is divided into four subsections containing several categories by which the laboratory activities are assessed (Fuhrman et al., 1978). Fuhrman and colleagues (1982) used the LAI to examine laboratory activities from biology, physics, and chemistry curricula in order to determine the extent to which the laboratory materials reflected the goals of the curriculum. After examining the coherence between stated curriculum goals and the structure of materials and procedures used by students, these researchers identified a low level of inquiry and independence in the laboratory activities, concluding that students commonly worked as technicians following explicit instructions, with relatively few chances for higher-level cognitive processing (Tamir and Lunetta, 1981). Lunetta and Tamir (1979) used these findings to provide a list of twenty-four skills related to the goals of inquiry and problem-solving, affirming the importance of selecting lab activities that enhance teaching goals, and making those goals explicitly clear.

The Classroom Observation Instrument was developed by Smith (1971) as a tool to analyze inquiry in earth science curriculum. Its central focus is upon observable behaviors exhibited by both the instructor and the students throughout the laboratory, during the three phases that characterize most laboratory activities: pre-lab, the experiment, and post-lab.
The ‘Levels of Openness’ framework (Schwab and Brandwein, 1962; Herron, 1971; Shulman and Tamir, 1973) and Continuum of Scientific Inquiry rubric (Lederman, 2004) characterize the degree to which students have the freedom to make choices before, during, and after the laboratory experiment, as opposed to follow prescribed directions. Lederman (2004) used this four-level continuum to analyze high school science laboratories, concluding that students are rarely asked to think for themselves during experiments.

Research question

Given the validity of Lederman’s Continuum of Scientific Inquiry in high school science classrooms, we wondered whether the levels would be valid for characterizing inquiry in undergraduate chemistry laboratories. Specifically, we sought to modify Lederman’s work to characterize undergraduate chemistry laboratory experiments developed under the auspices of the Research Experiences to Enhance Learning (REEL) Project, an NSF-funded Undergraduate Research Center. The goals of the REEL project include introducing authentic lines of research into first and second year chemistry laboratory courses, with an emphasis on general chemistry, environmental chemistry, and organic chemistry. We describe below our use of Lederman’s system and its reliability and validity in the undergraduate chemistry laboratory.

Methodology

Twenty-eight laboratory experiments were selected to establish the reliability of our rubric. General/environmental chemistry experiments were selected from three commercially published laboratory curricula (Abraham and Pavelich, 1999; Bauer et al., 2005; Wink et al., 2005), all of which use the word ‘inquiry’ in the name of their curriculum. Two of these inquiry
laboratory curricula were purposefully structured by their authors so as to include some experiments with lesser degrees of inquiry (e.g., guided inquiry) and other experiments offering greater degrees of inquiry (e.g., open inquiry). Organic chemistry experiments (Senkbeil, 1999; Krishnamurty et al., 2000; Ciacco et al., 2001; Wachter-Jurcsak and Reddin, 2001; Amburgey-Peters and Haynes, 2005; Baru and Mohan, 2005; Cough and Goldman, 2005; Kjonaas and Mattingly, 2005; Nicaise et al., 2005; White and Kittredge, 2005) were selected from the *Journal of Chemical Education*, by searching on the keywords of inquiry and discovery-based learning.

Experiments selected to validate the rubric were chosen to represent a broad selection of chemistry concepts, including the same concepts (e.g., sodium borohydride reductions) across sources in order to ascertain the extent to which the rubric could distinguish between chemically similar experiments. Experiments were also selected from both of the inquiry tiers self-identified by the authors to assess the capability of the rubric to make similar distinctions. (*This list of laboratory experiments, though not included in the original printing, can be found in Appendix 3*)

Given the structure of REEL initiatives across teams (general chemistry/environmental chemistry, and organic chemistry), inter-rater reliability (IRR) was calculated independently for the 18 general chemistry/environmental lab experiments, again for the 10 organic experiments, and then for all 28 experiments as a whole.

The method of analysis is described as follows. Experiments were examined section-by-section: pre-lab information, procedure, and calculations/results. First, the experiment was inspected to ascertain whether an explicit problem was posed, or a question asked, about a particular phenomenon. Next, experimental procedures were scored to reflect the extent to which they were prescriptive (telling students what to do and how to do it), or the degree to which
experimental procedures provided opportunities for the students to decide what actions to take. Finally, by examining the variety of questions asked in the post-lab section and making comparisons to the information provided in the pre-lab section, the laboratory experiments were judged as to what extent the students were to calculate answers and craft conclusions in echo of information provided/stated in the pre-lab in advance of the laboratory.

For example, the levels characterizing both ends of the inquiry continuum were readily recognizable by certain characteristic features:

- **Level 0** – The laboratory manual began with a description of the phenomenon under study (*e.g.* factors that affect rate of oxidation of ‘X’); an explicit method of data collection was presented with no option for alternate paths by the student; the manual contained a set of instructions for analyzing data and/or drawing conclusions already explained in the section(s) outlining the problem.

- **Level 3** – The laboratory manual directed the student to explore a general phenomenon (*e.g.* gases/gas laws); suggestions for lines of exploration were provided, but no specific procedures or methods of data analysis were given.

A team of three researchers evaluated each laboratory experiment twice. The researchers used the rubric to individually evaluate the experiments and subsequently met to discuss their evaluations. Each researcher evaluated the experiments again, allowing for changes if he/she desired. Finally, an inter-rater reliability (IRR) value was calculated for each experiment.
Results

Table 1 shows the results of inter-rater reliability calculations for the general/environmental experiments, for the organic chemistry experiments, and for all experiments. Of the twenty-eight experiments in the sample, one experiment was not rated using Lederman’s rubric due to insufficient detail regarding instructions given to students.

