THE STUDENT EXPERIENCE IN

TRADITIONAL AND INQUIRY-BASED CHEMISTRY LABS

by

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ABSTRACT

This project introduced two inquiry-based labs to an existing sequence of traditional labs in a sophomore chemistry class. The student experience in both types of lab instruction was examined through surveys, interviews, misconception probes, pre- and post-lab content quizzes, and student-teacher communication logs. It was found that both types of lab instruction had strengths and potential weakness, which indicate areas that require particular attention when using each instructional method.

INTRODUCTION AND BACKGROUND

Project Background

School Demographics and Culture

I teach at The Thacher School, an independent co-educational boarding school in Ojai, California. It is a small school with 245 students in 9th through 12th grades, nearly all of whom live on campus. Our student body is composed of students from across the United States and a variety of other countries. Ethnic diversity is self-reported by the students, and 36% of the student body self-indentifies as “students of color.” Thacher is a highly selective, rigorous college preparatory school. The admissions office reports that 20% of the 450 applicants are accepted each year, and of those accepted, 80% choose to attend the school. While the majority of our students come from economically privileged families, 32% of the student body receives financial aid. A number of the recipients of financial aid receive significant support in order to attend the school (McMahon, 2010).

In addition to academics, the school places great value on spending time in the outdoors—predominantly on horseback or backpacking. Each freshman is assigned a horse to care for and ride throughout the year. Twice during the year, the entire school participates in weeklong wilderness backpacking or horse camping trips lead by faculty members. After freshmen year, students may choose to ride a horse in the afternoons or participate on a number of athletic teams or activities; students are required to participate in a formal afternoon activity each season. In addition to after school activities, our students are rather active with nightly study hall, formal sit-down dinners four nights a week, and a number of club and community service opportunities.

Teaching Experience and Classroom Environment

In addition to other teaching, coaching, and dorm responsibilities, I teach two sections of introductory sophomore chemistry. Chemistry is a required, yearlong class at Thacher, and students are placed into either the honors or the regular sections based on their performance in freshman physics and math courses. This is my fifth year teaching at Thacher and my tenth year as a science teacher. Throughout my teaching career, I have witnessed students struggle to complete lab activities and write effective lab reports. Students consistently need significant assistance in laboratory investigations and find writing lab reports challenging and frustrating. Previously, I followed a pre-existing lab sequence that was in use in the schools where I have taught. While these lab sequences were helpful to me as a new teacher, I was frustrated with the disconnect between the higher level thinking that I intended labs to inspire and lower level skills that labs seemed to reinforced in the students.

Focus Question

My teaching experience and student observations influenced my primary focus question: How do traditional and inquiry-based methods of instruction shape the student experience in an introductory chemistry laboratory setting? I examined multiple aspects of the student lab experience that were addressed by the following sub-questions:

- How did both methods of lab instruction affect student confidence about their ability to complete labs and the level of independence in their work?
- How did both methods of lab instruction affect retention of chemistry concepts used in the lab?

- How did both methods of lab instruction affect students' ability to apply problem-solving skills to novel situations?
- How did both methods of lab instruction affect student interest in and engagement with chemistry topics?

CONCEPTUAL FRAMEWORK

Laboratory activities have been a part of science education since the contribution of German chemist Justus van Liebig to American science instruction in the 1880's. Early on, laboratory activities had the goal of preparing high school students for the study of sciences as undergraduates. Specific areas of content were deemed necessary in preparation for such study, and the laboratory was used to teach this content, along with laboratory skills (Singer, Hilton, & Schweingruber, 2006). Establishing and following a set of prescribed labs became the focus of laboratory work, and it was assumed that exposure to the concepts and experiences would guarantee student learning (Rudolph, 2005). After 1955, there was a shift in lab instruction where the lab activities were no longer separate from classroom instruction, but instead unified in an integrated approach to the content. In addition, labs were seen as an area in which students could experience what it was like to be a scientist by following the scientific method and using higher level cognitive skills rather than focusing on memorizing facts and lab techniques (Shymansky, Kyle, & Alport, 1983). In 1962 the concept of inquiry in laboratory instruction was introduced (Schwab, 1962).

The National Research Council (1996) redefined and highlighted the importance of inquiry in the *National Science Education Standards*. This work called for a shift in the focus of science education. Some changes that were stated included the following:

covering fewer concepts with more in-depth attention, replacing activities in which students strive to find a given answer to ones in which students use and develop their own explanations based on collected evidence, moving away from a focus on factual information and toward "understanding scientific concepts and developing abilities of inquiry" (National Research Council, 1996, p.113). Sutman, Schmuckler, Hilosky, Priestley, and Priestley (1996) reported that there was a lack of integration of laboratory and classroom activities in science courses at the high school and college level. In these labs, student and instructor energies were focused on following the procedural steps, which were typically not discussed or directly related to material from class. After the lab, time was not allocated for student discussion or exploration beyond the scope of the procedure. Singer et al. (2006) suggested that the structure of current laboratory instruction remains very much the same as it was in 1996.

In the current science laboratory there are various methods of instruction, which have been outlined and compared in a number of papers. The current role of the laboratory is still hotly debated given that there is little agreement among teachers, educational governing bodies, and education researchers about the goals of laboratory instruction and the best means for achieving those goals (Singer et al., 2006).

Laboratory activities in which the teacher provides very specific guidelines in the form of a set of procedural steps that students are expected to follow in order to obtain a predetermined result are expository in form (Domin, 1999b). Expository activities are classified as deductive in nature, because the teacher introduces a concept and students review this concept through repetition and application (Domin, 2007; Prince & Felder, 2006). While this instructional style differs little from the standard prior to 1955, it remains the most popular means of current laboratory instruction (Abraham et al., 1997; Domin; Singer et al., 2006). Abraham et al. (1997) reported that out of 203 of colleges surveyed, only 8% used inquiry based laboratories, and student survey responses reported that 91% of the time they followed "step-by-step instructions from the laboratory guide" (p. 593). Deters (2006) reported that 44.5% (*N*=571) of introductory chemistry teachers at the high school level reported on a survey that they do not use any inquiry based activities throughout the school year. For this survey, inquiry activities were loosely defined as any lab in which students produced the procedure. Of the 55.5% of teachers who did use inquiry, the average number of inquiry activities per semester was 3.3. The same group responded they used an average of 11.3 traditional labs per semester, which displays the preference for traditional labs over inquiry labs in the respondents (Deters, 2006).

In another study, Domin (1999a) used Bloom's taxonomy as a lens for examining the cognitive processes addressed by eleven general chemistry laboratory manuals. Domin found that the majority of these manuals only called upon lower level cognitive processes from Bloom's taxonomy including knowledge, comprehension, and application. These expository laboratories were frequently called *cookbook* labs because the teacher provided the students with a set list of instructions in the procedure, the goal of the lab was predetermined, and the labs served to confirm what students already knew about a topic (Llewellyn, 2005). These traditional cookbook labs were criticized because they did not require students to exercise higher levels of cognitive processes, critical thought, or allow for creative problem-solving (Monteyne & Cracolice, 2004; Gallet, 1998; Dinan, 2005; Prince & Felder, 2007). Gallet argued that students who had no conceptual understanding of the related material could successfully complete cookbook laboratories. Based on data from student surveys, Cooper and Kerns (2006) categorized the level of student involvement in a “conventional style laboratory” as “very passive…basically [their role was] to listen, watch, and learn” (p. 1360).

There are benefits to be gained by students performing expository laboratories, such as developing basic laboratory manipulation skills and reinforcing conceptual understanding. It has been argued that cookbook labs provide the necessary structure for this foundational learning (Ault, 2002; Horowitz, 2008). Ault proposed that students require procedures to serve as scaffolding upon which learning can be supported and from which students can branch out and make modifications. He used the cookbook comparison to strengthen his point, noting that students might display similar creativity in lab as they do when they deviate from a recipe when the required ingredients are missing or when their confidence and creativity inspires improvisation (Ault, 2002). There were a number of direct and indirect responses to Ault’s claims that provided a great deal of criticism of expository methods of lab instruction and offered alternative means of instruction. Domin (2007) reflected on the student experience in *cookbook* labs and noted that while the skills required to complete the lab required “low levels of cognitive engagement” (p.149), the more complex thinking occurred outside of the lab as long as the students were required to reflect upon their lab activity.

Inductive methods of instruction provide an alternative to expository instruction. Prince and Felder (2007) described inductive methods as those “in which the instructor begins by presenting students with a specific challenge, such as experimental data to interpret, a case study to analyze, or a complex real-world problem to solve” (p. 14).

"Inquiry-based learning, problem-based learning, project-based learning, and case-based teaching" (Prince & Felder, 2007, p. 14) are all methods that fall under the umbrella term of inductive learning. A variety of studies have shown that specific inductive methods were more effective than expository methods at addressing higher level cognitive processes, problem solving, engagement with and ownership of the material, creativity, and laboratory skills (Cooper & Kerns, 2006; Dinan, 2005; Domin, 1999a; Gallet, 1998; Oliver-Hoyo et al., 2004; Prince & Felder, 2006).

Despite these key advantages in student learning, there are barriers to implementing inductive methods. Methods of inductive instruction take more time to prepare and complete in comparison to expository laboratories (Prince & Felder, 2007). Oliver-Hoyo et al. (2004) noted that inquiry-guided instruction required that less content be covered in comparison to similar courses that used traditional or expository laboratory instruction. Given the amount of interaction needed between instructor and students, inductive styles required small class sizes (Prince & Felder). Gallet (1998) noted that the Problem-Solving Teaching approach to lab instruction was much more labor intensive and expensive as students could explore a number of different approaches and were more likely to make mistakes and consume more materials. Inquiry-guided instruction can also be met with student resistance (Domin, 1999b; Gallet; Oliver-Hoyo et al., 2004; Prince & Felder). This student based resistance was often because the desired result was not identified by the instructor, the path to be taken in pursuit of the answer was not clear, and the method of instruction was not familiar to the students (Oliver-Hoyo et al., 2004). Kelly and Finlayson (2008) noted that students who lack prior experience with the subject were more resistant to nontraditional lab methods in comparison to students who had previous experience studying the topic.

Despite the frustration that students experienced, there was evidence of positive effects on student attitude in response to inductive teaching methods (Prince & Felder, 2007). Students were frustrated, found the work challenging and time consuming, but "for the most part, believed that their hard work paid off…they also acknowledged that this [method of instruction] was part of why they learned more" (Oliver-Hoyo et al., 2004, p. 24). During the process of a problem based lab students were "at some point in the lab, in a state of cognitive dissonance which they had to think through to reestablish cognitive equilibrium" (Domin, 2007, p.149). Domin (1999) noted that students took greater ownership for their work in inquiry-guided instruction based laboratory work than they did of expository laboratories. Cooper and Kerns (2006) reported that students developed increased independence, empowerment, and confidence once they adjusted to the new project-based method of laboratory instruction. Dinan (2002, 2005) made note of improved student engagement with topics, class attendance, and retention of content in case-study-based and problem-based team learning laboratories.

Whatever the instruction style, it has been clearly documented that students enjoy taking part in the lab experience and identify the laboratory component as one of the best parts of their science courses (Gabel, 1999; Hofstein & Lunetta, 1982, 2004). While the debate about the best method of instruction continues, it will be important that research determines if the goals of lab instructors match the outcomes of student learning (Hofstein & Lunetta, 2004). Numerous studies have compared traditional expository labs to alternative curricula. Cacciatore and Sevian (2009) addressed the question of whether incremental implementation of one inquiry-based laboratory provided similar benefits for student learning as the adoption of an entirely inquiry-based curriculum has shown in previous studies. In the implementation of one inquiry-based chemistry lab, Cacciatore and Sevian observed a noticeable shift towards improved student engagement with the material, higher level thinking in the laboratory, and evidence of improved content retention. Cacciatore and Sevian also noted the scarcity of research that focuses on the effects of small-scale implementation of inquiry-based laboratories, indicating that this is an aspect of educational research that deserves more attention.

Domin (2007) suggested that the majority of these comparative studies set out with the predetermined goal of finding one method superior to the other. By categorizing labs in a more flexible way Domin (1999b) took into account the approach (inductive or deductive), the procedure (student or teacher created), and the outcome (predetermined or not) of each. Domin (2007) also suggested that by expanding the two categories and describing methods of lab instruction in a more complete manner, perhaps it would be recognized “that the different styles possess their own unique strengths and weaknesses and constrain the learning environment in different ways” (p. 143). Domin (2007) highlighted the benefits and limitations of expository and problem-based labs and concluded that both have the potential to engage students. The difference in student experience using these methods was whether they are engaged while they collaborated with their classmates in a problem-based lab or if it was during the reflection that came after an expository lab, while they wrote up a lab report (Domin, 2007).

