TEACHING REACTIONS AND STOICHIOMETRY: A COMPARISON OF GUIDED INQUIRY AND TRADITIONAL LABORATORY ACTIVITIES.

By

Lynn Meister Thomas

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Physical Science – Interdepartmental

2012

ABSTRACT

TEACHING REACTIONS AND STOICHIOMETRY: A COMPARISON OF GUIDED INQUIRY AND TRADITIONAL LABORATORY ACTIVITIES

By

Lynn Meister Thomas

There is a major movement in science education towards the inclusion of science inquiry and process. Guided-inquiry instruction is expected to have a positive impact on students' concrete and conceptual knowledge along with their ability to engage in the practices of science.

This study examined the impact of inquiry-based teaching on student achievement. The topics of reactions and stoichiometry were taught in two different periods of first-year secondary honors chemistry. Both classes received the same lectures and assignments for this curriculum and both classes performed the same laboratory activities. However, one class received traditional, step-by-step (often called "cookbook") laboratory instructions while the other class developed their own procedures and made decisions about data to complete the laboratory activities. Pre- and post-tests were given to each class, followed by a test of retention after ten weeks.

The results of this study indicate that inquiry-based instruction has a positive impact on student achievement. A significant increase between pre- and post- test scores for the experimental group as opposed to the scores for the control group suggests that achievement was correlated with guided inquiry instruction methods. Additionally, a notable trend suggested that guided inquiry instruction has a positive effect on learning retention.

ACKNOWLEDGMENTS

I am thankful to the people who helped me develop this thesis: my cohorts in the graduate program and the instructors at Michigan State University. Dr. Merle Heidemann deserves special recognition for her guidance and modeling of excellent inquiry instruction.

Dr. Paul W.W. Hunter and Mr. Sheldon Knoespel renewed my enthusiasm for inquiry in the chemistry lab. Their course made me rediscover the learning and fun that occur when students investigate and problem-solve as collaborators. You will be missed, Dr. Hunter.

Finally, I would like to thank my husband, Chuck. Your patience, encouragement, and support made this work possible. My summers spent at MSU proved the adage: “absence makes the heart grow fonder.”

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Introduction

Nationwide, there is a prominent movement in science education toward an emphasis on science inquiry and process (Anderson, 2002; Minner, Levy, & Century, 2010). It has long been recognized that rote learning of content is not enough; students also need an understanding of the practice of science. Understanding the process of science has a profound impact on our daily lives. It helps us make decisions about everything from healthcare to politics to consumer buying decisions. Technology and science play an increasingly important role in our everyday experience. Indeed, science practice has an impact on the future of our nation, as President Obama asserted in a speech to the National Academies of Science, “Reaffirming and strengthening America’s role as the world’s engine of scientific discovery and technological innovation is essential to meeting the challenges of this century” (Rhee, 2009).

The interest in and commitment to inquiry science instruction spans many years. Inquiry instruction has been defined as many different things; however, it is based on a philosophy of learning known as constructivism (Cakir, 2008; Colburn, 2000). Inquiry-based approaches emphasize that knowledge is constructed by an individual through active thinking, requiring organization of information and integration of information with existing knowledge, and that an individual has to be actively engaged in order for learning to take place. The National Research Council (2000) describes the “essential features of classroom inquiry” as follows:

1) Learners are engaged by scientifically oriented questions.

2) Learners give priority to evidence, which allows them to develop and evaluate explanations that address scientifically oriented questions.
3) Learners formulate explanations from evidence to address scientifically oriented questions.
4) Learners evaluate their explanations in light of alternate explanations, particularly those reflecting scientific understanding.
5) Learners communicate and justify their proposed explanations.

Within the past two decades or more, publications such as *Science for All Americans* (Rutherford and Ahlgren, 1989) and *Benchmarks for Science Literacy* (American Association for the Advancement of Science, 1993) promoted the inclusion of inquiry in science education. Inquiry has been encouraged in the National Science Education Standards (NSES) as an instructional method that models scientific practice and encourages students to gain content knowledge. Scientific inquiry is defined in the NSES as follows (NRC,1996):

> "Scientific inquiry refers to the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work. Inquiry also refers to the activities of students in which they develop knowledge and understanding of scientific ideas, as well as an understanding of how scientists study the natural world."

Recently, the National Research Council developed the *Framework for K-12 Science Education* (2011), identifying the nature of learning science and the science all K-12 students need to know. Currently, a state-led development of the Next Generation

Science Standards is underway with the vision “that students, over multiple years of school, actively engage in science and engineering practices and apply crosscutting concepts to deepen their understanding of the core ideas in each field.” (NRC, 2011). The *Framework* emphasizes and strengthens the goal in science education to engage in scientific inquiry. However, it emphasizes “practices” rather than inquiry. The use of “practices” means that students should be provided with learning experiences that “engage them with fundamental questions about the world and with how scientists have investigated and found answers to those questions.” Bybee (2012) indicates that the point of view of the *Framework* is not one of replacing inquiry; rather, it expands and clarifies the inquiry practices of science. The emphasis on practice instead of inquiry is described as an improvement because “it minimizes the tendency to reduce scientific practice to a single set of procedures” and avoids the mistaken idea that there is one scientific method.