The IRR for each sub-group of experiments and the collection of experiments overall is good, given the standard minimal value of 0.70 as a cut-off for establishing reliability. Based on discussions between the raters during the IRR process, we found more detailed descriptions were required than were provided in Lederman’s continuum. For example, levels 2 and 3 needed a more specific description of the activities carried out by students in order to refine the characterization of that particular type of experiment. We found it important to be able to differentiate among experiments as to whether students were expected to develop procedure(s), decide what data to collect, and/or determine how the data should be interpreted in order to propose a viable solution. Table 2 presents modified descriptions of the levels found in Lederman’s continuum to provide clear criteria for determining the relative levels of inquiry. Table 3 provides a visual comparison across the levels of inquiry.

Table 1. Calculation of inter-rater reliability.

<table>
<thead>
<tr>
<th>Final Ratings</th>
<th>Number of Experiments With Agreement</th>
<th>Total Number of Experiments</th>
<th>Inter-rater Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Chemistry / Environmental Chemistry</td>
<td>16</td>
<td>18</td>
<td>0.89</td>
</tr>
<tr>
<td>Organic Chemistry</td>
<td>7</td>
<td>9</td>
<td>0.78</td>
</tr>
<tr>
<td>Overall</td>
<td>23</td>
<td>27</td>
<td>0.85</td>
</tr>
</tbody>
</table>
Table 2. Rubric to identify level of inquiry.

<table>
<thead>
<tr>
<th>Level of Inquiry</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Level 0</strong></td>
<td>The problem, procedure, and methods to solutions are provided to the student. The student performs the experiment and verifies the results with the manual.</td>
</tr>
<tr>
<td><strong>Level 1</strong></td>
<td>The problem and procedure are provided to the student. The student interprets the data in order to propose viable solutions.</td>
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<td><strong>Level 2</strong></td>
<td>The problem is provided to the student. The student develops a procedure for investigating the problem, decides what data to gather, and interprets the data in order to propose viable solutions.</td>
</tr>
<tr>
<td><strong>Level 3</strong></td>
<td>A ‘raw’ phenomenon is provided to the student. The student chooses the problem to explore, develops a procedure for investigating the problem, decides what data to gather, and interprets the data in order to propose viable solutions.</td>
</tr>
</tbody>
</table>

Table 3. Levels of inquiry across undergraduate chemistry laboratory experiments.

<table>
<thead>
<tr>
<th>Level</th>
<th>Problem/Question</th>
<th>Procedure/Method</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>0</strong></td>
<td>Provided to Student</td>
<td>Provided to Student</td>
<td>Provided to Student</td>
</tr>
<tr>
<td><strong>1</strong></td>
<td>Provided to Student</td>
<td>Provided to Student</td>
<td>Constructed by Student</td>
</tr>
<tr>
<td><strong>2</strong></td>
<td>Provided to Student</td>
<td>Constructed by Student</td>
<td>Constructed by Student</td>
</tr>
<tr>
<td><strong>3</strong></td>
<td>Constructed by Student</td>
<td>Constructed by Student</td>
<td>Constructed by Student</td>
</tr>
</tbody>
</table>

Figure 1 depicts the distribution of the twenty-seven experiments as rated across the levels of inquiry. A wide range of experiments were sampled, from those with essentially no inquiry features (Level 0) to those which require the student to define the problem of interest as well as appropriate methods of data collection and data analysis (Level 3).
Figure 1. Distribution of experiments across levels of inquiry.

Figure 2 shows the ratings of selected experiments within the three commercially published lab manuals sampled for this research. Inquiries into Chemistry (Abraham and Pavelich, 1999) provides laboratory experiments characterized as either guided inquiry [“specific instructions as to what experiments to conduct … (student) should do work in the order indicated” (p. 3)] or open inquiry [“designing and carrying out (student’s) own experiments … no detailed instructions on how to approach these systems.” (p. 275)] Our modified rubric identified these different characterizations of inquiry as consistent with Level 1 and Level 3.

Laboratory Inquiry in Chemistry (Bauer et al., 2005) describes its curriculum as one in which students assume the role of chemist and “design their own experiments”, (Bauer et al., 2005, p. v) adapting techniques to their specific problems. Analysis of the Laboratory Inquiry in Chemistry experiments placed them among both Level 1 and Level 2 using the modified inquiry rubric.

Working with Chemistry (Wink et al., 2005) structures laboratories in experiment groups, each one containing a skill-building laboratory that “shows students how to use a technique” (p. x) and an application laboratory in which students utilize concepts from skill-building labs for
use in a given “professional scenario which is more open in inquiry style.” (p. x) Use of the modified inquiry rubric to score Working with Chemistry laboratories showed experiments to occupy both Level 0 and Level 1.

<table>
<thead>
<tr>
<th>Inquiries Into Chemistry</th>
<th>Lab: Inquiry in Chemistry</th>
<th>Working with Chemistry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 3 50%</td>
<td>Level 1 50%</td>
<td>Level 1 38%</td>
</tr>
<tr>
<td>Level 1 50%</td>
<td>Level 2 62%</td>
<td>Level 1 50%</td>
</tr>
<tr>
<td>Level 0 50%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2.** Ratings of commercially published inquiry laboratory programs.