METHODOLOGY

Two inquiry-based laboratory activities were compared to two traditional laboratories during the course of a yearlong sophomore chemistry class. Because I teach at a boarding school, the Head of School, who acts *in loco parentis* for the students during the school year, signed the Exception Regarding Informed Consent form (Appendix A) for all participants. The research methodology for this project received an exemption by Montana State University's Institutional Review Board, and compliance for working with human subjects was maintained. Students performed traditional laboratories following predetermined procedures from the Reaction of Solid Copper and Aqueous Silver Nitrate Handout (Appendix B) and the Exploring the Properties of Gases Handout (Appendix C). Inquiry-based laboratories were assessed based on responses to provided questions, student designed procedures, and other reflections on observations from the Air Bags Challenge Handout (Appendix D) and the Rate of Evaporation Lab Handout (Appendix E). The four labs were administered in the order presented here.

When we began the first of the two inquiry-based labs, I explained some basic differences between traditional and inquiry based labs to my students. In the previous years, my students have expressed frustration when faced with inquiry-based approaches or anxiety in reaction to this approach. I warned both classes that I expected them to be frustrated at points during the lab, but that they had the information they needed, were up for the challenge, and would all be successful in the end after working together as a group. I also encouraged them to use me as a reference, explaining that often times my answers would be in the form of questions that would lead them in the right direction, rather than just provide answers. In all cases, the laboratory activities were completed by students working in groups of two or three and were conceptually integrated into the course curriculum.

Each lab was examined in the same manner in order to assess the following components of the student experience: retention of content, confidence and independence in lab, problem solving ability and interpretation of novel scenarios, and engagement with and interest in chemistry topics. Content Quizzes were administered before and after each lab (Appendices F, G, H, and I). Comparisons of performance on the Lab Content Quizzes before and after each lab were made using the average normalized gain (g) as described by Hake (1998). Hake defined the average normalized gain as the "ratio of the actual average gain (%{post}-%{pre}) to the maximum possible average gain (100-%{pre})" (p. 64). This method of comparison focused on changes in percentage of points earned in the context of number of points missed; changes in percentages are normalized according to the possible level of improvement for each question. The calculated gain values fell into one of three categories: "high-g" was defined as any value greater than or equal to 0.7, "medium-g" was assigned to values less than 0.7 and greater than or equal to 0.3, and "low-g" values were less than 0.3 (Hake, p. 65).

The Lab 1 Content Quiz was a bit too ambitious, took the students much longer than I had planned, and created quite a bit of unintentional student anxiety. In response, each subsequent Content Quiz was a bit more streamlined in order to minimize student frustration and maintain student cooperation throughout the project. These Content Quizzes included three sections: content questions, chemistry application questions, and misconception probes.

Content questions on the quizzes were of two different types. First were questions that mimicked the calculations used directly in lab, and second were questions that required students to apply previously learned concepts in novel ways. For each of the four labs, the questions on the Content Quizzes tested the same calculations, using different numbers in the problems before and after each lab. Normalized gains in average student scores on the individual Content Quizzes questions were used to compare the level of retention of material and response to novel questions between the two methods of lab instruction.

Misconception probes on the Content Quizzes were used before and after each lab to assess students' abilities to interpret concepts in novel situations. Student responses to the misconception probes were graded for percent of correct responses and individual explanations were coded to quantify the level of comprehension in each response. Results of administering the misconception probes, before and after each lab, were used to discern any improvement in the overall number of students who could answer the probe correctly and in an individual student's ability to explain answers. The levels of improvement made in each method of lab instruction were compared to determine the impact of each method on student ability to interpret misconception probes.

Chemistry application questions were used before and after each lab to assess the level of student engagement with the concepts. Responses to these questions were scored based on whether the application was correct, the complexity of thought was expressed, and the degree to which student responses showed connection to the content. The normalized gains in average scores from before and after each lab were compared to measure any changes in student engagement with the material. Normalized gains were compared between both methods of lab instruction to determine the impact of each method on student engagement with and interest in chemistry topics.

Lab Inspired Test Questions, which were included on the unit tests associated with each lab, assessed conceptual and problem-solving ability for related topics (Appendix J). These questions also assessed student ability to retain concepts from lab when they were presented on unit tests. The average student scores on the Lab Inspired Test Questions were used to compare levels of retention of material between both methods of lab instruction.

Student confidence in their lab abilities, their perceptions of independence in lab, and level of engagement with the material were measured using the Student Confidence and Attitude Survey after each lab (Appendix K). These surveys were administered via www.surveymonkey.com, and each student completed the survey in class immediately after handing in each completed lab report. Comparisons were made between both methods of lab instruction to determine the differences in student confidence about and attitude towards each lab.

At three times during the project, I selected a sub-set of six different students for interviews. These students represented the full spectrum of achievement in the course. I selected the individuals by ranking the students based on their numerical average in the course, divided the class into thirds based on these rankings, and used a random number generator to select two students from each achievement-based group. Students were interviewed after both traditional labs were completed and a different group of students were interviewed after both inquiry labs were completed. This process addressed the student lab experience through the Student Confidence and Attitude Post-lab Interviews

(Appendix L). After all four labs, I selected another sub-set of six students in the same manner and interviewed them using the Comparative Interview: Student Reflections on Inquiry and Traditional Labs (Appendix M). These interview data were used as qualitative evidence to expand upon the Student Confidence and Attitude Post-lab Surveys. Due to logistics with student availability, one of the six students selected was unable to attend for all three interviews conducted, so five students were interviewed each time.

The level of student independence and confidence in their abilities was also assessed using the Student-Teacher Lab Communication Log (Appendix N). I carried an iPad, used the “voice recorder” app to record these conversations, and reviewed the recordings to further analyze the types of interactions that occurred in each of the four labs. Listening to the audio files, I used the Student-Teacher Communication Log to code each question according to one of five types. The Data Triangulation Matrix includes the focus question, sub-questions, and instruments used in this study (Table 1).

Table 1
Data Triangulation Matrix

Focus Question: How did traditional and inquiry-based methods of lab instruction affect the student experience in a laboratory setting?			
Sub-questions	Data Source		
Sub-question 1: How did both methods of lab instruction affect student confidence about their ability to complete labs and the level of independence in their work?	Student-Teacher Lab Communication Log	Student Confidence and Attitude Surveys (pre- and post-lab)	Student Confidence and Attitude Post-lab Interviews
Sub-question 2: How did both methods of lab instruction affect retention of chemistry concepts used in this lab?	Content Quizzes (pre- and post-lab)	Lab Inspired Test Questions	
Sub-question 3: How did both methods of lab instruction affect students' ability to apply problem solving skills to novel situations?	Content Quizzes (pre- and post-lab)	Lab Inspired Test Questions	Misconception Probes (pre- and post-lab)
Sub-question 4: How did both methods of lab instruction affect student interest in and engagement with chemistry topics?	Student Confidence and Attitude Surveys (pre- and post-lab)	Student Confidence and Attitude Post-lab Interviews	Chemistry Application Cards (pre- and post-lab)

DATA AND ANALYSIS

Student Confidence and Independence

Student confidence about their ability and the level of independence in lab work was assessed in a number of ways. Student-posed questions were tallied, recorded, and coded using the Student-Teacher Lab Communication Log (Appendix N). The average number of questions asked showed that the students asked more questions in inquiry-based labs than they did in traditional labs in study (Table 2).

Table 2
Summary of Student-Teacher Communication Log Data

Number of Questions Asked per Laboratory Type			
Traditional		Inquiry	
Silver Nitrate and Copper Lab	111	Air Bag Challenge Lab	155
Gas Laws Lab	76	Rate of Evaporation Lab	77
Average	94		116

If the Gas Laws and Rate of Evaporation Labs are compared directly, the number of student-posed questions was nearly identical. In this instance, results indicated that students looked for guidance, information, or support in traditional and inquiry-based labs with similar levels of frequency. There was also a greater range of student-posed questions (155, 77) in inquiry-based labs in comparison to traditional labs (111, 76). Because traditional labs followed a familiar pattern and the procedures for both traditional labs were more similar to each other than the inquiry-based labs, students varied less in the number of questions asked from one traditional lab to the next. More variation occurred between inquiry-based labs, which were less familiar in both pattern and process.

Despite a small variation in the number of student-posed questions, coding questions from the Student-Teacher Communication Log revealed a substantial difference in the types of questions asked during each method of lab instruction. The questions were coded according to one of six categories, spanning from the procedural to the conceptual, and percentages for each category were calculated for both traditional and inquiry-based labs (Figure 1).

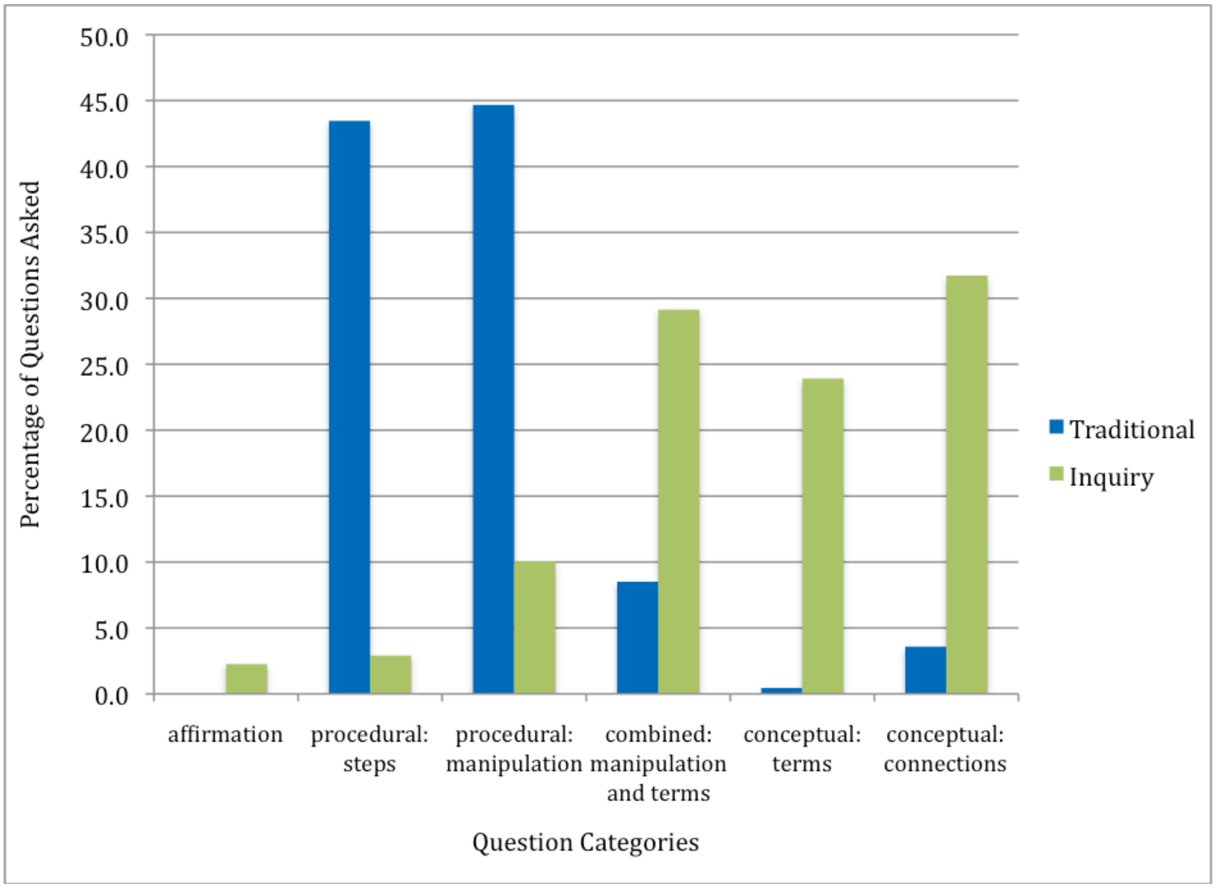

Figure 1. Percentage of questions observed in six categories for traditional (*N*=187) and inquiry-based labs (*N*=232). The question categories included: affirmation, procedural (steps or manipulation), conceptual (terms or connections), and a combination between manipulation and term-based conceptual questions.

Most questions posed in traditional labs (*N*=187, 88.2%) were assigned to the procedural categories; many sought clarification, such as the following question from the Reaction of Aqueous Silver Nitrate and Solid Copper Lab, *Student:* It says rinse the beaker three times and...then it says transfer the rinses into the test tube, but that doesn't seem to make sense because the test tube's not big enough, right?

Teacher: A rinse doesn't mean fill it to the top and then pour it. A rinse [means] use as little as you can, rinse all the edges, [and pour that into the test tube].

These procedural questions, and their requisite answers, tended to be short in duration and finite in scope because of the close-ended nature of the question.

In contrast, the majority of questions posed during inquiry-based labs (*N*=232, 85%) were conceptual in nature or ones that connected conceptual understanding to the manipulation of lab materials. The questions asked in inquiry-based labs also tended to be more complex and open-ended, which in turn inspired more questions and collaboration within and between groups, such as this series of questions from the Air Bags Challenge Lab,

Student A: We're just generally confused at this point.

Teacher: Okay.

Student B: Because we did everything right, but we're getting small weird numbers...we got 0.00165 moles...and then...