Additionally, the AP Chemistry curriculum framework to be implemented in 2013-2014 contains an emphasis on science practices (College Board, 2011). The framework defines practice as a way to “coordinate knowledge and skills in order to accomplish a goal or task. The science practices enable students to establish lines of evidence and use them to develop and refine testable explanations and predictions of natural phenomena.” Specifically, *Science Practice 4* states: “The student can plan and implement data collection strategies in relation to a particular scientific question.”

Based on these national recommendations, inquiry is frequently the key word used to describe good science teaching and learning. However, researchers (Minner, Levy, & Century, 2010; Anderson, 2002) note that there are several uses of the term inquiry. Indeed, even within the National Science Education Standards (1996), there are references to at least three distinct explanations: what scientists do, how students learn, and how teachers design lessons. The rather broad definition of inquiry can lead to various interpretations of the term, but it can generally be summed up as either a certain type of activity or a desired method of teaching. Of the varied types of explanations, inquiry teaching is the one of central concern and a focal point for educational reform efforts. It is generally agreed that inquiry refers to specific teaching techniques that are "more student-centered and less step-by-step teacher directed learning" (Anderson, 2002). There is a transition in the teacher's role from knowledge dispenser to coach or facilitator, while the student's role changes from passive recipient to self-directed learner.

Despite the national acceptance of student-centered inquiry as sound pedagogical practice, there is little evidence that this consistent drive for science education reform has been implemented in classrooms. Wilson, Taylor, Kowalski, and Carlson (2009) discuss two large-scale studies from Horizon Research, Inc., Chapel Hill, NC (Hudson, McMahon, & Overstreet, 2002; Weiss, Pasley, Smith, Banilower, & Heck, 2003) that "highlight the uncommonness of inquiry-based teaching in the United States." Surveys indicated that traditional teaching methods and learning goals, such as lecture and "cookbook-style" labs, vastly outnumbered inquiry teaching practices. From classroom observations and interviews with 364 science and mathematics teachers, Weiss et al. (2003) found that inquiry was a focus of only 2% of science lessons in grades 9-12. The Hudson, et al. (2002) survey found that only 12% of U.S. teachers said they had implemented recommendations from the National Science Education Standards. Wilson, et al. (2009) point out that there are many barriers to the inclusion of inquiry in the classroom, including teacher beliefs about learning and assessment. They feel teacher accountability and an increased emphasis on standardized tests have led to the belief that accountability and inquiry-based reform are incompatible. Teachers feel pressured to cover large amounts of content and factual knowledge at the expense of inquiry-based lessons.

Effectiveness of Inquiry-Based Materials and Teaching

In light of this apparent dichotomy between accountability and inquiry-based curricula, it seems important to demonstrate the successful impact of inquiry-based teaching on student achievement. Many researchers have found inquiry and minimally guided instruction to have a positive impact on learning (e.g., Bopegedara, 2011; Geier, et al., 2008; Lewis and Lewis, 2005; Rudd, Greenbowe, Hand, & Legg, 2001). However, others claim that studies indicate minimally guided instruction is either less effective or not significantly different than direct instruction (e.g., Kirschner, Sweller, & Clark, 2006; Mayer, 2004; Pine, et al., 2006).

In particular, Kirschner, et al. (2006) argue that although minimally guided instruction is “intuitively appealing”, these approaches “ignore both the structures that constitute human cognitive architecture and evidence from empirical studies … that consistently indicate that minimally guided instruction is less effective and less efficient than instructional approaches that place strong emphasis on guidance.” Much of their argument is supported by the Atkinson and Shiffrin (1968) cognitive model, which refers to the relations between working memory and long-term memory. According to Atkinson and Shiffrin, when information is first presented, it enters short-term (“working”) memory. However, working memory has limited space and memories only reside for a limited time; therefore, as new items enter, old ones leave. On the other hand, each time information is rehearsed while it is in working memory, it also increases its strength in long-term memory and the longer an item stays in short-term memory, the stronger the association becomes in long-term memory.

Kirschner, et al. (ibid.) maintain that the goal of instruction is to alter long-term memory. If nothing has changed in long-term memory, nothing has been learned. Problem solvers with expertise in an area draw on experiences stored in long-term memory, from which the best procedures for solving problems are quickly selected and applied. When processing new information, working memory is very limited, both in duration and in capacity. Solving a new problem requires problem-solving search and this search involves the use of the limited working memory. Kirschner, et al. (ibid.) contend that problem-solving search is an inefficient way to alter long-term memory and indeed, “problem-solving search can function perfectly with no learning whatsoever.” However, when material is already stored in long-term memory and is transferred from long-term memory into working memory, the limited duration and space of the working memory is not important. Hence, it is only when encountering novel information that the limits of working memory come into play. Cognitive load theory suggests that minimally guided exploration of complex situations may produce a heavy cognitive load that is unfavorable to learning (Paas, Renkl, and Sweller, 2003). Therefore, instruction should be designed to reduce the working memory load. They believe that one way to reduce this load is to provide guided instruction and background information for the working memory to build on.

In agreement with the cognitive load theory, other researchers have come to similar conclusions regarding inefficient and/or ineffective learning from pure discovery techniques. For example, in their research on instruction in the use of computers to construct FileMaker Pro databases, Tuovinen and Sweller (1999) found that discovery learning caused an increased cognitive load and led to poorer learning than guided techniques such as worked-examples practice. In studies of guided feedback, Moreno (2004) found that low-prior knowledge students achieved better retention and transfer scores from strongly guided learning than from discovery in multimedia instruction of botany content to college students who were unfamiliar with botany. Mayer (2004) concluded that decades of research have consistently shown that “guided discovery was more effective than pure discovery in helping students learn and transfer.”