**Discussion**

Lederman’s continuum was originally developed for use in high school science classrooms, including, but not limited to, chemistry. Our modifications and application of the inquiry rubric to a wide spectrum of chemistry experiments support the validity of using it to characterize varying levels of inquiry in the undergraduate chemistry laboratory. The high inter-rater reliability across both general/environmental chemistry and organic chemistry classifies this rubric as robust. The findings from this research can distinguish among levels of inquiry as identified by commercially published laboratory programs.

**Significance of the inquiry rubric and its potential uses**

The significance of this research lies in its ability to move forward the conversation regarding the most appropriate goals and pedagogies for the undergraduate chemistry laboratory.
As of late, inquiry has gained status as a ‘buzzword’ of sorts, with many chemists using it (sometimes somewhat indiscriminately) to describe their instructional approach to laboratory. Case in point - each of the laboratory experiments in the sample for this research was self-identified by their respective authors as ‘inquiry.’ And yet, our findings clearly show that not all instances of inquiry are equivalent, *i.e.*, they do not necessarily imply or describe the same learning opportunity for students. There exist shades of inquiry with varying degrees of freedom in the student experience.

Potential uses of this inquiry rubric include the opportunity to equip chemists with a quantitative means of comparing and debating the levels of inquiry as they design curriculum and seek to improve learning for students of chemistry. Experiments that might on the surface appear to be essentially equivalent in terms of core concepts and measurements can now be compared directly to one another as to which affords more structure and which provides more inquiry for the student experience. Faculty whose instructional goal is to move students from structured laboratory experiences to increased responsibility for decision making in the laboratory can use the rubric to arrange their experiments in order of increasing levels of inquiry.

For example, consider a laboratory where students are asked to confirm that the rate of reaction increases with temperature. Students might be given a chemical system to investigate, a data table to fill out, and post laboratory questions to answer. Using the inquiry rubric this laboratory would be a Level 0, the students are simply verifying the relationship. However, the level of inquiry could be increased by stating that the students are to investigate the relationship between temperature and reaction rate. The chemical system could still be given, but the students could be asked to develop a hypothesis, data collection and analysis procedures, and viable
conclusions consistent with the data that evaluate the veracity of the hypothesis. This laboratory experiment has been transformed into Level 2.

The inquiry rubric also lends itself to use in curriculum evaluation. Departments that are engaged in programmatic evaluation can use this reliable and robust rubric to characterize the current curriculum. If results from using the inquiry rubric indicate a poor fit between the declared departmental or programmatic goals and the reality of student experience, then the rubric provides a roadmap to direct meaningful data-driven change. For example, if the general chemistry laboratory curriculum is analyzed and none of the laboratories are rated as level 2 or 3, then the curriculum can be modified. Level 0 or Level 1 laboratory experiments could be replaced with Level 2 experiments that use a more open inquiry approach. Alternatively, current laboratory activities could be modified to include experiences where the students design data collection and analysis procedures, and proposed viable solutions based upon the data.

Systematic use of the inquiry rubric to guide choices in laboratory instruction will facilitate chemists’ transition from choosing laboratory experiments because they provide easy to follow directions toward choosing laboratory experiments because they provide carefully crafted opportunities for chemistry students to engage in inquiry.

Acknowledgements

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Appendix 2 – Structuring the Level of Inquiry in Your Classroom

The reprint of a peer-reviewed manuscript, regarding the inquiry rubric discussed in Appendix 1, is included in this Appendix. This manuscript describes the use of the rubric and suggests possible methods of structuring the high school chemistry curriculum to include inquiry.


Abstract:
Inquiry activities vary widely in the structure provided for students to conduct experiments. This paper provides a rubric to compare experiments, as well as suggests trajectories for structuring inquiry across the curriculum.

Structuring the Level of Inquiry in Your Classroom

The scientific literature is replete with innovative activities that enable teachers of all levels in the sciences to introduce inquiry into their curriculum. Many laboratory experiments, available through NSTA publications, exemplify various strategies that can potentially raise the students’ level of responsibility in the laboratory over the course of a semester/year (Polacek & Keeling, 2005; Reeve et al., 2004; Regassa & Morrison-Shetlar, 2007). Inquiry is not only abundant in the literature; it is also a key feature of the National Science Education Standards, NSES (NRC, 1996). Thus, all science teachers are urged to use inquiry in their teaching. In light of the numerous available resources, how can a teacher make an educated decision about which experiments to incorporate into lesson plans? Are some forms of inquiry better than others, or just different? A teacher may wonder if one activity exemplifies inquiry better than another.

Despite the prevalence of valuable and worthwhile activities that offer science students the chance to engage in scientific thinking, many teachers report that it is difficult to implement
inquiry activities in their curriculum. Sundberg cites issues such as limited resources and support; he also claims that it is difficult to modify the entire curriculum to include such activities (Sundberg et al., 2000). A factor that compounds the issue is the current state of science instruction (particularly in chemistry) at the pre-service level. The undergraduate preparation of future high school chemistry teachers ranges from B.S. degrees in chemistry to taking only general chemistry. Regardless, most undergraduate chemistry faculty teaching courses required for pre-service teachers do not engage them in inquiry. In particular, undergraduate chemistry laboratory courses typically require students to follow detailed instructions in order to learn previously known facts or principles (Fay et al., 2007). This experience is common to students at all levels of science education. The painful truth is that beginning science teachers who have not experienced inquiry as learners may find it difficult to implement such a curriculum in their classroom.