Teacher: I would agree that you're doing everything right...it's just a conversion issue.

Student A: Can we even use this (points to calculations)?

Teacher: Yeah, I would start here (points to calculations). What's this 31? What's the unit on this number?

Student B: That's how much baking soda we need.

Student A: No that's the...

Student B: No that's how much milliliters...[sic]

Student C: Wait is that supposed to be *inches* of mercury? Wait, oh! Ms. Grant, is that supposed to be inches of Hg?

Teacher: Yup.

Student C: I was so confused! Oh! So one inch equals 25.4 millimeters. So we need to use that.

Student A: So we need to convert inches to millimeters.

Teacher: Yes. But your process is good besides that [conversion].

When interviewed about the experience in lab, another student reflected on how the question and answer process led to further discussions and discovery,

> In the inquiry labs...the fact that we weren't all asking the same questions and the fact that other people's questions were also benefiting us, helped a lot and...even though it seemed somewhat stressful, the uncertainty of it, it was more fun than it was uncertain and...that fun also helped us to grasp the material better. Or at least it helped me.

Overall, the Student-Teacher Communication Log data indicated that student ability and independence appeared similar based on the average number of questions in the two lab types, but results did display more independent thought in terms of the types of questions asked in inquiry-based labs.

Results obtained from the Student Confidence and Attitude Survey (Appendix K) data demonstrated the difference in students' confidence about their work in traditional and inquiry-based labs (Figure 2).

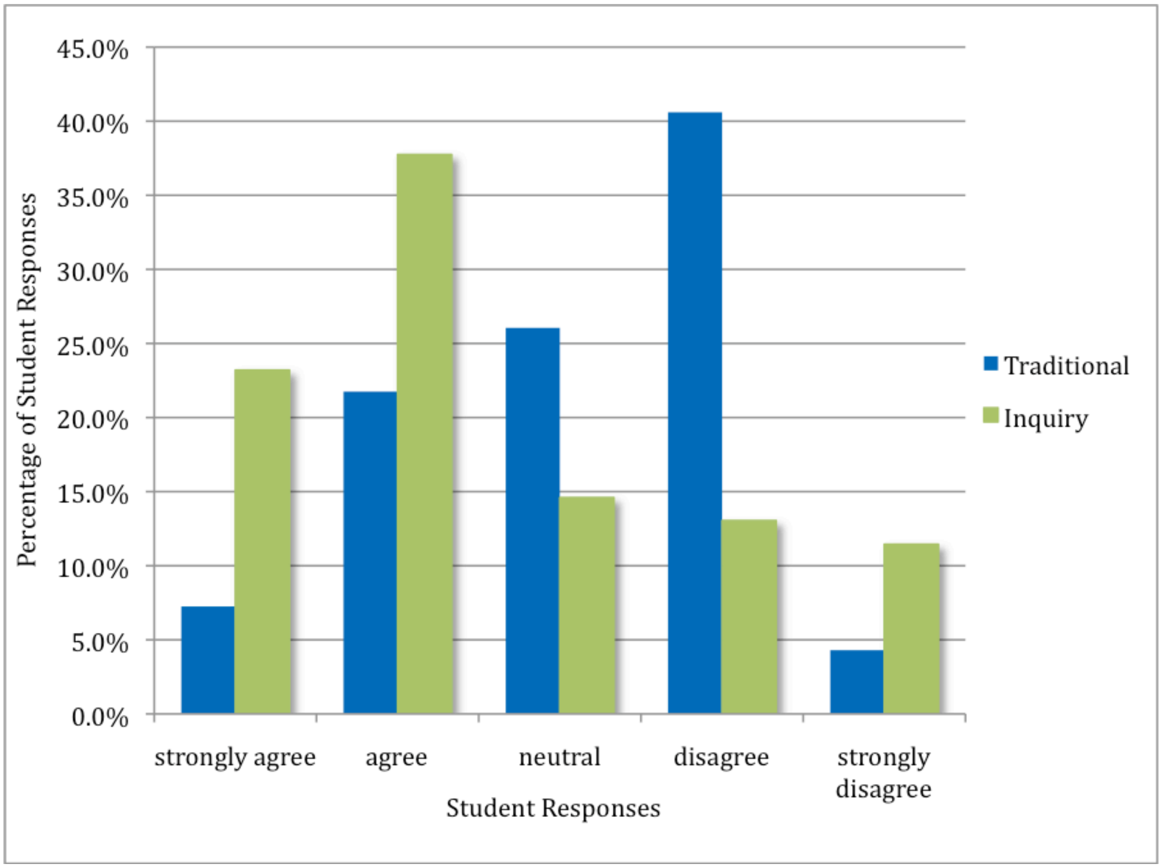

Figure 2. The percentage of student responses to the survey question "I was confident in my ability to successfully perform this lab activity independently, without assistance from my lab partner or the teacher." Responses from both traditional (*N*=69) and inquiry-based labs (*N*=69) were sorted according to categories from strongly agree to strongly disagree.

Students completing inquiry-based labs (*N*=69) were most likely to agree (37.8%) or strongly agree (23.2%) with the statement that they were "confident in [their] ability to successfully perform this lab activity independently, without assistance from [their] lab partner or the teacher." Students in traditional labs (*N*=69) were more likely to disagree (40.6%) or be neutral (26.1%) in response to the same statement. One student's description of what skills make a person successful in traditional labs, reflected this lower level of confidence in completing traditional labs,

> [you need the] ability to work with...your lab partners..., follow directions, because you can even not know the information all the way, but if you actually do the steps like you tell us to do [you'll be successful] and...listening to what you say at the beginning of the lab and then for like later on even just keeping good notes as you go [sic].

Another student's response about what makes a person successful in each type of lab provides a good contrast of the two types of lab. She said, "For the inquiry labs you kind of have to think outside of the box and you have your own steps, there's no set idea of what you should be doing as opposed to the traditional where you have every single step written out, you know what you're doing in the prelab, and for postlab."

From my observations of student behavior, traditional labs usually ended with students hurrying to finish the steps, obtaining the end result, and cleaning up lab areas hastily. In inquiry-based labs, there was more emotional investment in the material and process of learning. This emotional investment resulted in frustration for all groups at some point. In the Air Bag Challenge Lab, one student asked a general, "How do we do this?" type of question. When I wouldn't provide direct instruction, she responded "Ah, please tell me! I'm so bad at Chem." I reminded this student that inquiry-based labs were more challenging and frustrating because the steps weren't provided, but that was expected and okay. She responded with, "This really makes me like other labs we've done *a lot* more." However, in the end of an inquiry-based lab, it was common for students to express their feeling of satisfaction for accomplishing the task. Overall, inquiry-based labs may have called student confidence into question at points when frustrations ran high, but these experiences also led to a greater sense of accomplishment in the end than completing traditional labs. During interviews, one student reflected on her experience and the connection between confidence and independence in both types of labs. Her statements illustrated what the survey data displayed and what my observations noted, "Well, coming up with the experiment, what we were going to try, we had a basic idea, but then it got a little frustrating for a couple of minutes..., but after that, like I said, once we were performing the experiment, once we were done with it, it was really satisfying that we had done it, like, all by ourselves only using what we had learned in class." Another student compared the experience in traditional and inquiry-based labs by highlighting the skills needed to perform each successfully,

> [In traditional labs] it's really important to just be able to follow directions and then like towards the end you get the knowledge and stuff and you're able to understand it and that's all good. But with the inquiry ones, it's more you have to figure out by yourself so it's, I feel like the learning process happens in the middle. You know, as you're doing it. So it's more important to be able to just kind of figure it out and be able to adapt well—instead of just following directions—[based on] prior based on knowledge [sic].

Retention of Content

Evidence from the Lab Content Quizzes (Appendices F-I) administered before and after each lab and the Lab Inspired Test Questions (Appendix J) indicated that neither traditional nor inquiry based labs had a noticeable impact on student retention of content. Performance on the Lab Content Quizzes from before and after each showed that there were individual questions with notable improvement for each lab, but trends could not be identified for one type of lab or for a comparison between types. Four of the six content questions posed on the Lab Content Quizzes before and after traditional labs displayed high (0.75) or moderate (0.33, 0.35, 0.48) average normalized gain values, and one of the two content questions posed on the Lab Content Quizzes before and after inquiry-based labs displayed a moderate (g = 0.67) average normalized gain (Table 3).

Table 3
Results from Individual Questions on Lab Content Quizzes

	Questions from Lab Type				
Results	Traditional (Lab 1)	Traditional (Lab 1)	Traditional (Lab 2)	Traditional (Lab 2)	Inquiry (Lab 3)
pre-lab average	75.4 %	76.5 %	44.1 %	38.2 %	87.0 %
post-lab average	83.4 %	94.1 %	63.7 %	67.6 %	95.7 %
percent change	8.0 %	17.6 %	19.6 %	29.4 %	8.7 %
normalized gain	0.33	0.75	0.35	0.48	0.67

Despite these individual areas of improvement, other questions on Lab Content Quizzes showed meager or negative gains (losses, data not shown).

Following completion of traditional labs, most students (*N*=69) agreed (42.1%) or were neutral (37.6%) about the idea that labs helped them understand the theory covered in regular chemistry class (Figure 3).

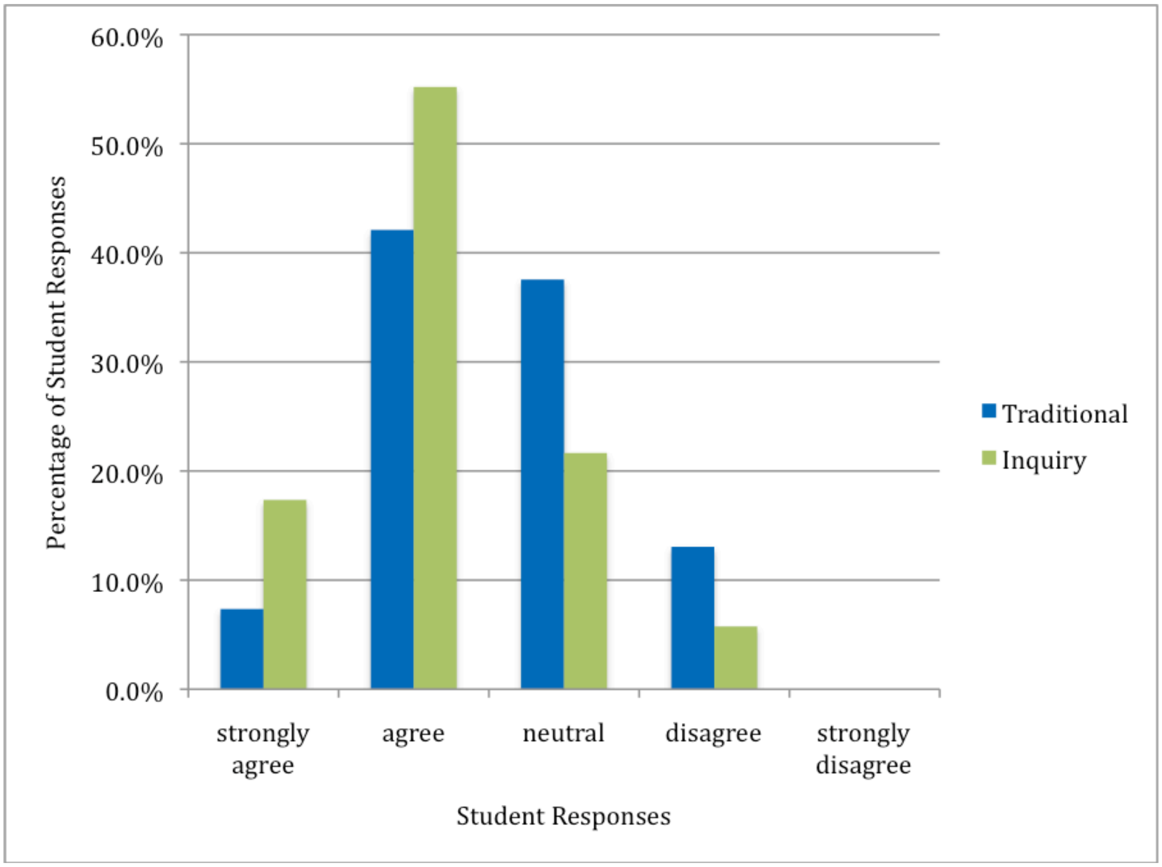

Figure 3. The percentage of student responses to the survey question, "What we did in lab helped me understand the theory covered in regular chemistry class." Responses from both traditional (*N*=69) and inquiry-based labs (*N*=69) were sorted according to categories from strongly agree to strongly disagree.

Student perception was a slightly more positive about the impact that inquiry-based labs had on their ability to understand material from class, compared to the impact of traditional labs. The majority of students (55.2%) agreed that inquiry labs helped them understand the material from class. When asked to explain this relationship in the interviews, students reflected that either the inquiry labs or both labs helped them remember the material, but none noted that traditional labs were instrumental in their understanding of the material.