Pine, et al. (2006) compared the performance of students using hands-on curricula with an equal number of students using textbook curricula. The goal was to assess whether students gained the “ability to do scientific inquiries” as indicated by the National Science Education Standards. Student performance was assessed using both hands-on performance assessments and multiple-choice items. They found little or no effect from hands-on versus textbook instruction; but rather, found a strong correlation of “ability to do scientific inquiries” with cognitive ability. These results imply that inquiry-type lessons do not impact a student's ability to engage in the process of science; rather, this ability depends on inherent intellectual capability.

In a study on open-inquiry instruction with college chemistry students, Berg, Bergendahl, Lundberg, and Tibell (2003) found a positive influence on students' *attitudes* towards science lessons; however, they did not find this approach to have a significant effect on improving students' academic achievements.

Despite research that finds pure discovery instruction ineffective, many studies demonstrate that inquiry instruction has a positive impact on learning. For example, Hickey, Wolfe, and Kindfeld (2000) found that at-risk high school students who learned in an open-ended inquiry environment through the use of Gen-Scope software (a tool that students can use to investigate a variety of phenomena in genetics) exhibited learning gains significantly higher than students in comparison classrooms. In addition, Lewis and Lewis (2005) implemented a guided inquiry instructional method in a college level general chemistry class. An experiment was run over the course of one semester comparing two sections of general chemistry. One section received traditional lectures three times a week while the experimental section attended lecture twice a week and participated in peer-led guided inquiry once a week. Comparison of student performance on the course exam and the final exam showed that the experimental group consistently outperformed the control group.

Additionally, Geier et al. (2008) implemented an inquiry intervention program in an urban setting over the course of a three-year period. Approximately 5000 students were involved in the study, along with 37 teachers in 18 different schools. The science curriculum was designed as a series of 8- to 10-week units that incorporated scaffolded inquiry investigations. The inquiry units were scaffolded using technology tools that supported student questions and data collection, along with providing curricular support for model-building and scientific reasoning. It was found that middle school students in science classes that used inquiry-based materials received significantly higher pass rates on the Michigan Educational Assessment Program (MEAP) than their peers in traditional classrooms. They also found that a higher level of participation in inquiry resulted in higher learning gains, i.e., there is a cumulative effect when science inquiry is pursued at multiple grade levels.

Hmelo-Silver, et al. (2007) agree with Kirschner, et al. (2006) that there is “little evidence to suggest that unguided and experientially-based approaches foster learning.” However, they argue that although Kirschner, et al. (ibid.) label inquiry instruction as “minimally guided”, inquiry learning should not be lumped with unguided “pure discovery” learning because it is far from being “minimally guided.” They point out that inquiry involves scaffolding and guidance that supports learning. They assert that this decreases cognitive load because the learner is led to focus on the tasks that are relevant. This provides the guidance required for a novice learner.

The significant conclusion that can be drawn from the argument about cognitive theory and inquiry learning is that there is a difference between pure discovery and guided inquiry. It seems that part of the disagreement stems from different interpretations of what inquiry instruction looks like. Kirschner (2006) defines minimally guided instruction as a method in which “learners, rather than being presented with essential information, must discover or construct essential information for themselves." Mayer (2004) points out that students often do not learn the rule or principle under pure discovery, so some "amount of guidance is required to help students mentally construct the desired learning outcome." Hence, pure discovery without the provision of any essential background information is likely to be ineffective. However, an appropriate amount of guidance in inquiry instruction appears to result in positive learning gains.

It is frequently assumed that in order for students to be engaged in inquiry-oriented activities they need to design and perform investigations from scratch, as demonstrated in the assumptions made by Kirschner, et al. (2006) in their assessment of minimally guided instruction. However, most students need considerable practice before they can conduct their own investigation from start to finish (Bell, et al., 2005). Banchi and Bell (2008) describe the levels of inquiry as a four-level continuum: confirmation, structured, guided, and open. Confirmation and structured inquiry methods provide students with the question and the procedure, and students either compare their results to a known expectation, or they develop an explanation based on their data. These methods are lower inquiry but provide students with practice in conducting investigations. Guided inquiry provides the students with a question, but the students develop their own procedure and devise their own explanations. Open inquiry is the highest level of inquiry where students develop their own questions, investigations, procedures, and conclusions.

The majority of labs used in high school are taught from a lab manual provided by the textbook publisher, referred to as traditional "cookbook" type labs. Typically, students follow the directions in the lab manual, perform the experiment, record the data, and fill out the worksheet provided. Witzig, et al. (2010) developed mini-journals as a means of converting typical first-year college chemistry cookbook labs into an inquiry-driven format that encourages scientific practice. The mini-journal resembles an authentic peer-reviewed scientific journal article, including data and findings. The discussion section guides the students toward a limited set of follow-up questions that are testable. In the lab, students then develop their own procedures to address their research questions, collect data and interpret their results. Using this process, students use inquiry to engage in many of the same activities and thinking processes as practicing scientists.