How, then, can the scientific community guide teachers to better implement inquiry into their classroom activities? A first step toward answering this question is to enable teachers to evaluate their curriculum with user-friendly analytical tools. Several efforts to categorize inquiry in the classroom have been proposed since the 1960s (Herron, 1971; Schwab, 1964; Chinn and Malhotra, 2002; McComas, 2005; Fay et al., 2007). The National Research Council recently recognized a rubric (Lederman, 2004) developed to provide the opportunity for teachers and researchers to quantitatively evaluate laboratory activities on a continuum of “levels of openness” for student independence.

This body of research has clearly established that not all inquiry-related laboratory activities are equivalent. Yet, given the importance of inquiry in science education, the word is frequently invoked without specifying its meaning. Our research has shown that many uses of
the word ‘inquiry’ do not necessarily imply nor describe the same learning opportunity for students (Fay et al., 2007).

Consider these three experiments which might be done in a high school freshman physical science course:

- **Experiment A** – Ms. Smith teaches at an urban high school. She does not have access to many resources for her laboratory activities, so she tries to do experiments that involve materials her students can bring from home. One of these experiments requires popcorn kernels. The students bring popcorn to class and follow a detailed procedure which instructs them on proper methods to determine percent water content in the kernels. They are told what data to collect and how to calculate their final number. Ms. Smith tells her students how much water is usually in popcorn kernels, and the students report how close their calculation comes to that value.

- **Experiment B** – Mr. Jones teaches physical science to freshmen, too. He has heard about Ms. Smith’s ideas for experiments, but he likes to put a different twist on them. Instead of telling the students how to calculate the percent water content, Mr. Jones only provides the students with the procedure for measuring the mass and popping the corn. He informs them that they must work with their lab partner to figure out how to find the amount of water in the average popcorn kernel. The students report their findings before being told the known percent water.

- **Experiment C** – Mrs. Lawrence is another science teacher at the same school. She has several lessons set aside each year that require her students to come up with their own experiments. One of these lessons is scheduled for the beginning of the school year when she teaches about measurement. The assignment requires the students to
come up with an idea for their own experiment; they have time in class to work with partners on their plan, and they must have it approved by Mrs. Lawrence. One of the experiments devised by a pair of students is similar to the popcorn experiment Ms. Smith and Mr. Jones use. The students took many more measurements than necessary in their experiment, because they were not sure what information they would need. However, in the end they reported that popcorn kernels lose a certain amount of mass, on average, after being popped. They only speculated about what happened to the mass, but Mrs. Lawrence was pleased to see that the students did not assume that it was destroyed in the process of the experiment.

Clearly, experiments provide opportunities for inquiry, yet offer varying degrees of freedom within student laboratory experiences. The purpose of this paper is to discuss the significance of these degrees of freedom as they pertain to high school science instruction and to empower teachers with a rubric to guide their choices among laboratory experiments and plan differing trajectories of inquiry for their curriculum.

A Rubric for Comparing Laboratory Activities

In order to distinguish among the degrees of inquiry exhibited in laboratory experiments, a rubric must facilitate a comparison of teacher responsibilities versus student responsibilities. Three high school chemistry laboratories that are reasonably equivalent in terms of the difficulty of the concepts involved are described below, followed by a discussion of their relative degrees of inquiry:
Experiment D requires students to perform a titration to determine the concentration of hydrochloric acid prepared in advance by the instructor. In the pre-lab section, an explanation of the underlying acid-base chemistry is described in detail. The students are told how to use a buret and Erlenmeyer flask, what measurements to take, and how to organize and analyze the data.

Experiment E describes a situation where the students must solve a problem similar to one an environmental chemist is likely to encounter. They are given a scenario and are told that they must determine the level of Mg\(^{2+}\) in their water supply, so that they can evaluate the “hardness” of the water. The teacher directs students to valuable resources available to them, but the students are expected to develop their own methods of analysis and to decide what data to collect. Finally, the students are required to report their findings to the class.

Experiment F assigns the task of analyzing household products. Students are directed to explore the chemistry of soaps and detergents. They must decide on a question to investigate, as well as develop both an appropriate experimental method and an analysis scheme (all approved by the teacher); finally, they must reach a viable conclusion based on their data analysis.

How do these chemistry experiments differ from one another? Do any of them exemplify the construct of inquiry? Do all of them? The inquiry rubric in Table 1 (Fay et al 2007) can be used to differentiate among these experiments. The rubric is structured according to three parts to a laboratory activity: 1) the problem or question under investigation, 2) the procedure used by the student to collect data, and 3) the solution or conclusion to which the student comes in the end.
The rubric is based on the premise that there are distinguishable degrees of student freedom. These four levels of inquiry assign increasing responsibility to the student with decreasing direction from the teacher. A detailed description of each level can be found in Table 2.

Table 1. Levels of inquiry rubric (Fay et al, 2007)

<table>
<thead>
<tr>
<th>Level</th>
<th>Problem/Question</th>
<th>Procedure/Method</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Provided to student</td>
<td>Provided to student</td>
<td>Provided to student</td>
</tr>
<tr>
<td>1</td>
<td>Provided to student</td>
<td>Provided to student</td>
<td>Constructed by student</td>
</tr>
<tr>
<td>2</td>
<td>Provided to student</td>
<td>Constructed by student</td>
<td>Constructed by student</td>
</tr>
<tr>
<td>3</td>
<td>Constructed by student</td>
<td>Constructed by student</td>
<td>Constructed by student</td>
</tr>
</tbody>
</table>

Table 2. Description of each Level of Inquiry; characteristic descriptors of each level are shown in bold.