Problem-Solving Skills

Evidence from the Lab Content Quizzes (Appendices F-I) administered before and after each lab and the Lab Inspired Test Questions (Appendix J) indicated that neither traditional nor inquiry based labs had a noticeable impact on student ability to interpret data and employ problem-solving skills in novel situations. One novel problem-solving question on the Lab 1 Content Quiz showed a moderate (0.35) average normalized gain. All other questions had low or even negative gains. Similar results were seen in response to the misconception probes on the Lab Content Quizzes. One probe yielded a moderate average normalized gain (0.33), but all of the other probes showed little improvement when the pre- and post-lab results were compared.

Interestingly, in a related observation, there were specific instances when students displayed mastery of the content in class before doing both inquiry-based labs. On the Lab 3 Content Quiz, a novel question was posed that required the same basic calculations that students would use to solve the Air Bag Challenge Lab. The average score on that question before completing the lab was 56%, which was much higher than I had anticipated given the challenging nature of the question and fact that the students had not previously been asked to solve problems of this type. They proposed the correct series of calculations to solve the question, integrating previous knowledge from stoichiometry into their more-immediately familiar use of the ideal gas law.

Prior to the Rate of Evaporation Lab, I had students brainstorm everything they knew or wanted to know about three topics: how evaporation works, how evaporation might be different for different substances, and what factors affect the rate of evaporation for a substance. Students brainstormed first in desk pairs and then we created one list for each class. Items on the brainstorming list indicated that my students were aware of everything I hoped this lab would cover, content wise, from the following inquiry-based lab. The brainstorming session produced correct and detailed information about the influence of intermolecular forces, molecular weight, kinetic energy, and temperature changes on evaporative processes. Yet, the students really struggled to apply that information in novel ways to tasks that required nearly the same calculations as in the Air Bag Challenge Lab, and struggled to develop a testable question and hypothesis about the content in the Rate of Evaporation Lab.

Interest in and Engagement with Chemistry

Originally, I anticipated being able to measure student engagement by their abilities to see chemistry in the "real world," yet data from the Chemistry Application Cards indicated that students really struggled with this task. Students were asked on each Content Quiz to provide up to three examples of real world applications, such as how gas laws applied to everyday life or what industries would be interested in limiting reactant calculations. During the administration of the Lab 1 Content Quiz, this "real-world" section caused some students so much anxiety that I observed a number of them staring at this section for up to ten of the twenty minutes allotted for the assignment. Other students, on the verge of tears, turned in sheets with this section blank or with a note about being "stupid" for not knowing any examples. Some students were able to imagine applications with relatively little difficulty, but the majority couldn't imagine how the topics we discussed related to the real world outside of the life of chemists, chemistry students, or chemistry teachers. One student's somewhat rambling response to an interview question illustrated the challenge that many students seemed to experience.

She said, “Um, my mind doesn't exactly work like that still, but um I thought it was more helpful to see it, of course like if I ever experience a car crash, I'll be like, ‘that's a chemical reaction, cool!’” Another student stated a similar idea in a different way that highlighted the thought that concepts from lab would only be applicable to “real life” for chemists. She said,

> [In class it] is always like, ‘this lab and it's hands on,’ but it's just something we would do in a chemistry class, and I don't really imagine about the outside world. I mean, obviously chemists, would. I can imagine them doing that...type of stuff. I guess, yeah, it’s the real world, yeah. But real world application I sometimes [think of] like of like natural world, like, outside-outside...but if I take it back to this, chemistry, with chemists working in labs, yeah I can really imagine that.

Despite what was clearly a frustrating experience on the Lab Content Quizzes, students reflected on their experiences in lab in a positive light. Students complete teacher evaluation/course surveys for every course each year. To a free response question of “What aspect of this course do you find most enjoyable?,” 59% (*N*=29) of the students responded with, “lab.” In contrast, after completing traditional labs, student responses to the statement “Completing this lab activity made me more interested in chemistry as a subject,” were distributed fairly symmetrically around the most common response of neutral (46.4%, *N*=34.5), with virtually equal numbers of students who agreed (26.2%) and disagreed (26.1%) with that statement (Figure 4).

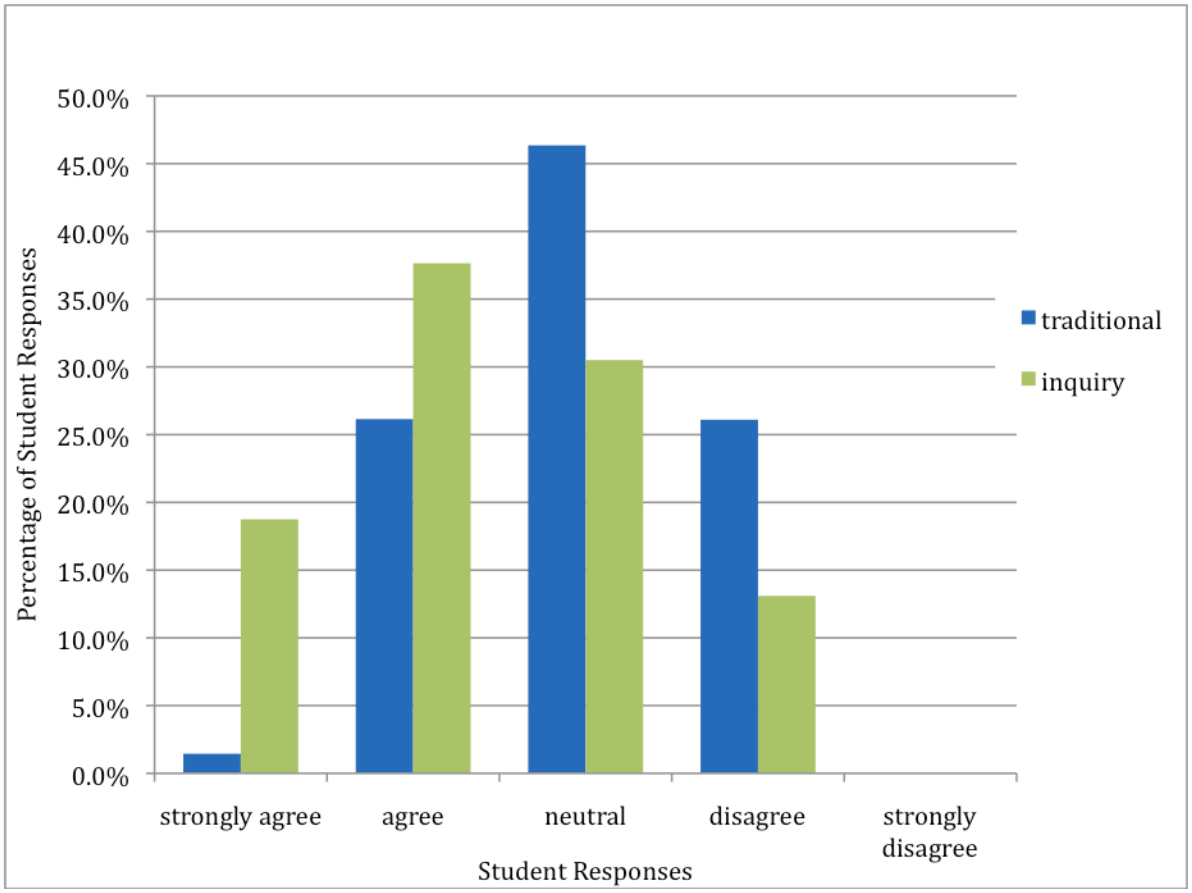

Figure 4. The percentage of student responses to the survey question "Completing this lab activity made me more interested in chemistry as a subject." Responses from both traditional (*N*=69) and inquiry-based labs (*N*=69) were sorted according to categories from strongly agree to strongly disagree.

Responses to the same question after the inquiry-based labs demonstrated a shift towards more positive answers, with 18.8% who strongly agreed with the statement, 37.7% in agreement, and 30.5% who were neutral. Students echoed and expanded upon this positive sentiment in the interviews. One student commented on how he enjoyed the additional challenge of inquiry-based labs. He said,

> In an inquiry lab I'm more challenged, but in a traditional lab I feel like I know exactly what I'm learning or what I'm supposed to be learning because it's on a piece of paper in front of me. And in the inquiry-based lab, I have to figure out what I'm learning. I prefer the inquiry lab because...I kind of liked figuring out what we were supposed to do. It was fun.

A common complaint about traditional labs focused on the tedious nature of the lab report format. So, some of the preference for inquiry-based labs might also be attributed to the departure from the lab report format.

In addition to enjoying lab in general, identifying it as one of the best parts of the course, and seeing it as an aspect of the course that makes them more interested in chemistry as a topic, students responded favorably to the idea that labs "provided a better understanding of what it is like to do real science" for both methods of lab instruction. The majority of students (*N*=69) in traditional labs either agreed with (46.5%) or were neutral about (40.6%) the approach's ability to provide a better understanding of what it is like to do real science (Figure 5). Again, there was a shift towards more positive responses to the same question for inquiry-based labs, in which 49.3% agreed with the statement, 30.3% strongly agreed, and 17.6% were neutral about this concept.

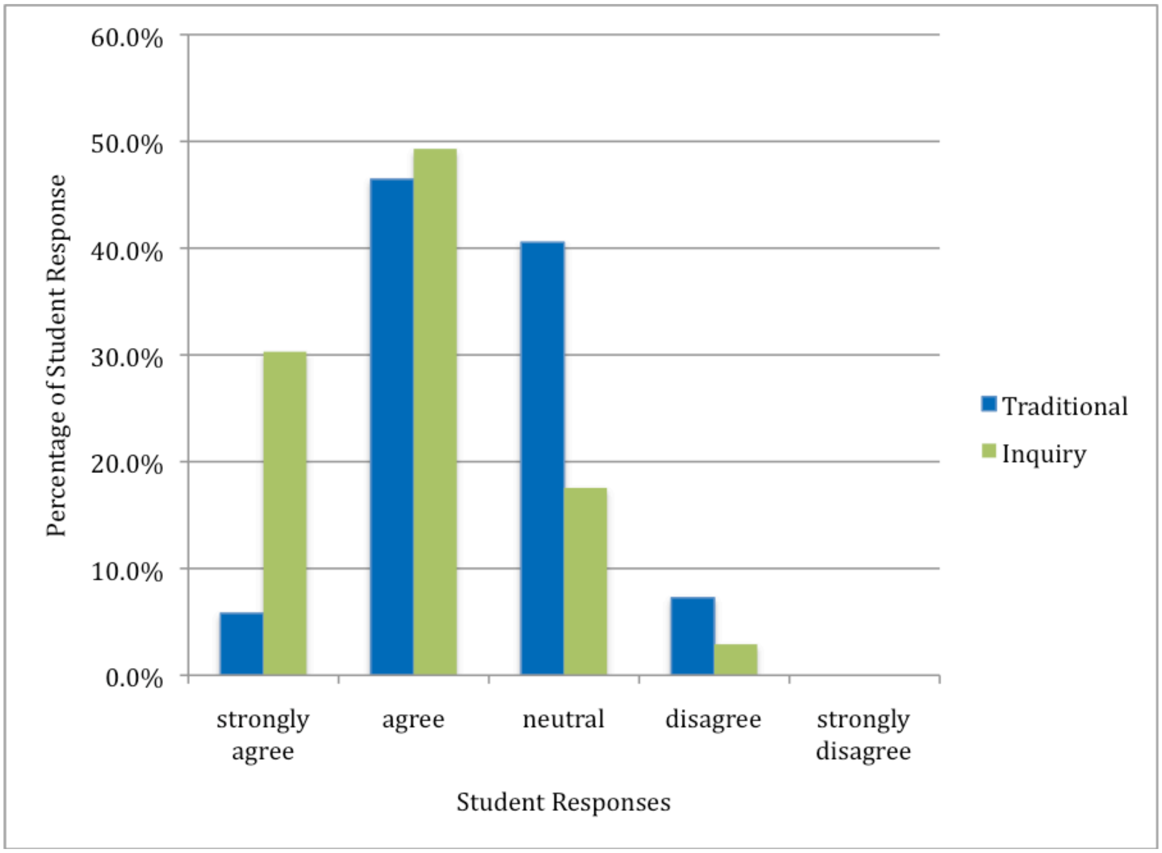

Figure 5. The percentage of student responses to the survey question "This lab format provided me with a better understanding of what it is like to do real science." Responses from both traditional (*N*=69) and inquiry-based labs (*N*=69) were sorted according to categories from strongly agree to strongly disagree.