Hanson (1982) maintains that students often perceive lab work as “boring” and separate from the lecture material. However, a goal of the lab is certainly to reinforce content learned in lecture. The goal in the laboratory-centered approach is to carefully connect theory with practice with the inclusion of chemical discoveries (Bopegedera, 2011). Bopegedara’s implementation of the laboratory-centered approach includes a scaffolded approach. Her experience indicates that it is unrealistic to expect students to have the knowledge and experience to do inquiry-based labs at the beginning of the year. She begins the year with verification-style labs and transitions to guided inquiry labs, with the culmination of a final open-inquiry lab project developed entirely by students. Bopegedara’s assessment of the laboratory-centered approach includes the observation that students are enthusiastic and active participants who are able to apply learned concepts to solve problems.

Classroom inquiry experience must be combined with subject matter in a way that allows students to use scientific reasoning to develop their understanding of science. Banerjee (2010) created a professional development model that trains teachers in converting cookbook-style labs into inquiry labs. This method provides an emphasis on data collection that leads students to reflect on questions such as “What counts? What data do we keep? What patterns exist?” Data on student pre- and post- test scores in science inquiry showed an increase of 20%. Additionally, an attitude survey indicated that a majority of the students liked guided inquiry and felt it helped them improve their confidence.

Rationale for the Study

In light of the recommendations from the National Research Council (2011), teachers face a challenge. It is very clear that science learning needs to be grounded in scientific practices and inquiry. However, teachers also face the pressure of accountability and high-stakes testing. There is an apparent dichotomy that suggests teaching for performance on standardized tests and teaching via inquiry are incompatible. This is further complicated by differing views on the definition of inquiry and on the efficacy of its educational impact. The question: is it possible to prepare students to learn specific science content while developing a deeper understanding and ability in the practice of science? It is surmised that systematic integration of inquiry learning in the curriculum may solve this apparent dichotomy.

Rationale for Choice of Content Area

The content area selected for this study, stoichiometry, was chosen because it is both one of the most difficult and one of the most important concepts for a chemistry student to master. Stoichiometry is the study of quantitative relationships in chemical reactions. In a balanced chemical equation, the relationship between quantities of reactants and products form a whole number ratio. This ratio can then be used to find quantities such as amount of products that can be produced with a given amount of reactants. The quantities of reactants or products can be expressed in moles, mass, volume, or number of particles. Stoichiometry is essential for other practical applications of chemistry such as percent yields and empirical formulas.

Students often find stoichiometry difficult because it is an abstract concept. Gabel (1999) points out that stoichiometry is taught at the highest level of abstraction, the symbolic level. She indicates that chemists represent both the macroscopic and the microscopic levels symbolically through the use of chemical symbols, chemical formulas, and chemical equations. Students must understand how to balance equations, and they are expected to interpret what the balanced equation represents. Coefficients are used to represent the particulate nature of matter, but students are asked to express amounts in quantities such as the mole, a number so huge it is impossible for most students to imagine. Or, students are asked to relate the mass of macroscopic materials to the number of atoms or particles in the substance. In addition, solving of a stoichiometry problem involves a complex algorithm.

Deters (2003) conducted a survey of approximately 300 college chemistry instructors asking them to choose the top five topics from a list of twenty-two topics that students need to master prior to entering college chemistry. The top five topics on the compiled list were, in order: basic skills, moles, dimensional analysis, stoichiometry, and naming and writing formulas. An examination of this list indicates that in addition to being the fourth topic on the list, all of these important topics are related to the study of stoichiometry. Hence, mastery of stoichiometry is of central importance to the study of chemistry.

Davidowitz, Chittleborough and Murray (2010) showed that while students could solve algorithmic chemistry problems, they had difficulties in answering conceptual problems covering the same topics. Nakhleh (1992) found that although many high school students could correctly balance equations, half of these students couldn't draw a correct molecular diagram to explain the equations. This demonstrates that students can often solve problems using algorithms without possessing the reasoning and processing skills that indicate conceptual understanding. Fully understanding a balanced equation can be helpful in considering chemical reactions at the molecular or atomic level. Students who fully understand stoichiometric relationships can more easily visualize the breaking of bonds and rearrangement of individual atoms. Therefore, in addition to the quantitative application, it is useful as a model for the particulate nature of matter, a fundamental abstract concept.

Cohen et al. (2000) described various methods used to help high school science students improve their problem solving skills. They noted that problem solving frequently becomes an exercise in mere symbol manipulation, particularly for novice problem solvers. It was pointed out that ratios are fundamental to many aspects of chemistry and it is valuable to help students articulate the meaning of ratios. Using stoichiometry with a balanced equation is essentially an exercise using ratios, and it stands to reason that many students have trouble with stoichiometry because they do not fully understand the meaning of ratios. In addition, they also point out that "the difficulties associated with proportional reasoning do not diminish with additional years of science training."

Many techniques have been suggested to help students make concrete sense of stoichiometry problems (Cohen et al., 2000; Davidowitz, et al., 2010; Felder, 1990; Haim, Corton, Kocmur, Galagovsky, 2003). The study described in this document was designed to determine if participation in guided inquiry labs would help students comprehend and retain this abstract concept. It was expected that participation in inquiry labs would help students develop a clear picture of the physical situation associated with numerical answers to stoichiometric problems, leading to deeper conceptual understanding.

Development of Laboratory Activities

Once it was determined that guided inquiry laboratory investigations might be an effective method both to develop skills in the process of science and also in deeper understanding of content, time was spent developing appropriate laboratory activities. One concern was the amount of time required for the activity. The experimental design required one group of students to follow a traditional cookbook lab in the same amount of time as another group participated in a similar inquiry lab. Thus, it was important to develop activities that would require comparable amounts of time. In addition, in order to reinforce underlying concepts, it was desirable to construct labs that would give “good results.” In other words, stoichiometric calculations predict an expected amount of product, and to reinforce that concept, it is preferable to have results that are reasonably close to the expected outcome. Therefore, the laboratory investigations had to be “forgiving” of possible errors.