<table>
<thead>
<tr>
<th>Level of Inquiry</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 0</td>
<td>The problem, procedure, and methods to solutions are provided to the student. The student performs the experiment and verifies the results with the manual.</td>
</tr>
<tr>
<td>Level 1</td>
<td>The problem and procedure are provided to the student. The student interprets the data in order to propose viable solutions.</td>
</tr>
<tr>
<td>Level 2</td>
<td>The problem is provided to the student. The student develops a procedure for investigating the problem, decides what data to gather, and interprets the data in order to propose viable solutions.</td>
</tr>
<tr>
<td>Level 3</td>
<td>A ‘raw’ phenomenon is provided to the student. The student chooses the problem to explore, develops a procedure for investigating the problem, decides what data to gather, and interprets the data in order to propose viable solutions.</td>
</tr>
</tbody>
</table>

According to this rubric, experiment D does not permit, nor expect, the student to plan how to execute the experiment; it is scored at Level 0. The analytical procedure and conclusions in experiment E are open to the students’ judgment; therefore it is at Level 2 per
this rubric. Finally, the degrees of freedom afforded students (allowing them to make
decisions) in experiment F exemplifies the highest level of the rubric, Level 3.

Thus, these activities do not provide equivalent student learning experiences with
regard to inquiry because they are representative of the different levels in the rubric.
Educators who make it their goal to offer students the opportunity for inquiry should note
that an experiment at Level 3 offers the highest degree of freedom to students. This is
consistent with the National Science Education Standards [NSES – Teaching Standard B,
(NRC, 1996)].

**Raising the Level of Inquiry through the Year**

How then should a teacher structure a course to help students learn through inquiry? Bell
(2005) advised careful scaffolding of the curriculum to provide adequate support for students as
they progress toward higher levels of inquiry. The following account describes this
“scaffolding” in more detail. Figure 1 provides a graphical representation of several inquiry
trajectories. Using any of these approaches will support students to achieve a greater
independence in the laboratory. The authors have not collected evidence to suggest that one
trajectory is better than another; pros and cons are listed for each tactic. (Modifications to these
trajectories are certainly possible; Figure 1 should not be considered an exhaustive set.)
Trajectory 1 represents a curriculum that begins at Level 0 (skill building, becoming acquainted with techniques). The level of inquiry increases slowly over the first half of the year, allowing the students ample time to develop the manual dexterity needed to collect valuable data in the laboratory setting. Then the curriculum gradually accelerates to Level 3 activities (maximum student independence) in the second half of the year. The benefit of remaining longer at lower levels of inquiry is significant, because students have the chance to become familiar with the layout of the lab and the equipment. However, it is possible that this method does not challenge them soon enough to go beyond their comfort zone and to work at Level 1. Thus, teachers may encounter significant resistance from students who have grown accustomed to
having each experimental step, and all of the results, spelled out for them ahead of time. Planning an inquiry curriculum to resemble Trajectory 1 may make it more difficult to expect the students to function at higher levels of inquiry later in the year. A detailed review of such resistance to reform by students can be found in Anderson (2001).

Trajectory 2 offers a strategy that may help to counter the difficulty proposed in Trajectory 1. In this scheme, students still begin at Level 0, but the experiments can quickly increase in the expected degree of student freedom. Soon after the start of the year, the students will be acquainted with the rules of the laboratory, and they may be more able to use prior content knowledge to help the teacher to devise investigations that pertain to the present subject matter. By challenging the students to work at higher levels of inquiry early in the year, the teacher may avoid the undesirable situation mentioned above where the students become frustrated by the change in effort they are required to put forth. A major downfall of this approach could be that students are brought up to Level 3 with a large portion of the school year left (possibly as much as half of the year); it may be difficult for high school students to maintain this level of independence as the curriculum carries them through many changes in topics (Anderson, 2001).

Trajectory 3 is a linear approach. Students will progress through the levels more steadily than with either Trajectory 1 or Trajectory 2. They could spend approximately one quarter at each level, but such a timeline is not mandatory. This approach maintains a delicate balance between the extremes of the previous trajectories, and thus there are fewer problems anticipated by the authors. By progressing slowly from highly teacher-centered activities to student-centered ones, the students experience slow changes in the amount of effort required, and they do not have to work at the highest effort for a very long time.
Finally, Trajectory 4, which resembles a sine wave, suggests another option for inquiry. This oscillating approach implies rapid fluctuation through the levels and avoids spending too much time at the highest level. Although it appears to fluctuate excessively, the flow of such a curriculum is appealing. The students would complete laboratory exercises in large conceptual units; each unit would begin with an experiment that allows the students to familiarize themselves with new techniques beneficial to investigating the current phenomena. Following this introductory experiment, a collection of successively higher-level activities would be assigned, so that by the end of the unit the students will be working on their own, independently developed project. When the next unit begins, the students will once again be at Level 0, getting used to new techniques. This trajectory is similar to a commercially available collection of college-level chemistry laboratory experiments. (Wink et al., 2005)

It is important to note that the trajectory descriptions and analyses included here are specific to a single academic year in high school. However, these trajectories can be applied across the entire high school science curriculum, from the beginning of freshman year to the end of senior year, as indicated in Figure 1.

Conclusion

Both the National Science Education Standards and a majority of state standards require the implementation of inquiry within the science curriculum. Additionally, it is evident that various levels of inquiry, or degrees of student freedom, exist for science laboratory activities. Clearly, not all uses of the word ‘inquiry’ are equivalent. Since many teachers face the challenge to incorporate inquiry activities into their lessons, supportive and practical help is needed. This issue of The Science Teacher is dedicated to examples of inquiry in the science classroom. We
have illustrated four possible trajectories for inquiry that can serve as guides for science teachers to integrate these inquiry activities into their classroom. With this article, we hope to instill in science teachers the confidence to open the lines of inquiry for their students, so that students have the opportunity to experience scientific intrigue.