INTERPRETATION AND CONCLUSION

In this capstone project, there were areas in which traditional and inquiry-based labs showed little difference and other areas of clear difference. Even so, the fundamental experience in lab seems to have a number of commonalities that apply across the distinction of traditional or inquiry-based instruction. The student experience in chemistry labs was overall a positive one; it improved student confidence and perceived understanding of the material, along with contributing to their enjoyment of the material being taught. The role of lab in improving retention of content, however, was not significant based on the data collected here. The study data displayed a bit of a disconnect between student perception of how lab affected their understanding and their performance on the Lab Content Quizzes taken before and after lab. Results did not support the idea that labs improve student retention of content. This finding may indicate that either that the content quizzes were not accurately measuring student comprehension of related topics or that the students believed that they understood the ideas, even if they truly did not. I also wonder the degree to which some variation of performance anxiety may have affected student work on the Lab Content Quizzes. Despite my best efforts to explain the goal of the Lab Content Quizzes, it was clear that my students were quite discouraged, frustrated, and shaken by the task of completing these assignments. Explaining that they would not be graded or have their standing affected in the course did little to discourage questions such as, “Yeah, but what will you think if I don’t get any of it right?”

The questions geared towards assessing problem solving skills on novel questions were particularly challenging for students, as was the process of applying content they clearly understood to the laboratory setting. These non-traditional activities provided a new type of challenge, which threw many of them off balance and may have shaken their confidence about the material. In general, my students are high-achieving and are used to experiencing relatively high levels of success by employing familiar techniques in their approach to school work. Inquiry-based labs require that students move beyond superficial understanding of the material to apply it in new ways, so even though they knew the content, these labs provided significant challenge because of the skill required for success.

In comparing the two methods of lab instruction, there were also some clear areas where the methods differed. The results from this project support the idea that students feel a greater sense of satisfaction from the challenges presented in inquiry-based labs, from which they are more likely to develop confidence and imagine the role of scientists at work. Although students expressed frustration with the process of inquiry-based labs, they were more invested with the content and expressed more interest in the material with this method. Traditional labs elicited a slightly less positive response from students, but they acknowledged that they mostly disliked the format of the lab report itself. They often felt the pre-lab assignment was tedious, but noted the value of post-lab questions for traditional labs. When answering these questions, students were encouraged to reflect upon the conceptual significance of the data they collected, and they recognized that this process was important for their understanding of the material.

The small scope of this project might have prevented a definitive comparison between the two methods of lab instruction, as students and teacher were still getting used to this “new” way of doing lab. Similar to the reflect made by Cacciatore and Sevian (2009), it seemed that more conclusive data about content retention and ability to interpret novel scenarios could be collected if additional inquiry-based labs were completed over a longer time period.

VALUE

This project allowed me to examine the student experience in lab in order to determine if my intent for lab was being achieved by either or both methods of instruction. I learned a great deal about how students navigated labs, what they gained from the experience, and what sort of support they needed in order to be successful. This project also made me reflect upon how I measure success in lab. While it has never been my immediate intent for lab to improve content retention, I assumed that student content retention would be improved by the experience of lab. My data showed however, that this wasn't the case; labs seemed to have little noticeable affect on content retention, which corresponds with the findings of Hofstein and Lunetta (1982).

Even if labs don't contribute to content comprehension or retention, this project does reinforce the positive impact that labs do have on student learning. This study shows that inquiry-based labs require students to develop and use skills that other aspects of the course do not call upon to the same extent, such as effective collaboration methods and complex problem solving. Inquiry fosters engagement with and ownership of the material—it becomes *their* lab, rather than my lab that they have to do.

In the setting of an introductory chemistry course, traditional labs also have value in teaching skills necessary to successfully and safely complete the lab, as stated by Domin (2007) and Llewellyn (2005). My close observation of student work in lab during this project pointed out the importance of teaching lab skills. While not central to my focus question or sub-questions, this project has informed my teaching practice in relation to these lab skills. Many students asked questions that illuminated significant gaps in their rudimentary understanding of lab equipment and usage. These were areas in which I assumed they had previous experience or were receiving a satisfactory level of instruction in this course. In the future, I plan to integrate more explicit instruction for lab technique, using performance assessment as a means for providing direct feedback to students about their ability to complete a set list of lab skills. It might also be useful to observe other science teachers in lab or at least brainstorm with my department about methods for teaching these skills effectively.

Domin (2007) also stated the importance that traditional labs incorporate post-lab assignments that require higher-order thinking of students. In this project, students reflected that the postlab questions were really difficult, but important because they made them think about the material. And most students noted that this is when the lab really made sense to them. Areas in which I hope to improve my traditional labs include the way in which students complete the pre-lab assignment and in the wording of the procedures in order to minimize confusion. Part of the prelab assignment includes taking notes on the procedure, and my students often see this section of the lab as just “busy work.” I’ve tried to encourage them to see the benefit of this process and to have them avoid just copying steps from the handout. In the future, I will focus my attention to research that focuses on the lab report and how best to retain the structure and instructional benefits of traditional labs, while minimizing frustration with the tedium of following the instructions and maximizing the higher-order thinking with post-lab questions.

Students clearly appreciated the novel approach of inquiry labs and many stated that they wished we did more inquiry during the year. In the future, I hope to integrate more inquiry-based activities into the course of the year and to expand upon some of the changes I’ve made to my classroom in general—brainstorming, using drawing to connect the molecular or atomic level to the macroscopic observation, and converting demonstrations to discrepant events. The integration of inquiry-based materials into my lab and classroom practice illustrates the biggest change that I have undergone as a teacher due to this action research project. As a student of science, nearly all of my formal education took the form of traditional methods, both in the classroom and lab setting. I learned how to be successful within the constructs of those methods, assumed that was just the way science was taught, and used that template for crafting my own teaching style early on in my career. Throughout this project, I have been exposed to alternative means of assessment and student-focused instruction. These methods have challenged me to grow as an educator and have allowed me to make the material I teach accessible to a greater spectrum of learners. There have been times during lectures in the past, when I have thought, "This is too boring! I'm losing these kids. There's got to be a better way to do this!" Exploring methods of inquiry-based instruction have encouraged me to break up lecture with small group or partner work, to introduce topics with brainstorming or discrepant events, and to ask questions that lead to more questions. The process of crafting better questions and intentionally soliciting feedback from all members of the classroom are areas where I feel I can continue to grow. We are starting a new peer-evaluation process for the faculty at my school next year, and I hope to participate in the process in order to learn more from my colleagues.

This project has reinforced my belief that there is no one right method of lab instruction. There are benefits and limitations to both traditional and inquiry-based labs. With the goals of fostering student engagement and ownership of the experience, complex problem solving and collaboration with in groups, and mastery of lab skills and safety there is a clear place for both methods of lab instruction in the introductory chemistry course.

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APPENDICES

APPENDIX A

EXEMPTION REGARDING INFORMED CONSENT FORM

THE THACHER SCHOOL

Exemption Regarding Informed Consent

I, Michael K. Mulligan, Head of School of The Thacher School, verify that the classroom research conducted by Heather M. Grant is in accordance with established or commonly accepted educational settings involving normal educational practices. To maintain the established culture of our school and not cause disruption to our school climate, I have granted an exemption to Heather M. Grant regarding informed consent.

____
(Signed Name)

Michael K. Mulligan
(Printed Name)

11/17/10
(Date)

5025 Thacher Road • Ojai • California • 93023 •9001 • 805•640•3201 • Fax 805•640•1033

APPENDIX B

REACTION OF SOLID COPPER AND AQUEOUS SILVER NITRATE HANDOUT

Reaction of Solid Copper and Aqueous Silver Nitrate

In this lab, you will predict and balance the equation that represents the reaction between solid copper wire and aqueous silver nitrate, identify the ***limiting and excess reactants***, calculate the ***theoretical yield***, determine the ***experimental yield***, and calculate the ***percentage yield***.

The amount of products that are generated as a result of a chemical reaction is dependent upon both the amount of reactants present, and the mole ratio in which they react. Consider an analogous situation where we have a list of ingredients and a recipe for an apple pie:

Ingredients Available:	**Mom's Apple Pie Recipe:**
5 dozen apples	1 dozen apples
6 sticks butter	1.5 sticks butter
6 cups sugar	1 cup sugar
10 cups flour	2 cups flour

How many pies can we make? First we have to compare the amount of each ingredient available to the amount called for in the recipe (in chemistry, the recipe is a ***balanced chemical equation***). We have enough apples to make 5 pies, enough butter to make 4 pies, enough sugar to make 6 pies, and enough flour to make 5 pies. The ingredient that limits how many pies we can make in this example is butter—we only have enough butter for 4 pies. In a chemical reaction, the reactant that limits how much of the products we make is called the ***limiting reactant***. In our pie analogy, butter is the limiting reactant.

If we were to make as many pies as we could given the information above, we would have 4 pies to bake and still have 1 dozen apples, 2 cups sugar and 2 cups flour left over. In a chemical reaction, the maximum amount of products that can be made from a given amount of reactants is called the ***theoretical yield***. In our pie analogy, our theoretical yield is 4 pies. The reactants that remain after the reaction is complete and the products have been made are said to be ***excess reactants***. In our pie analogy, apples, sugar and flour are each present ***in excess*** (often abbreviated INXS, which is where the Australian rock band popular a few years back got its name).

Let's carry the pie analogy one step further. We calculated that we have enough ingredients to make 4 pies. Imagine that in the course of our pie assembly and baking, we accidentally overcook a pie so that the crust is burned and the pie is inedible. We have 3 pies where we calculated we would have 4. In chemistry, the actual amount of products made during a reaction is called the ***experimental yield***. The theoretical amount of products that could have been made under ideal conditions is called the ***theoretical***

yield. The ***percentage yield*** is the experimental yield divided by the theoretical yield (x 100%). In our pie analogy, we got 3 pies when we anticipated 4, for a 75% yield. For an experiment to be considered a complete success, the percentage yield should be very close to 100%.

Refer to pages 365-373 of your textbook for additional explanation and sample problems.

MATERIALS

approximately 3.00g $AgNO_3$
copper wire
distilled water in washbottle
large test tube
100, 250 mL beakers
utility clamp
ring stand
one-hole rubber stopper for test tube
filter paper
funnel
acetone
drying oven
stopwatch

PRELAB

1. Write the balanced chemical equation for the reaction of solid copper with aqueous silver nitrate, which produces aqueous copper (II) nitrate and solid silver. Remember to include the physical states of all reactants and products.
2. Classify the reaction type that you have identified above.
3. Read the experimental procedure thoroughly, and set-up appropriate tables in your lab notebook that contain: **Data Table)** the **Raw Data** to be collected in the order it is obtained in the procedure, and **Calculations Table)** the **Calculated Values** to be determined in processing the data. Make sure to report appropriate units and significant figures in your data tables.

PROCEDURE

Leave room in your notebook for a sketch of the experimental apparatus.

1. Obtain and wear goggles! **CAUTION: Silver nitrate (solid or solution) reacts with skin and turns it black. It can also cause blindness if it gets into your eyes.** Wear goggles at all times while conducting this experiment. Notify your teacher and wash your hands immediately in the event of an accident or a spill.
2. Obtain a piece of copper wire that is 4 or 5 cm longer than a large test tube. Straighten the wire with your hands as much as possible. Starting at one end of the straightened wire, wrap a second piece of copper wire around the straightened wire to within 4 or 5 cm of its other end.
3. Weigh the copper wire assembly and record its mass to the nearest 0.001 g.
4. Using a weighing dish that has been tared on your balance, weigh approximately 3.000 g of silver nitrate and record its mass to the nearest 0.001 g.

5. Add distilled water to the large, clean test tube so that it is about half-full. Transfer the distilled water to a clean, 100 mL beaker. Add the solid silver nitrate to this beaker, and swirl the beaker gently until the silver nitrate is completely dissolved.

6. After fixing the large test tube to a ring stand with a utility clamp, pour the silver nitrate solution into the test tube. Briefly rinse the beaker 3 times with distilled water, transferring each rinse to the test tube. Be careful to leave 1-2 cm of space at the top of the test tube in order to accommodate a rubber stopper.

7. Put the copper wire assembly into the test tube. Start the stopwatch to record elapsed time for the reaction. Make sure the wire is centered at the bottom of the test tube. Put a one-hole rubber stopper over the wire assembly and fit it loosely into the top of the test tube.

8. Observe carefully and record in your lab notebook any changes that take place for the next several minutes. Let the assembly stand for 30-45 minutes. During this time, determine the mass of a piece of filter paper to the nearest 0.001 g. After properly folding the paper into a cone, fit it into a funnel and moisten it with distilled water from a wash bottle so that the paper adheres to the sides of the funnel. During this time, you may also perform the calculations necessary to identify the limiting reactant and determine the theoretical yield according to the reaction you balanced in the prelab.

9. After 30-45 minutes, observe carefully and record in your lab notebook any additional changes that have occurred in the test tube.

10. Remove the rubber stopper, and gently shake the wire assembly so that the crystals fall to the bottom of the test tube. Remove the wire from the test tube and stop the timer, recording the elapsed reaction time in your lab notebook. Use your wash bottle to rinse onto the filter paper any crystals that still adhere to the wire. Dip the wire in the acetone solution located in the fume hood, and then wave the wire in the air for approximately 30 seconds or until dry. Then weigh the wire and record its mass to the nearest 0.001 g.

11. Pour the contents of the test tube into the filter, collecting the filtered solution in a 250 mL beaker. Use your wash bottle to rinse any remaining silver particles from the test tube into the filter. Wash the silver thoroughly with distilled water. Dispose of the solution in the waste beaker located in the fume hood.