Another major concern was safety. Because students would be constructing their own procedures for the investigations, materials used could not hold the potential for dangerous interactions and outcomes. In addition, the possible processes developed by students should not lead to a choice of hazardous techniques. However, by the time students would be participating in these inquiry activities, they would have several months of experience in the lab and would already be trained in many laboratory techniques and safety rules. Methods and materials were chosen with a reasonable expectation for safety, with the understanding that students would continue to be instructed in safe laboratory behavior.

Demographics / Research Setting

Escanaba is located in Delta County on the shores of Lake Michigan in Michigan’s Upper Peninsula. At the time of the 2010 U.S. Census, population of the city of Escanaba was 12,616 with a median household income of $29,130. Of residents age 25 and older, 89.3% are high school graduates and 18.3% have Bachelor’s degree or higher. There are 19.7 % persons below poverty level with many families experiencing financial distress due to a slow economy and limited jobs in the area. Escanaba is home to Bay College, a community college that graduates approximately 500 students each year.

The Escanaba Area Public School District has three elementary schools, one middle school, one high school, and one alternative high school. In addition, the Delta-Schoolcraft Intermediate School District Area Vocational Technical Center is located next to the high school and offers occupational programs and vocational education. In the school year 2011-2012, there were approximately 980 students enrolled in Escanaba Area Public High School. The ethnic makeup of the school was 92% white, 5% American Indian, and 3% other. The graduation rate was 87%, with 7% off track but continuing, and a 5% dropout rate. The school district had 59.6% students eligible for free and reduced lunch, well above the state average of approximately 36%.

This study was conducted in two first-year Accelerated Chemistry classes at Escanaba High School.

Implementation

This study was implemented in the spring of the 2011-2012 school year. Students in two first-year Accelerated Chemistry classes took part in this study. First-year chemistry is required for all students at Escanaba High School; however, the Accelerated Chemistry classes are honor-level classes. Students who enroll in these classes are self-selected, with additional advisement and approval from guidance counselors. These students usually have a grade point average above 3.0 and typically plan on pursuing a college degree following graduation. Many of the students do not plan on obtaining a degree in a science- related field, although up to one-third express interest in medical or engineering fields of study.

Because a goal of this study was to investigate whether causal inferences could be made about the effectiveness of guided inquiry-based instruction, a randomized control design was desired. Although students self-select for the course, the division into two sections is done randomly through the scheduling process. Forty-eight students gave consent to participate in the study, with 25 students in the section that received the inquiry laboratory instruction and 23 students in the section that received the traditional laboratory instruction. The gender distribution was essentially 50:50 in each class, with the guided inquiry group having 13 boys and 12 girls, and the traditional laboratory section having 11 boys and 11 girls. Four students enrolled in the classes were not included in the study: three were absent for extended periods of time and missed much of the reaction/stoichiometry unit and one opted out of the study on the research consent form.

The general design of this study follows: The topics of reactions and stoichiometry were taught in two different periods of first-year accelerated chemistry. Both classes received the same lectures, assignments, and activities for this curriculum and both classes performed the same laboratory investigations. However, one class received traditional, step-by-step “cookbook” laboratory instructions (hereafter referred to as “control” or “cookbook” group) while the other class developed their own procedures and made decisions about data collection to complete the laboratory activities (hereafter referred to as “inquiry” or “experimental” group). Pre- and post-tests were given to each class, followed up by a test of retention after ten weeks.

Before implementation of the inquiry-based stoichiometry unit, students had participated in more than a semester of chemistry content using instructional methods such as lecture, note taking, reading, traditional laboratory activities, and in-class and homework practice. Pupils had already divided into student-selected lab groups consisting of two or three partners per group and had established working relationships and roles within lab groups.

The sequence of instructional segments appears in Table 1. The activities are listed for each topic, along with the class time spent on each segment. The activities include the pieces of instruction that were not altered between classes, such as reading guides, lectures, mini-labs, and practice. Investigations that were developed for use in this study are denoted in bold with an asterisk (**LAB***). These designated investigations (**LAB***) were performed as cookbook style labs for the control group and inquiry style labs for the experimental group; however, each group performed the same basic experiment (see Appendices A-E).

Table 1. Implementation outline.

Content Topic	Objectives (The learner will...)	Instructional Activities	Time
Balancing Equations	1. Write a formula equation for a chemical reaction. 2. Balance chemical equations applying the conservation of matter.	• Reading Guide • Lecture • Practice	2 class periods
Classifying and Predicting Products of Chemical Reactions	1. Define and give general equations for synthesis, decomposition, combustion, single replacement, and double replacement reactions. 2. Recognize and classify a reaction. 3. Use the activity series to predict products of single replacement reactions. 4. Predict products of double replacement reactions.	• Lecture • Practice • *Mini-lab*: Observing Single- and Double-Replacement reactions • **LAB*** Determining an Activity Series • *Mini-lab*: Observing Ionic Compounds • *Lab Practical*: Predicting and Classifying Chemical Reactions	6 class periods
Stoichiometry	1. Calculate the moles of a reactant or product from the moles of a different reactant or product. 2. Calculate the mass of a reactant or product from the mass of a different reactant or product. 3. Calculate the volume of a gaseous reactant or product from the amount of a different reactant or product. 4. Identify the limiting reactant when given the masses of more than one reactant. 5. Determine the amount of product formed when given the masses of more than one reactant. 6. Distinguish between theoretical yield, actual yield, and percent yield. 7. Calculate percent yield.	• Reading Guide • Lecture • Practice • *Mini-lab*: Observing Limiting Reactants • **LAB*** What happens when iron is burned? • **LAB*** How Can You Change Baking Soda into Table Salt? • **LAB*** Air Bag Experiment • **LAB*** Foiled Again!	12 class periods