References

Wink, Gislason & Kuehn, (2005), *Working with Chemistry: A Laboratory Inquiry Program*, W.H. Freeman: New York,
## Appendix 3 – List of Laboratory Experiments Used to Establish Inter-rater Reliability

### Source
1. **Inquiries into Chemistry**
   - 1. Spectral analysis for Cu\(^{2+}\) (aq)
   - 11. Bleach and bromocresol green
   - 17. Gas volume and temperature relationships
   - 8. Introduction – Acid Base systems
   - 12. Introduction – Mass relationship systems
   - 22. Introduction – Kinetics systems

2. **Laboratory Inquiry in Chemistry**
   - 2. What’s in the Flask?
   - 3. Are pollutant gases harmful to plant life?
   - 7. How much gas is produced?
   - 9. What is the rate law?
   - 15. What is the pH of the soil?
   - 24. How much cobalt is in the soil?

3. **Working with Chemistry: A Laboratory Inquiry Program**
   - 5. Experiment Group D – Spectrophotometry of Dyes
   - 13. Experiment Group F – Analysis of an Antacid
   - 20. Experiment Group G – Stabilization of pH with Buffers
   - 6. Experiment Group D – Total Serum Iron Assay
   - 14. Experiment Group F – Tree Leaves and the Global Carbon Cycle
   - 16. Experiment Group J – Control of Temperature in Chemical Reactions

4. **Journal of Chemical Education Organic Experiments**
   - 4. Thermal Degradation and Identification of Heat-Sensitive Polymers
   - 23. The Addition of Bromine to 1,2-Diphenylethene
   - 26. Inquiry-Based Approach to a Carbohydrate Analysis Experiment

### Description
- Guided Inquiry
- Open Inquiry
- No Stratification
- Skill Building
- Application
- Keyword: Inquiry
<table>
<thead>
<tr>
<th>Source</th>
<th>#</th>
<th>Title of Experiment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>27</td>
<td>Epoxide Chemistry: Guided Inquiry Experiment Emphasizing Structure Determination and Mechanism</td>
<td></td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>Diastereoselective Synthesis of (+/-)-1,2-Diphenyl-1,2-propanediol</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Generation, Isolation, and Characterization of a Stable Enol from Grignard Addition to a Bis-Ester</td>
<td></td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>Acid-Catalyzed Isomerization of Carvone to Carvacrol</td>
<td>No Inquiry Keyword</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>A Microwave-Assisted Reduction of Cyclohexanone using Solid-State-Supported Sodium Borohydride</td>
<td></td>
</tr>
</tbody>
</table>
Appendix 4 – Template for Innovator Email Invitation

Dear ___________,

We are writing to invite you to participate in an NSF-funded research project about learning in the undergraduate chemistry laboratory. We are contacting you due to your department’s implementation of innovative methods for teaching in the chemistry laboratory.

[Insert specific comments here.]

We plan to interview chemistry faculty across the U.S. who are implementing innovations in the chemistry laboratory. The purpose of this study is to investigate the diversity of faculty goals for the undergraduate chemistry laboratory, the array of strategies used to teach in the laboratory, and the assessments faculty utilize to measure the extent to which they meet their goals. We are very interested in your perspectives on the undergraduate chemistry laboratory.

We would like to conduct a telephone interview with you which will last approximately 45 minutes. We ask that you carefully consider this opportunity to participate in our research. You and your department were specifically selected as an exemplary program for this research. If you feel that one of your colleagues in your department would be better suited to talk with us, we would very much appreciate your referral of that colleague’s name.

Attached is the informed consent waiver that research participants are required to sign; additional information is included therein. Please print one copy, sign it, and return via fax. We welcome any questions you might have regarding this study.

We respectfully request notification of your acceptance or decline of this invitation at your earliest convenience, but by no later than December 4, 2006. Should you accept our invitation to participate in this research project, we will contact you via email to schedule a mutually convenient time for the phone interview to take place.

Thank you for your consideration.

Sincerely,

Principal Investigator:  
Stacey Lowery Bretz, Professor  
Department of Chemistry & Biochemistry  
Miami University  
FAX: 513-529-3731  
bretzsl@muohio.edu, 513-529-3731  
Fax: 513-529-5715

Co-Principal Investigator:  
Marcy Hamby Towns, Professor  
Department of Chemistry  
Purdue University  
mtowns@purdue.edu, 765-496-1574  
Fax: 765-494-0239
Appendix 5 – Template for Status Quo Email Invitation

We are writing to invite you to participate in an NSF-funded research project about learning in the undergraduate chemistry laboratory. We are contacting you as the Chair of the Chemistry Department at ___________________.

We plan to interview chemistry faculty across the U.S. who are involved with organizing the chemistry laboratory curriculum. The purpose of this study is to investigate the diversity of faculty goals for the undergraduate chemistry laboratory, the array of strategies used to teach in the laboratory, and the assessments faculty utilize to measure the extent to which they meet their goals. We are very interested in your perspectives on the undergraduate chemistry laboratory.

We would like to conduct a telephone interview with you which will last approximately 45 minutes. We ask that you carefully consider this opportunity to participate in our research. If you feel that one of your faculty colleagues in the department would be better suited to talk with us, we would very much appreciate your referral of that colleague's name and contact information. (Please note that we wish to interview only full-time faculty, not part-time, adjunct, or laboratory prep staff.)