12. Set the filter paper cone into a beaker labeled with a grease pencil, and place it in the drying oven to be dried overnight.

13. The next day, record the combined mass of the filter paper and silver crystals to the nearest 0.001 g.

The raw data table in your laboratory notebook should include the following measurements:

1. mass $AgNO_3$ (g)
2. initial mass Cu wire (g)
3. mass filter paper (g)
4. final mass Cu wire (g)
5. mass Ag, filter paper (g)
6. time elapsed for the reaction (s)

OBSERVATIONS

BE DESCRIPTIVE: Describe the wire and solution *before* the reaction (color, clarity). Describe the color, size, texture, and location of the crystals on the wire. What color is the solution? Is this color uniformly distributed throughout the test tube? How does the appearance of the wire change with progress of the reaction? How does the appearance of the solution change?

The calculations table in your laboratory notebook should include the following calculated values:

2. mass change of Cu wire (g)
3. mass Ag obtained (g)
4. moles copper reacted (mol)
5. moles silver produced (mol)
6. mole ratio Cu:Ag
7. theoretical yield Ag (g)
8. percentage yield Ag (%)

PROCESSING THE DATA

In your lab notebook, perform the calculations below and summarize their results in your data table. Then answer the questions that follow in your lab notebook.

1. According to your observations, identify the limiting and excess reactants. Explain how you can identify which reactant is limiting and which is in excess without any doing any calculations.

2. Calculate the change in mass of the copper wire during the experiment.

3. Calculate the mass of silver obtained from the reaction.

4. Calculate the number of moles of copper that participated in the reaction.

5. Calculate the number of moles of silver produced.

6. Determine the ratio of moles silver produced to moles copper reacted (expressed as a decimal rounded to the nearest tenth).

7. Calculate the theoretical yield of silver given the amount of the limiting reactant present.

8. Calculate the percentage yield of silver given the amount of silver produced in your experiment.

9. Does the mole ratio you calculated in step 6 agree with your balanced chemical equation from the prelab?

APPENDIX C

EXPLORING GAS PROPERTIES HANDOUT

Exploring the Properties of Gases

The purpose of this investigation is to conduct two experiments, each of which illustrates a different gas law. You will be given a list of equipment and materials and some general guidelines to help you get started with each experiment. Three properties of gases will be investigated: pressure, volume, and temperature. By assembling the equipment, conducting the appropriate tests, and analyzing your data and observations, you will be able to describe the gas laws, both qualitatively and mathematically.

OBJECTIVES

In this experiment, you will

- Conduct two experiments, each of which illustrates a gas law.
- Gather data to identify the gas law described by each activity.
- Complete the calculations necessary to evaluate the gas law in each activity.
- From your results and references in your textbook, derive a single mathematical relationship that relates pressure, volume, temperature, and number of molecules.

MATERIALS

Vernier computer interface	large-volume container for water bath (at least 10 cm in diameter and 25 cm high)
computer	125 mL Erlenmeyer flask
Vernier Gas Pressure Sensor	hot-water supply (up to 50°C) or hot plate
Temperature Probe	Ice
20 mL gas syringe	100 mL graduated cylinder
plastic tubing with two Luer-lock connectors	textbook
rubber stopper assembly with two-way valve	

PRE-LAB EXERCISE

Review both parts of this experiment before starting your work. You will need to decide the best way to conduct the testing, so it is wise to make some plans before you begin. You may wish to conduct a test run without collecting data, in order to observe how the experiment will proceed.

In both parts of the experiment, you will investigate the relationship between two of the four possible variables, the other two being constant. In this pre-lab exercise, sketch a graph that describes your hypothesis as to the mathematical relationship between the two variables; e.g., direct relationship or inverse relationship.

Part I Pressure, P, and volume, V (temperature and number of molecules constant).

Part II Pressure, P, and absolute temperature, T (volume and number of molecules constant).

PROCEDURE

Part I Pressure and Volume

1. Obtain and wear goggles.

2. Position the piston of a plastic 20 mL syringe so that there will be a measured volume of air trapped in the barrel of the syringe. Attach the syringe to the valve of the Gas Pressure Sensor, as shown in Figure 1. A gentle half turn should connect the syringe to the sensor securely. **Note:** Read the volume at the front edge of the inside black ring on the piston of the syringe, as indicated by the arrow in Figure 1.

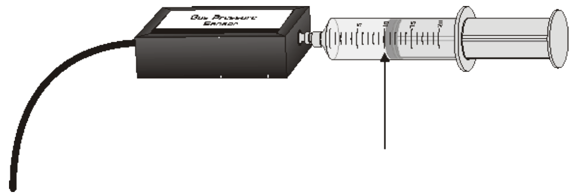


Figure 1

3. Connect the Gas Pressure Sensor to Channel 1 of the Vernier computer interface. Connect the interface to the computer using the proper cable.

4. Start the Logger *Pro* program on your computer. Open the file "30a Gases" from the *Advanced Chemistry with Vernier* folder. This file allows you to collect pressure data from the Gas Pressure Sensor, using Events with Entry mode. For each pressure reading you take with a Keep button, this mode lets you enter a volume value.

5. Measure the pressure of the air in the syringe at various volumes. Depress or pull back on the plunger to change the volume and collect a data point by clicking on the  button when the pressure reading stabilizes. Do not click on STOP button until you have collected all of the data points. The best results are achieved by collecting at least six data points.

6. Graph the data, making sure to include an appropriate title and axis labels including units. Add a trendline to the graph, using the **curve fit** and selecting either a **linear** or **inverse** based on the trend of the data (try each to see which one fits the data better). Linear should be used for data that exhibit a direct relationship and inverse should be used for data that exhibit an inverse relationship. Be sure to choose the appropriate fit for the data collected.

7. Print one graph per lab group. Data from the curve fit line will be used in the processing the data section.

Part II Pressure and Absolute Temperature

In this experiment, you will study the relationship between the absolute temperature of a gas sample and the pressure it exerts. Using the apparatus shown in Figure 2, you will place an Erlenmeyer flask containing an air sample in a water bath and you will vary the temperature of the water bath.

6. Connect the Gas Pressure Sensor to Channel 1 and a Temperature Probe to Channel 2 of the interface.

7. Assemble the apparatus shown in Figure 2. Be sure all fittings are airtight. Make sure the rubber stopper and flask neck are dry, then twist and push hard on the rubber stopper to ensure a tight fit.

8. Set up water baths in the large-volume container as you need them, ranging from ice water to hot water.

9. Open the file "30b Gases" from the *Advanced Chemistry with Vernier* folder. This file is set up to collect pressure and temperature data from the attached sensors, using Selected Events mode. This mode allows you to collect a data pair simultaneously from the Gas Pressure Sensor and Temperature Probe by clicking on the button.

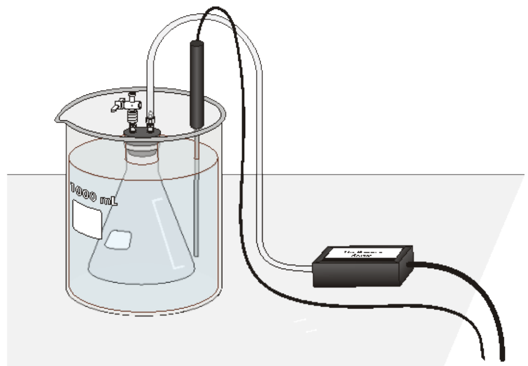


Figure 2

10. Collect pressure data at several different temperatures. Using a water bath submerge the Erlenmeyer flask like in Figure 2, wait for the pressure and temperature readings to stabilize and collect a data point by clicking on the button. Do not click on STOP button until you have collected all of the data points. The best results are achieved by collecting at least four data points.

11. Graph the data, making sure to include an appropriate title and axis labels including units. Add a trendline to the graph, using the **curve fit** and selecting either a **linear** or **inverse** based on the trend of the data (try each to see which one fits the data better). Linear should be used for data that exhibit a direct relationship and inverse should be used for data that exhibit an inverse relationship. Be sure to choose the appropriate fit for the data collected.

12. Print one graph per lab group. Data from the curve fit line will be used in the processing the data section.

DATA ANALYSIS—PROCESSING THE DATA

<u>Experiment 1:</u>

1) From the equation for the curve fit, which relationship was chosen? Is this expected based on the mathematical relationship between pressure and volume? Explain your reasoning based on the graph.

2) Look at the data table and answer the following questions:
    a) What happens to the pressure when the volume is halved?
    b) What happens to the pressure when the volume is quadrupled?

<u>Experiment 2:</u>

3) Think about the significance of the y intercept for the data. What *should* its value be and why? How does the fit value compare to the theoretical value for the y-intercept?

<u>Experiment 1 and 2:</u>

4) For both parts of the experiment, write an equation using the two variables and a proportionality constant, k (e.g., for Part I, $P = k \times V$ if direct, or $P = k/V$ if inverse)

5) Calculate the constant, k, for each of the gas laws that you tested. This value can be an average for each of the data pairs in each part of the experiment.

6) Based on the mathematical relationship and equation that you obtained in Step 4 above for both parts of the experiment and the information about the relationship between amount of gas and volume (on page 439 in your text book), combine all four variables into a final equation. This "combined equation" will contain P, T, V, and n, as well as a new proportionality constant, K. Be sure to explain how you obtained your result (how you combined the equations).

7) Do your results match your expectations for these relationships? Did your graphs display the relationships you expected? What factors may have contributed to success (or failure) of the data collection?

APPENDIX D

AIR BAG CHALLENGE HANDOUT

Air Bag Challenge

(Parts of this lab are direct quotations or modifications from Allen et al. (2006))

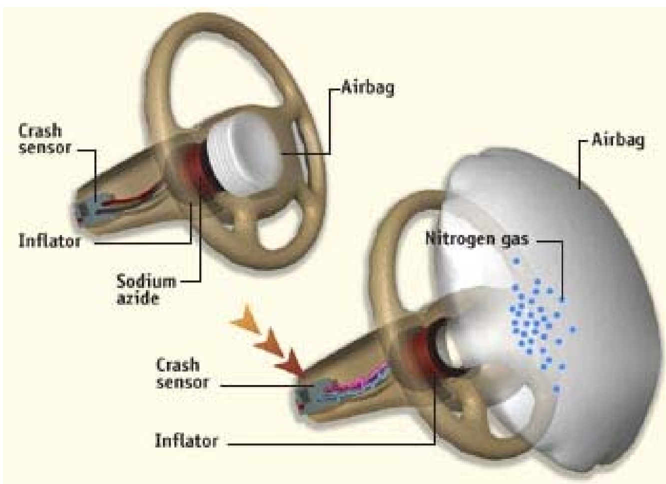
Objective: You will use your knowledge of gas laws and stoichiometry to design, construct, and test a plan for a simulated automobile air bag.

Background Information: In most cars today you will find an air bag. The air bag has three main parts. First the bag, which is made of a thin nylon fabric, holds the chemicals and sensors and folds into the steering wheel or the dashboard. The electron components contain a sensor that detects a collision force equal to running into a brick wall at about 10-15 mph and an igniter that detonates the first chemical reaction. The chemical component in the airbag is a mixture sodium azide (NaN_3) together with KNO_3 and SiO_2. The first reaction has a high activation energy and an electrical impulse is require to start the reaction. This reaction liberates a large volume of nitrogen gas, which fills the air bag.

$$2\ NaN_3 \text{ --> } 2Na + 3N_2$$

The sodium by-product of reaction 1, and the potassium nitrate generate additional nitrogen for the airbag in a second reaction

$$10\ Na + 2\ KNO_3 \text{ --> } K_2O + 5\ Na_2O + N_2$$



(http://www.lanl.gov/quarterly/q_sum03/airbags.shtml)

These two reactions leave potassium oxide and sodium oxide to react with the third compound of the mixture, silicon dioxide, forming alkaline silicate, which is a safe and stable, un-ignitable compound.

$$K_2O + Na_2O + SiO_2 \text{ --> alkaline silicate}$$

The nylon bag actually has small holes in it and will deflate soon after inflating to allow the passenger to escape the accident.

Challenge: Your task is to simulate the construction of an air bag using a ziplock bag, baking soda ($NaHCO_3$), and vinegar (0.900 moles/Liter $HC_2H_3O_2$). You may use a balance, weigh boat, and a graduated cylinder. Your task is to mix the reagents in the bag to inflate but not burst the bag. The best design will be one that fills the bag with enough gas so that you cannot pinch the bag in the middle and have both sides touch. Balanced equation:

$$NaHCO_{3(s)} + HC_2H_3O_{2(aq)} \rightarrow H_2O_{(l)} + CO_{2(g)} + NaC_2H_3O_{2(aq)}$$

Things to include in your notes:

- **all calculations** and have it initialized by me before beginning—which approves that it is safe, not that it is the correct method.
- How will you get both reagents in side the bag without losing gas? If you need other materials for your procedure, check with me.
- You notes should include a well-designed plan, observations, and results.
- Conclusions—were you successful? What would you change next time?