The instructional methods that were consistently used in both the experimental and control group included reading guides, lectures, practice, and mini-labs. These techniques have been used in previous years for content instruction and are part of the general scaffolding provided in each class. *Reading guides* consist of a series of written prompts students must answer while reading the textbook. For example, students may be directed to look at a picture or diagram and make an inference related to the content, or they may be asked to think of an everyday example related to the textbook material. *Lectures* consist of the teacher's presentation during which students are expected to fill in a lecture outline. Students have the opportunity to ask questions or make comments, but student input is minimal. *Practice* refers to problem sets from the textbook or worksheet that review and reinforce the content from lecture. These may be assigned as in-class practice or as homework. *Mini-labs* are observation labs that provide concrete observation of the recently presented ideas. This type of lab activity contains specific directions and does not take the entire class period to perform. For example, after learning how to predict the products of a single replacement reaction, students are prompted to combine different metals in ionic solutions and observe the reactions in the lab. Students typically fill in a worksheet where they are asked to make predictions, then perform the investigations and follow up with observations and conclusions. This type of activity is similar to Bopegedara's (2011) "verification lab" used as scaffolding in the progression to guided and open inquiry investigations.

Additionally, all control and experimental students took part in a *lab practical*, a cooperative assessment given after students had completed the material related to classification and prediction of chemical reactions. Students, along with their lab partner(s), proceeded around the laboratory and performed simple investigations at various stations. For example, one station gave students the instructions to perform the catalyzed decomposition of hydrogen peroxide; after which they were directed to insert a glowing splint into the test tube (observing that it reignited in the presence of oxygen gas). Following this, students were required to write observations, balance the equation, identify the type of reaction, and answer an inference question explaining why the wood splint reignited. Again, this type of activity serves as scaffolding for the inquiry-based labs used in the study. Students gained experience working cooperatively, a significant skill needed in performing inquiry investigations (Davis, 2000).

Description and Analysis of Activities:

Lab: Determining an Activity Series for Metals

The first investigation used in this study was “Determining an Activity Series” (Appendix A). All students were given samples of four metals: zinc, copper, iron, and magnesium, along with four solutions of the metallic salts. Students in the control group participated in a traditional “cookbook lab.” On a lab report sheet, they were given explicit directions for combining the metals and solutions, along with a prepared data table to fill in, and specific questions to answer. They were then asked to develop an activity series that ranked the metals from most active to least active and to compare their results to a reference standard activity series. The students completed this investigation with ease and had no trouble filling in the prepared lab report sheet. The only questions arose from occasional difficulty in observing whether a reaction had occurred.

The students in the guided inquiry group were given the same metallic salt solutions and metal samples. However, they were given the following task: “Design a procedure to test the metals for their relative activities. From your data, you should rank the four metals so that you end up with a list of the metals in order of decreasing activity (most active first).” They were asked to record their procedure, any relevant data and observations, make a conclusion and include a discussion of theory explaining their reasoning.

This was the first time the students had performed a lab without any directions. There was considerable dismay. Some groups obtained their materials, brought them to their lab table, and just stood there. When questioned, they responded, “We don’t have any idea what to do.” It was then advised that they begin combining some of the substances and make observations, suggesting that this might lead to some ideas. It was also suggested that students refer to previous problems they had done regarding single-replacement reactions. Once students began combining metals in solutions, they began discussing the problem. Several students became excited as they realized they could figure out a procedure. However, they had difficulty communicating their procedure. One student recorded the procedure by stating, “Mix metals with solutions not containing the metal,” while another stated with more clarity, “In a well-plate, place 4 samples of each metal. Add three drops of each metal nitrate solution to each sample of metal. Observe and record what happens to each.”

Another difficulty arose in deciding how to record their results. Some groups simply drew a grid resembling the arrangement of their experimental well-plate, and recorded their observations in the appropriate space. Others listed each combination of metals and solutions and recorded the results next to the list.

Finally, although many groups could determine the order of activity for the metals, they struggled to explain their reasoning. However, after much discussion, most groups developed adequate explanations. Common explanations included statements such as, “Magnesium is the most reactive because it reacted in the most solutions.” Another response indicated, “If a visible chemical reaction occurs, the metal in the well is higher on the activity series than the metal in the solution you added to it.”

A few groups exhibited misconceptions in their explanations. For example, a few students chose the metallic ion in the solution that had the most reactions as the most active metal, rather than the solid metal that reacted the most. When asked to compare their activity series to the standard series found in the textbook, a student stated, “My activity series is completely opposite compared to the one in the book.” Even in light of this error, the students in this lab group did not reconsider their conclusions, rather, they indicated that their “data must be off.” Overall, most students showed evidence of conceptual understanding. Many students expressed satisfaction that they figured out how to test the metals, and even more satisfaction when they received the expected results.