Attached is a document file containing the informed consent waiver that research participants are required to sign; additional information is included therein. Should you agree to participate in this study, and we hope you will, please print one copy, sign it, and return via fax to 513-529-5715. We welcome any questions you might have regarding this study.

We respectfully request notification of your acceptance or decline of this invitation at your earliest possible convenience. Should you accept our invitation to participate in this research project, we will contact you via email to schedule a mutually convenient time for the phone interview.

Thank you for your consideration.
Sincerely,

Michael Fay, Graduate Associate
Stacey Lowery Bretz, Professor & Principal Investigator
Department of Chemistry & Biochemistry
Miami University
bretzsl@muohio.edu, 513-529-3731
Fax: 513-529-5715

Marcy Hamby Towns, Professor & Co-Principal Investigator
Department of Chemistry
Purdue University
mtowns@purdue.edu, 765-496-1574
Fax: 765-494-0239
Appendix 6 – Informed Consent

Consent to Participate in Research Study

The purpose of this study is to investigate the diversity of faculty goals for undergraduate chemistry laboratory, the array of strategies used to teach in laboratory, and the assessments faculty utilize to measure the extent to which faculty meet their goals.

I understand that I will be asked questions about myself, my teaching, and my department and university. If I wish I may see a copy of the interview questions before I decide to participate. I give my permission for the interview to be tape recorded and transcribed. I understand that the purpose of the tape recording is to assure that what I say is represented accurately in the research process. The transcriptions will be stored on the researchers’ computers and backed up on zip disks or memory sticks. I understand that the researchers may use these files as sound bytes or quotes for presentations. The audio/video recordings will be stored in a locked faculty office until 2010, at which time they will be destroyed.

I understand that I will be asked to submit copies of all laboratory materials (syllabi, lab manual, instructors’ notes, etc.) used in the courses discussed during the interview. The time required to complete the interview and gather these laboratory materials will be less than 90 minutes.

I understand that my participation in this study is completely voluntary and that I can withdraw at any time. I can refuse to answer specific questions at any time. If I withdraw from the study, the information I have given up to the time of my withdrawal will be retained for the study unless I request that it not be used. The foreseeable risks or ill effects from participating in this study are minimal, if not non-existent.

I understand that my responses to the interview questions will be kept confidential and my name will not appear on any of the study documents or in the final report. I understand that only group results will be reported. Only the researchers will know how I answer the questions. The information I provide may be used for additional research or publications, but because my name is not used, my identity will be protected.

If I have questions about my rights as a human subject, I should contact the Miami University Office for the Advancement of Research and Scholarship, Oxford, OH 45056 (513-529-3734) or humansubjects@muohio.edu.

I ____________________________, agree to participate in this research project entitled, “Mapping the Dimensions of the Undergraduate Chemistry Laboratory: Faculty Perspectives on Curriculum, Pedagogy, and Assessment.” I have had the study explained to me and my questions
have been answered to my satisfaction. I have read this description of this project and hereby give my consent to participate. I understand that I will receive a copy of this informed consent form to keep for future reference.

<table>
<thead>
<tr>
<th>Participant’s Signature</th>
<th>Date</th>
</tr>
</thead>
</table>

Principal Investigator:
Stacey Lowery Bretz, Professor
Michael Fay, Graduate Assistant
Department of Chemistry & Biochemistry
Miami University
bretzsl@muohio.edu, 513-529-3731
Fax: 513-529-5715

Co-Principal Investigator:
Marcy Hamby Towns, Professor
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Purdue University
mtowns@purdue.edu, 765-496-1574
Fax: 765-494-0239
Appendix 7 – Interview Protocol for Innovators

Mapping the Dimensions of the Undergraduate Chemistry Laboratory: Faculty Perspectives on Curriculum, Pedagogy, and Assessment

Dr. Stacey Lowery Bretz, Miami University, Dept. of Chemistry and Biochemistry
in collaboration with
Dr. Marcy Hamby Towns, Purdue University, Dept. of Chemistry

Interview Protocol for CCLI Grant

1. What type of institution do you currently work at? (Research I, mid-level, primarily undergraduate, public, private, liberal arts, etc.)

   Follow-ups:
   ▪ How many students are enrolled in general chemistry?
   ▪ How many students are chemistry majors? (ACS accredited? Biochem ACS, or other ACS accreditation?)

2. Describe the class in which you direct or contribute to the development of the laboratory curriculum.

   Follow-ups:
   ▪ How many faculty teach the lecture portion of this course? Are they all tenured or tenure track? (how many tenured, tenure-track, and/or contract)
   ▪ How many faculty have decision making power or influence over the laboratory curriculum? How does this collaboration take place?
   ▪ How is the laboratory curriculum communicated to the faculty at your institution?
   ▪ Is this course required for chemistry majors at your institution?
   ▪ How many credit hours is the laboratory portion of this course worth?

3. Describe the goals that you consider for a laboratory course. (student careers, skills, concepts, connections to real world, scientific writing, etc.)

   Follow-ups:
   ▪ Why have you chosen these goals?

4. Over the past five years, has the laboratory curriculum for this course changed? In what way? What prompted this change?

5. Describe exemplars of laboratories you really like, or dislike, which are used in this course.
Follow-ups:
- Why have you chosen these specific laboratories? (go one by one through them all for the entire laboratory curriculum)
- How do they meet your goals for the course/lab?
- What opportunities do students have to design their own data collection procedures or analysis?
- Is the data display/arrangement given to the student?
- Are the data analysis procedures given to the student or do they develop them on their own?
- How are the students directed towards the findings of the lab?
- Are the conclusions/findings apparent to the student before the laboratory is started?