Post lab assignment:

Each group will type one final reflection from their notes about this lab, organized in the following labeled sections:

1. Title, names of group members
2. Conceptual Background
   - explain your thought process in solving this challenge
   - include as much chemistry content as applies
   - fully explain ideas in complete sentences
   - organize these ideas into a logical sequence, even if the actual process was a bit more convoluted in lab
3. Procedure: outline the steps you followed to create the air bag in a bulleted list
4. Observations, Results and Conclusions:
   - What observations did you make.
   - Were you successful? Explain.
   - How would you modify your procedure next time?
5. Calculations:
   - attach a sheet of clearly organized hand-written work for every calculation that was made in lab
   - be sure to include units on all numbers and to put boxes around final answers

APPENDIX E

RATE OF EVAPORATION HANDOUT

Rate of Evaporation Lab

Post lab assignment:

Each group will type one final reflection from their notes about this lab, organized in the following labeled sections:

1. Title, names of group members
2. Conceptual Background
    - Define alkane and alcohol
    - Explain evaporation on a molecular level
    - Describe how molecular weight, IMFs, and any other variables affect rate of evaporation
    - State the aspect of evaporation that you explored in this lab and identify which molecules you selected to test this question. Possible molecules:
        - ethanol
        - 1-propanol
        - 1-butanol
        - n-pentane
        - methanol
        - n-hexane
3. Hypothesis: Based on your background info, what do you predict will happen?
4. Procedure:
    - outline the steps you followed to collect data in order to answer this question in a bulleted list
5. Data and Results:
    - Graph of LoggerPro Data
    - Table with information about the characteristics of the molecules used
        - Molecular weight
        - Structural fomula
        - Type of IMFs
        - Change in temperature or slope as measure of evaporation rate
        - Etc.
6. Conclusions and Reflection
    - Were you successful? Did your results support your hypothesis? Explain.
    - How would you modify your procedure next time?
    - What might type of experiment could you do based on these results if you had access to any materials? What is one application of evaporation to real world scenarios (other than sweating)? Use the internet to find a reference for this application.
7. References
    - include the URL for any website used for information on this lab (Wikipedia is acceptable)

APPENDIX F

LAB 1: CONTENT QUIZ

Name: ____________________________

Participation in this research is voluntary. Participation or non-participation will not affect your grade or class standing in any way.

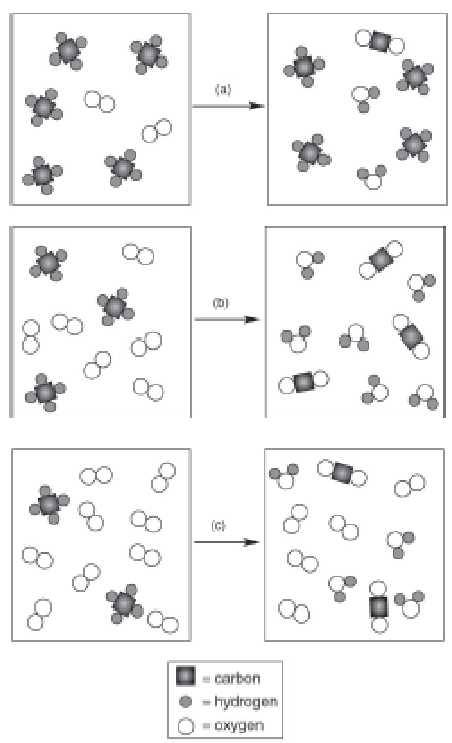
1. Using this reaction: $3Mg(OH)_2 + 2H_3PO_4 \rightarrow Mg_3(PO_4)_2 + 6H_2O$

   a. If 20.0 g of $Mg(OH)_2$ react with 40.0 g of H_3PO_4 **what is the limiting reactant?** (molar mass of $Mg(OH)_2$ = 58.32 g/mol ; molar mass of H_3PO_4 = 98.00g/mol; molar mass of $Mg_3(PO_4)_2$)

   b. How many grams of $Mg_3(PO_4)_2$ will be produced by the above reaction?

   c. Which reactant is in excess in the above reaction?

   d. After the reaction takes place, how much of the excess reactant will be left over?



2. Methane (CH_4) reacts with oxygen to form carbon dioxide and water according to the following balanced equation:
   $CH_4 + O_2 \rightarrow CO_2 + 2H_2O$

Using the diagrams on the right, which one of the diagrams best represents a situation in which methane is the limiting reactant?

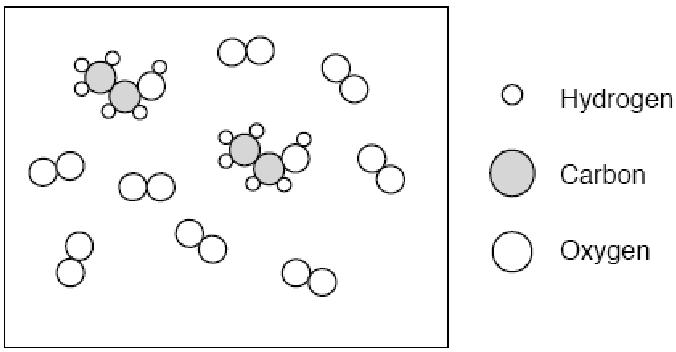
A B C (circle one)

3. Applications: What are possible fields of industry in which limiting reactant reactions would be important? Please list **up to three fields** and explain each application in one sentence.

4. Ethanol (C_2H_6O) reacts with oxygen in a combustion reaction to produce carbon dioxide and water according the following balanced equation:

$$C_2H_6O + 3O_2 \rightarrow 2CO_2 + 3H_2O$$

The following diagram represents a mixture of ethanol and oxygen in a closed container.



Products after reaction takes place:

After this mixture was allowed to react, draw what the products of the reaction would look like.

5. A sophomore chemistry student, after seeing the gummi bear demo on the first day of chemistry class, decided to try and recreate the demo in his dorm room. He bought some gummi bears in town and placed them on his desk. He remembered that Ms. Grant said that the sugar in the bear reacted with oxygen according to the following reaction:

$C_{12}H_{22}O_{12} + 12O_2 \rightarrow 12CO_2 + 11H_2O$ + (energy)

He also remembered that the oxygen for the reaction was supplied by the decomposition of $KClO_3$:

$2KClO_3 \rightarrow KCl + 3O_2$

Since he did not have access to $KClO_3$ the student hoped that if he waited long enough the gummi bear would eventually ignite. Why is he wrong?

A. The reaction is limited by the amount of sugar available

B. The gummi bear will only react with oxygen if it is melted
C. The reaction is limited by the amount of oxygen available
D. The sugar will only react with oxygen if KCl is also present

Explain your answer in terms of limiting reactants and stoichiometry:

Questions numbered 2 and 4 were modified from (Wood & Breyfogle, 2006)

<u>APPENDIX G</u>

LAB 2: CONTENT QUIZ

Name: ___________________________

Participation in this research is voluntary. Participation or non-participation will not affect your grade or class standing in any way.

1. If a sample of gas with a volume of 15.0 mL and pressure of 1.05 atm is compressed into a volume of 2.00 mL, what will be the pressure of the gas in atm (temperature and amount of gas are held constant)?

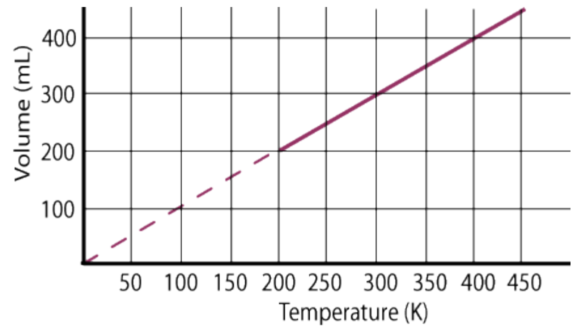
2. Using Avogadro's Law below, if the temperature and pressure are constant, what volume would 6.00 moles of gas occupy if 4.00 moles of the same gas occupy 85.0L?

Avogadro's Law: $\frac{V_1}{n_1} = \frac{V_2}{n_2}$

3. An oxygen tank contains 30.0 L of gas at 40.0 atm and is being held in a room where the pressure is 1.00 atm. The volume of the room is 64 m^3 (1 m^3 = 1000 L). If the valve on the tank was opened, could the gas fill the room's entire volume? In other words, does the tank contain enough gas to fill the entire room?

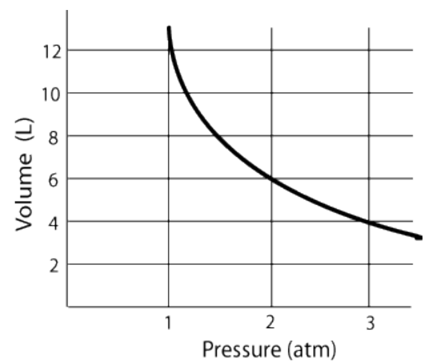
4. Applications: How do the properties of gases affect your everyday life? Please list **up to three specific areas** in which the properties of gases affect your everyday life and explain each application in one sentence.

6. What kind of relationship is displayed between the variables in the graph to the right: (image source: http://www.algebralab.org/img/717d3f69-1755-45fd-ae8f-d7718a399b9e.gif):



   a. parabolic
   b. directly proportional
   c. indirectly proportional
   d. exponential
   e. directly parabolic

6. Using the graph to the right, what do you expect the value of volume to be if the pressure was 4 atm? (http://www.algebralab.org/practice/practice.aspx?file=Reading_BoylesLaw.xml)



   f. 12 L
   g. 10 L
   h. 6 L
   i. 3 L
   j. 2 L

7. Party Time!! Last summer, I rented a helium tank, filled a number of balloons with helium, and placed them along the path from the main parking lot to the front of Upper School on the day before the party. Later that night, I took Gus for a walk and noticed that all of the balloons seemed to have deflated and were no longer floating in the air, but instead hung from the strings. I was frustrated that I would have to refill the balloons again in the morning and wondered what happened. The morning of the party, I was busy getting things ready and forgot to refill the balloons. By the time I took a break for lunch, I looked out the window and realized that the balloons seemed to be back to normal and were floating again. What happened?

http://free-extras.com/images/balloons-1300.htm

k. Changes in atmospheric pressure affected the balloon volume
l. Changes in temperature affected the balloon volume
m. The number of moles of helium affected the balloon volume
n. Changes in the mass of the helium in the balloon affected the balloon volume

Explain your answer based on your understanding of the Kinetic Molecular Theory and the gas laws:

APPENDIX H

LAB 3: CONTENT QUIZ

Name: ___________________________

Participation in this research is voluntary. Participation or non-participation will not affect your grade or class standing in any way.

1. If 0.100 moles of gas are in a 5.00 L container at 20°C, then what is the pressure of the gas measured in atm? (reference info: PV = nRT, R= 0.0821 L • atm/mol • K)

2. For this question, explain in words how you might solve the following question:

Yeast consume and break down sugar through anaerobic respiration, which is represented by the following balanced equation:

$$C_6H_{12}O_{6\,(s)} \rightarrow 2\ CH_3CH_2OH_{(l)} + 2\ CO_{2\,(g)}$$

sugar ethanol carbon dioxide

Placing the yeast and sugar in a sealed container, the carbon dioxide gas can be collected as the reaction takes place. The volume of gas collected is 10.5 L at 25°C at 1.00 atm. Based on the amount of gas produced, how might you calculate the grams of sugar that the yeast consumed in order to produce that amount of gas? Please explain your reasoning, even if you are not completely sure how to do the problem.

3. Applications: What are possible fields of industry in which the gas laws and chemical reactions would be important? Please list **up to three fields** and explain each application in one sentence.

4. In human cells, sugar reacts with oxygen to form carbon dioxide and water according to the following balanced chemical equation:

$$C_6H_{12}O_{6\,(s)} \quad + \quad 6O_{2(g)} \quad \rightarrow \quad 6\ H_2O_{\,(l)} \quad + \quad 6\ CO_{2\,(g)}$$

sugar + oxygen → water + carbon dioxide

How many million oxygen molecules would be needed to react completely with one million sugar molecules?

A. 3
B. 6
C. 9
D. 12

5. In a SCUBA training course, students are warned that when filling SCUBA tanks with gas, they should not store the tanks in the trunk of their cars. The danger is that the tank might explode as the car temperature in the car rises.

http://www.speedysigns.com/images/decals/jpg/H/450/100.jpg

The students discuss this concept and their understandings of the gas laws after class.

o. Bob says that temperature and volume are directly related, so as the temperature increases, the volume of the gas increases and the tank explodes.
p. Jeff says that temperature and the number of moles of gas are inversely related, so as the temperature increases, the number of moles of gas decreases and the tank explodes.
q. Jane says that temperature and pressure are directly related, so as the temperature increases, the pressure increases and the tank explodes.

Which student makes the most sense? Explain your answer based on the properties of gases and the kinetic molecular theory.