Lab: Burning of Iron

The second investigation in this study, "What happens when iron is burned?" (Appendix B) required students to determine which oxide of iron forms when steel wool is burned. The lab investigation was divided into two parts. In Part A, both the control group and the test group were asked to predict whether the mass of the product after burning would be greater, less than, or equal to the mass of the original iron. Very few students in either group selected the correct answer and explanation: greater than the original mass because the iron will chemically combine with oxygen from the air. Most students predicted the mass would be less with reasoning similar to, "some of the iron will disintegrate when it is burned." A few students chose "the same mass," citing the Law of Conservation of Mass as their reasoning.

After making their predictions, the cookbook lab group followed specific instructions on burning the steel wool in a Bunsen burner and recording relevant information in a prepared data table. They were then required to comment on their results and provide an explanation. The students recorded their results, discovered that the mass increased, and had difficulty explaining these results.

By contrast, the inquiry lab group was directed to "explain the procedure you will use to test your prediction. Be sure to include the type of data you will need to collect." All students in the inquiry group recognized that they needed to record both the mass of the steel wool before burning and the final mass of the burn product. However, many were uncertain in determination of when the reaction was complete. The students had burned magnesium metal in the past and expected a similar reaction, with a bright flame producing a final ashy product. However, the iron did not “burn” in an expected manner, rather, it glowed and sparked and did not have an obvious change in appearance. Careful observation was required to note that steel wool changed to a bluish-gray as it converted to the oxide. In addition, the steel wool remained unreacted where grasped by the crucible tongs, so students had to change their technique, rotating the position of the tongs.

Similar to the cookbook group, the inquiry group was asked to discuss results and provide an explanation. Both groups had difficulty deciding why the mass increased. Some students from each group were unwilling to change their preconceptions and concluded they must have made a measurement mistake, or as one student put it, “the balance must be off.” These students were encouraged to repeat the procedure for verification. They were then instructed to continue to Part B of the lab to obtain additional information to help with their explanation.

Part B led the students to write formulas for the possible oxide products of the combustion reaction: iron(II) oxide and iron(III) oxide. Students were also guided to write the balanced equation for the combustion reaction that would produce each oxide. The cookbook group was then led through stoichiometry problems to determine the expected mass of each oxide product from the original amount of iron. Comparing the expected masses to their actual masses, students were instructed to conclude which oxide of iron was more likely to have formed.

The inquiry group was given no guidance or suggestion to either use stoichiometry or to compare their experimental mass to the expected mass for each oxide formula. However, because they were guided to write the balanced equation for the combustion reaction producing each oxide, discussion between students eventually led to the idea that stoichiometry should be used.

Additionally, after looking at the formulas for the possible products of the combustion reaction, most students, both from the cookbook and the inquiry groups, could return to Part A and explain why the iron oxide burn product was a greater mass than the original iron sample.

Lab: Baking Soda into Table Salt

The third investigation in this study, “How can you change baking soda into table salt?” (Appendix C) was intriguing to students when they read the title. One student commented that it was like magic; many students were fascinated by the thought of changing one substance into another. This was a straightforward lab experience for the cookbook group. They followed explicit directions to perform the reaction between sodium bicarbonate and hydrochloric acid to produce sodium chloride, water, and carbon dioxide. They dried the product, found their theoretical mass, actual mass, and percent yield. Additionally, they were required to discuss specific sources of error. Students noted reasonable sources of error, most commonly that some spattering occurred as the evaporating dish was heated, resulting in a loss of product mass. Most students obtained close to the expected yield of sodium chloride; with no one obtaining over 100% yield.

The guided inquiry lab group was given the equation for the reaction and instructed to “design an experiment to produce and recover 1 gram of NaCl.” Having already successfully completed two guided inquiry investigations, it was evident the students were much more comfortable with planning their own procedure. After receiving the lab sheet and hearing introductory comments, they were impatient to begin. A few students said, “This is going to be fun!”, in sharp contrast to the apprehension when they were first asked to design their own experiment.

Because of safety concerns, the students were told to find a procedure that ensured they added enough hydrochloric acid solution without using an excess of hydrochloric acid. Students had not yet learned how to use the molarity of a solution to work stoichiometry problems, so they soon realized that they could not calculate the stoichiometric amount of hydrochloric acid needed to produce 1 gram of sodium chloride. After a period of time, if students did not come up with a method on their own, they were prompted to consider the production of carbon dioxide and eventually led to realize that they should add hydrochloric acid to the stoichiometric amount of sodium bicarbonate until the bubbling ceased. Students were also instructed in the safe use of an evaporating dish, a hot plate, and the laboratory drying oven.

Students in the inquiry group met some frustration while designing their experimental procedure. They had a general idea of what should be done, but had difficulty writing a thorough plan for obtaining the required data. When asked how they would recover the salt, many had trouble deciding how to get the final mass of the salt after drying. They considered scraping the salt out of the evaporating dish, or redissolving the salt to rinse it out of the dish. They quickly saw the problem with these methods, but it took a while to come up with the idea of recording the mass of the empty evaporating dish and determining the mass of the sodium chloride by difference.

The results from this investigation were reasonably accurate, with most students receiving between 85-95% yield. A few students in the experimental group received over 100% yield, but were able to come up with reasonable sources of error, such as insufficient drying of the salt crystals.