6. In implementing these laboratories, what strategies do you use to ensure that the goals are met?

Follow-ups:
- Is a pre-laboratory presentation of some variety delivered to the students? Who delivers it (faculty member, staff, graduate student, undergraduate student, none, electronic)?
- Who directs the laboratory while it is taking place? (faculty member, staff, graduate student, undergraduate student, none)
- Are there interactions taking place to ensure that the goals of the laboratory are met? (student-student; student-faculty or TA) Describe some that you have seen (obtain exemplars).

7. What laboratory assessments do you use?

Follow-ups:
- What type of work are the students expected to turn in when a laboratory is completed?
- Who grades the artifacts/reports/laboratory notebooks that are turned in?
- What criteria do the graders use when evaluating student work? (specifics on writing, experimental procedures, data analysis, display of data, display of results, conclusions/findings)
- What features do the graders look for?
- How are the students informed of their grade or assessment?
- Do they know the grading criteria in advance? (Is it the overall score, or do they know the rubric for each section?)
- How rapidly is the assessment information conveyed to the students?

8. In terms of assessments, how do you ensure that your laboratory goals for this course are met?

Follow-ups:
- What involvement do you have in reviewing student work from the laboratory portion of the course?
Is the laboratory curriculum improved or augmented based upon student assessments? How? Can you provide examples?

9. In a more general way, what do you intend for students to learn in a laboratory course at this, or any, level of chemistry?

Follow-ups:
- What learning outcomes do you think are most important? Why?
- What should students take away from their undergraduate laboratory experiences?
- What do you expect students to retain after taking laboratory courses? (skills, concepts, etc.)
Appendix 8 – Interview Protocol for Status Quo Participants

Mapping the Dimensions of the Undergraduate Chemistry Laboratory: Faculty Perspectives on Curriculum, Pedagogy, and Assessment

Dr. Stacey Lowery Bretz, Miami University, Dept. of Chemistry and Biochemistry
in collaboration with
Dr. Marcy Hamby Towns, Purdue University, Dept. of Chemistry

Interview Protocol for CCLI Grant

1. How would you describe the type of institution do you currently work at? (Research I, mid-level, primarily undergraduate, public, private, liberal arts, etc.)

   Follow-ups:
   a. How many students are enrolled in general chemistry?
   b. How many students are chemistry majors? (ACS accredited? Biochem ACS, or other ACS accreditation?)

2. How would you characterize the chemistry lab curriculum in terms of change over the last 5-10 years?

   Follow-ups:
   b. What factors contribute to that constancy?
   c. What factors led to changes?

3. Describe the class in which you direct or contribute to the development of the laboratory curriculum.

   Follow-ups:
   a. How many faculty teach the lecture portion of this course? Are they all tenured or tenure track? (how many tenured, tenure-track, and/or contract)
   b. How many faculty have decision making power or influence over the laboratory curriculum? How does this collaboration take place?
   c. How is the laboratory curriculum communicated to the faculty at your institution?
   d. Is this course required for chemistry majors at your institution?
   e. How many credit hours is the laboratory portion of this course worth?

4. Describe the goals that you consider for a laboratory course. (student careers, skills, concepts, connections to real world, scientific writing, etc.)

   Follow-ups:
a. Why have you chosen these goals?

5. Over the past five years, has the laboratory curriculum for this course changed? In what way? What prompted this change?

6. Describe exemplars of laboratories you really like, or dislike, which are used in this course.

Follow-ups:
   a. Why have you chosen these specific laboratories?
   b. How do they meet your goals for the course/lab?
   c. What opportunities do students have to design their own data collection procedures or analysis?
   d. Is the data display/arrangement given to the student?
   e. Are the data analysis procedures given to the student or do they develop them on their own?
   f. How are the students directed towards the findings of the lab?
   g. Are the conclusions/findings apparent to the student before the laboratory is started?

7. In implementing these laboratories, what strategies do you use to ensure that the goals are met?

Follow-ups:
   a. Is a pre-laboratory presentation of some variety delivered to the students? Who delivers it (faculty member, staff, graduate student, undergraduate student, none, electronic)?
   b. Who directs the laboratory while it is taking place? (faculty member, staff, graduate student, undergraduate student, none)
   c. Are there interactions taking place to ensure that the goals of the laboratory are met? (student-student; student-faculty or TA) Describe some that you have seen (obtain exemplars).

8. What laboratory assessments do you use?

Follow-ups:
   a. What type of work are the students expected to turn in when a laboratory is completed?
   b. Who grades the artifacts/reports/laboratory notebooks that are turned in?
   c. What criteria do the graders use when evaluating student work? (specifics on writing, experimental procedures, data analysis, display of data, display of results, conclusions/findings)
   d. What features do the graders look for?
   e. How are the students informed of their grade or assessment?
   f. Do they know the grading criteria in advance? (Is it the overall score, or do they know the rubric for each section?)
g. How rapidly is the assessment information conveyed to the students?

9. In terms of assessments, how do you ensure that your laboratory goals for this course are met?

Follow-ups:
   a. What involvement do you have in reviewing student work from the laboratory portion of the course?
   b. Is the laboratory curriculum improved or augmented based upon student assessments? How? Can you provide examples?

10. In a more general way, what do you intend for students to learn in a laboratory course at this, or any, level of chemistry?

Follow-ups:
   a. What learning outcomes do you think are most important? Why?
   b. What should students take away from their undergraduate laboratory experiences?
   c. What do you expect students to retain after taking laboratory courses? (skills, concepts, etc.)