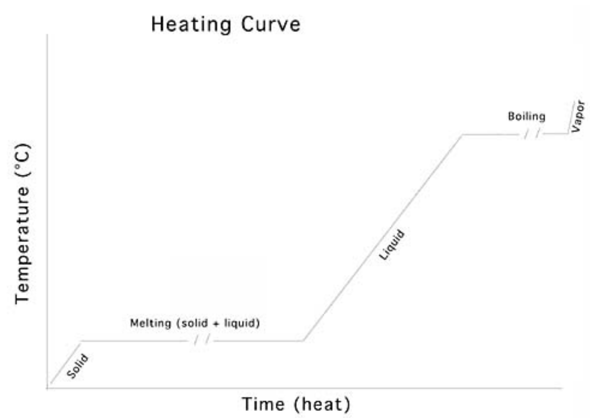
Questions numbered 2 and 4 were modified from (Wood and Breyfogle, 2006)

APPENDIX I

LAB 4: CONTENT QUIZ

Name: ___________________________
Participation in this research is voluntary. Participation or non-participation will not affect your grade or class standing in any way.

1. Based on the heating curve to the right, explain what happens to water molecules during the flat part of the curve labeled "melting." Be sure to include information about kinetic energy, heat, intermolecular forces, and changes in state.



http://users.humboldt.edu/rpaselk/C109.S09/C109_Notes/C109_lec30.htm

2. In a sample of water at room temperature, what happens if all of the intermolecular forces are broken?

r. The water undergoes a physical change and is now water vapor (gas).
s. The water undergoes a chemical change and is now water vapor (gas)
t. The water undergoes a physical change to produce hydrogen gas (H_2) and oxygen gas (O_2).
u. The water undergoes a chemical change to produce hydrogen gas (H_2) and oxygen gas (O_2).

3. Applications: In what ways do changes in the state of matter and the associated energy exchange affect your life on a day-to-day basis? Please list **up to three examples** and explain each application in one sentence.

http://events.colostate.edu/event_view.asp?ID=7&EID=21043

4. Just before administering the flu shot, Sean uses an alcohol wipe to sterilize the site of injection. The alcohol kills most microbes that are living on the patient's skin, minimizing the chances of infection after shot is given. Mary visits the clinic during her lunch break to get a flu shot. When Sean applies the alcohol to Mary's arm, she says, "Oh! That's cold!"

Why did Mary's arm feel cold?

v. The hospital storeroom was cold and dry, so the alcohol was colder. That's the only reason the alcohol would feel cold.
w. Mary just imagined that it felt cold; the alcohol had no affect on her temperature. Maybe it was just the air conditioning?
x. It probably had to do with the evaporation of the alcohol from Mary's skin.
y. All liquids make your on skin feel cold, the temperature of the alcohol has nothing to do with it.

Which answer makes the most sense? Explain your answer based on your understanding of particle motion and phase changes.

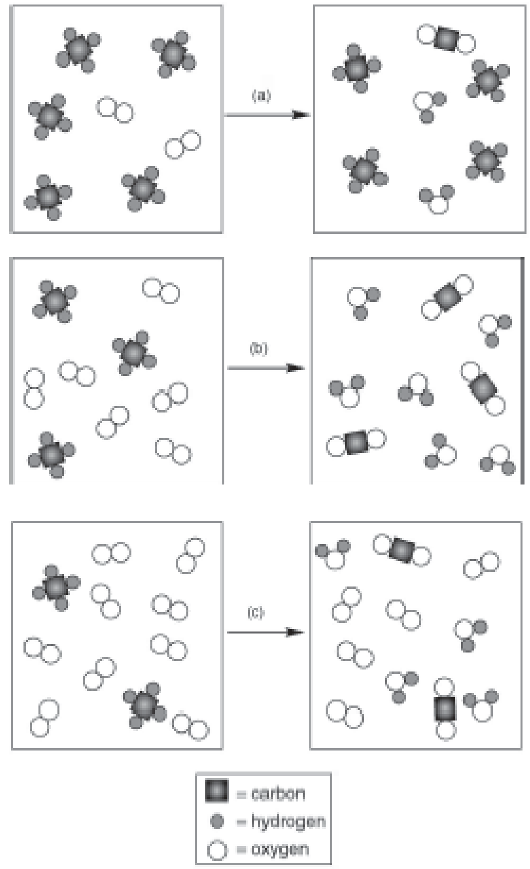
APPENDIX J

LAB-INSPIRED TEST QUESTIONS

Lab 1:

4) a. **Identify the limiting reactant**, when 22.6 g barium and 4.20 g nitrogen react to form barium nitride. **And what mass of barium nitride is produced?** (7 points)

reaction: $3\ Ba + N_2 \rightarrow Ba_3N_2$



Which of the diagrams on the right represents a reaction in which O_2 molecules act at the excess reactant? Explain how you can tell without doing a calculation. (1 point) (diagram from Wood and Breyfogle, 2006)

Lab 2:

The gas in a 20.0-mL container has a pressure of 235 kPa. When the gas is released into a 34.0-mL container at the same temperature, what is the new pressure of the gas, *measured in mmHg*? (4 points)

5) Which of the following graphs represents Boyle's law?

a.	b.
c.	d.

Lab 3:

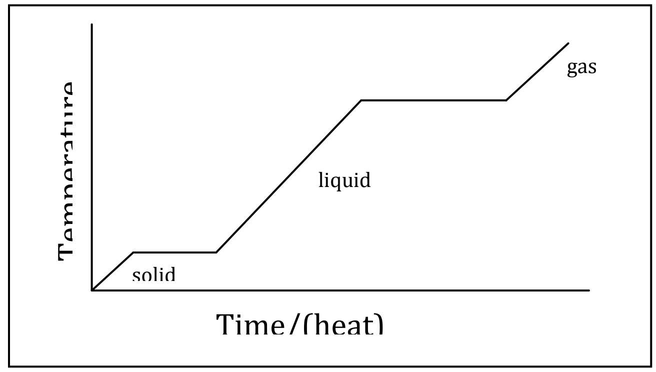
How many grams of oxygen gas would occupy 10.0L at 748 mmHg and 25°C? (5 points)

Lab 4:

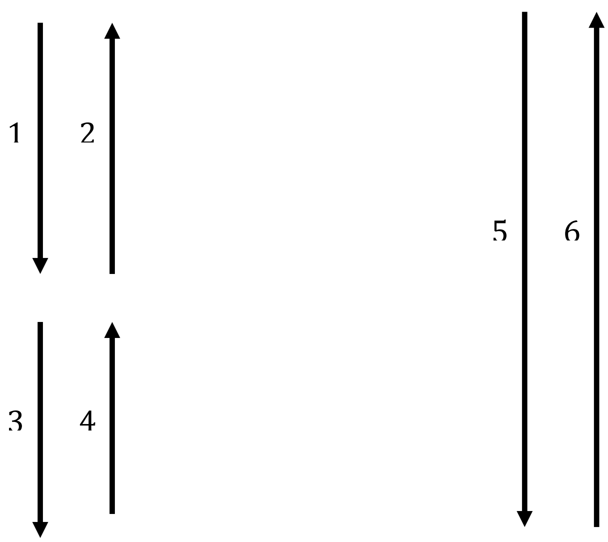
Diagrams

Label the following on the heating curve to the right (0.5 points each):

1. boiling point
2. melting point
3. heat of fusion
4. heat of vaporization



Label each arrow representing a change in state on the diagram (0.5 points each):



1. ______________________________

2. ______________________________

3. ______________________________

4. ______________________________

5. ______________________________

APPLICATIONS

Choose one change in state from the diagram above. Explain how that change in state occurs at a molecular level (1 point). Be sure to mention the level of kinetic energy the molecules have before and after the change (1 point). Lastly, relate this change in state to the heating curve at the top of the page. (1 point)

APPENDIX K

POST-LAB SURVEY QUESTIONS

Participation in this research is voluntary. Participation or non-participation will not affect your grade or class standing in any way. Reflect back on the lab you just completed when answering the following questions.

1. I was confident in my ability to successfully perform this lab activity independently, without assistance from my lab partner or the teacher.

   Strongly Agree Agree Neutral Disagree Disagree Strongly
   1……….……2……………3…………..…4……………….5

2. Completing this lab activity made me more interested in chemistry as a subject.

   Strongly Agree Agree Neutral Disagree Disagree Strongly
   1……….……2……………3…………..…4……………….5

3. What we did in this lab helped me understand the theory covered in regular chemistry class.

   Strongly Agree Agree Neutral Disagree Disagree Strongly
   1……….……2……………3…………..…4……………….5

4. A prior understanding of chemistry concepts was necessary in order to complete this lab successfully.

   Strongly Agree Agree Neutral Disagree Disagree Strongly
   1……….……2……………3…………..…4……………….5

5. This lab format provided me with a better understanding of what it is like to do real science.

   Strongly Agree Agree Neutral Disagree Disagree Strongly
   1……….……2……………3…………..…4……………….5

6. The topics we addressed in the lab were appropriately challenging.

   Strongly Agree Agree Neutral Disagree Disagree Strongly
   1……….……2……………3…………..…4……………….5

7. If you disagreed or strongly disagreed with the last question, were the labs

   a. wellbeyond your understanding (much too challenging)
   b. just beyond your understanding (somewhat too challenging)
   c. just below your understanding (somewhat too easy)
   d. well below your understanding (much too easy)

8. My understanding of how this lab related to what we are studying happened:

    a. before I completed the lab activity
    b. while I was completing the lab activity
    c. after I was done completing the lab activity
    d. after I was done completing the lab report
    e. never; I did not understand the connection between concepts from lab and class

9. Is there anything else I should know about your experience completing this particular lab?

Based on the Rovira-Figueroa Pilot Study Questionnaire (2009) and the Domin Laboratory Evaluation (2007).

APPENDIX L

STUDENT CONFIDENCE AND ATTITUDE POST-LAB INTERVIEWS

Traditional Lab Interview Questions

1. What do you like most about traditional chemistry labs? Explain why you like this aspect.

2. What do you like least about traditional chemistry labs? Explain why you don't like this aspect.

3. Please describe how you *felt* when performing traditional laboratory experiments.

4. What skills are needed to successfully complete traditional chemistry labs?

5. In what way(s) do traditional laboratory activities contribute to your understanding of chemistry?

6. In what way(s) do traditional laboratory activities contribute to your confidence as a student of chemistry?

7. Do you think you could have completed the traditional labs to the same degree of success if you were just given the instructions before the concepts were explained to you in class?

8. When (before lab, during lab, or after lab) did you fully understand the concepts from lab and how they related to the ideas we discussed in class?

9. Do you feel like traditional labs improved your ability to imagine ways in which this concept exists in real world application? Explain.

10. Is there anything else I should know about your experience performing traditional labs?

Inquiry-Based Lab Interview Questions

1. What do you like most about inquiry-based chemistry labs? Explain why you like this aspect.

2. What do you like least about inquiry-based chemistry labs? Explain why you don't like this aspect.

3. Please describe how you *felt* when performing inquiry-based laboratory experiments.

4. What skills are needed to successfully complete inquiry-based chemistry labs?

5. In what way(s) do inquiry-based laboratory activities contribute to your understanding

of chemistry?

6. In what way(s) do traditional laboratory activities contribute to your confidence as a student of chemistry?

6. Do you think you could have completed the inquiry-based labs to the same degree of success if you were just given the instructions before the concepts were explained to you in class?

7. When (before lab, during lab, or after lab) did you fully understand the concepts from lab and how they related to the ideas we discussed in class?

8. Do you feel like inquiry-based labs improved your ability to imagine ways in which this concept exists in real world application? Explain.

9. Do you feel like traditional labs improved your ability to imagine ways in which this concept exists in real world application? Explain.

10. Is there anything else I should know about your experience performing inquiry-based labs?

Based on the Rovira-Figueroa Pilot Study Questionnaire (2009) and the Domin Laboratory Evaluation (2007).

APPENDIX M

COMPARATIVE INTERVIEW: STUDENT REFLECTIONS ON INQUIRY AND TRADITIONAL LABS

Comparative Interview Questions

1. How did the format of the inquiry labs differ in comparison to traditional labs?

2. What skills are needed to successfully perform each type of chemistry lab—inquiry-based and traditional?

3. Please describe how you *felt* when performing each type of laboratory experiment.

4. In what way(s) does each type of laboratory activity contribute to your understanding of chemistry?

5. Which method of lab instruction, traditional or inquiry, helped you understand the concepts better?

6. Which method of lab instruction, improved your ability to imagine ways in which this concept exists in real world applications? Explain.

7. Did you prefer traditional labs or the inquiry labs? Why?

8. Is there anything else I should know about your experience performing traditional and inquiry-based labs?

Based on the Rovira-Figueroa Pilot Study Questionnaire (2009) and the Domin Laboratory Evaluation (2007).

APPENDIX N

STUDENT-TEACHER LAB COMMUNICATION LOG

Audio File Number	Type of question					
	Affirmation	Procedural		Combination	Conceptual	
		Steps	Manipulation	Manipulation / Terms	Terms	Connections