Lab: Air Bag

The fourth investigation, “Air Bag Experiment” (adapted from a laboratory investigation designed by Sheldon Knoespel, Michigan State University; Appendix D) directed students to construct a model air bag using a Ziploc bag, sodium bicarbonate, and 1.0 M hydrochloric acid. In both the cookbook and the inquiry version, the students’ task was stated: “The ideal result will be to fill the bag to plumpness, not to overinflate or underinflate the bag. The bag may also contain unreacted HCl and/or products of the reaction. The degree of “plumpness” will be part of your score.”

The cookbook group was then given a procedure that prompted them to find the volume of the bag using water and a graduated cylinder, then to calculate the mass of sodium bicarbonate needed to produce the volume of gas desired. They were directed to add both the acid and the baking soda to the bag without making contact until ready for the reaction to proceed. Students enjoyed the lab and had little trouble performing the activity. They filled in a lab sheet showing their stoichiometric calculations and turned in their successfully filled bag as part of their evaluation.

In contrast, the main challenge for the inquiry group was first to recognize they needed to determine the volume of gas desired; secondly, to devise a way to find the volume of the bag. Many groups just wanted to use a trial-and-error technique, varying the amount of reactants until they obtained the desired “plumpness” inside the bag. Although this was a valid method, students were discouraged from using it because it lacked efficiency and wasted supplies. Students discussed blowing up the bag with air, but couldn’t decide on a method to measure the volume of air. Once one of the groups came up with the idea of filling the bag with water, the idea quickly spread. However, some students used beakers to determine the volume of water instead of the more accurate use of graduated cylinders. These students were encouraged to transfer the volume of water from the beaker to graduated cylinders, and were subsequently surprised at the difference in the volume measurement.

Students were surprisingly proud when they were able to successfully fill their bag to “plumpness.” Students within lab groups gave each other “high fives” and made congratulatory comments such as, “We’re awesome!” or “We rock!” This supports other findings that inquiry instruction positively influences students’ perceived science competence and motivational beliefs about science (e.g., Hmelo-Silver, et al., 2007; Palmer, 2009; Walker, et al., 2011).

Lab: Foiled Again!

The fifth and final lab in this study, “Foiled Again!” (Appendix E) was an investigation of limiting reactants using a single-replacement reaction. When aluminum metal is added to copper(II) chloride, the resulting reaction is immediate and exothermic. The aluminum quickly dissolves, accompanied by bubbling, steam, and a rapid appearance of solid copper, making it an exciting observation of a single-replacement reaction. This investigation did not require collection of quantitative data; rather, physical observations were required to provide evidence for calculated predictions.

Both the inquiry and the control groups were given the procedure for this investigation, along with amounts of reactants to use. The amounts given ensured that aluminum would be the limiting reactant. Both groups were prompted to use calculations to predict the limiting reactant; however, the control group was given more specific instructions for problem set-up. The emphasis of this investigation was the use of physical observations along with calculations to support claims. The goal was that the students would be able to use physical observations to explain abstract concepts. The difference between groups was the instructional presentation of information used to determine the conceptual interpretation of a balanced equation and the meaning of limiting reactants.

The control group was presented with a lecture explanation of the chemical equation: $3\ CuCl_2(aq) + 2\ Al(s) \rightarrow 3\ Cu(s) + 2\ AlCl_3(aq)$. It was pointed out that the reactant, copper(II) chloride solution, is blue in color and the product, aluminum chloride solution, is colorless. In addition, aluminum is silver-colored and copper is reddish-brown. It was specifically stated that a visual observation could be used to determine which reactant was limiting. If the blue solution turned colorless and some of the original aluminum remained, it could be inferred that copper(II) chloride was limiting; whereas if the solution remained blue while the aluminum dissolved, the aluminum must be the limiting reactant.

Instead of lecture, the guided inquiry group was encouraged to draw particulate models of the reactants and products. Given information about the color of specific ions in solution, students were led to make inferences about the colors of reactants and products before conducting the lab.

After performing the reaction and making observations, students in both groups were asked two similar questions: "Based on your *observations*, what substance appeared to be the **limiting** reactant? Did this agree with what you expected from your calculations? Explain your reasoning." And, "Based on your *observations*, what substance appeared to be in **excess**? Did this agree with what you expected from your calculations? Explain your reasoning."

Although all students used the correct algorithm to determine the limiting reactant, some students still did not exhibit conceptual understanding. They could use calculations to determine the limiting and excess reactants and they could even state that the "limiting reactant is the one you run out of first." However, some were unable to make the connection between the meaning of the chemical equation for the reaction and the physical observations that support the concept. In the control group, students had an easier time explaining how they could tell aluminum was the limiting reactant rather than why they could observe that copper(II) chloride was the excess reactant. Ninety-five percent of the students correctly gave observational evidence that aluminum was the limiting reactant because it was used up. However, only forty-three percent of the control group explained they could observe that copper(II) chloride was in excess because the solution was still blue (or had not become colorless). Of the students who did not give observational evidence, most answers were similar to this student's response: "Copper(II) chloride was in excess because there was more of it than copper and aluminum."

The inquiry group also had some difficulty using observational evidence. Only eighty-one percent of these students explained that aluminum was limiting because it was used up; however, eighty-one percent also gave evidence that copper(II) chloride was in excess because the solution was still blue or had not turned colorless. The five students who did not give observable evidence that aluminum was limiting simply answered, "yes, aluminum was limiting and agreed with what I expected from my calculations", but did not give an observable reason. It is not possible to judge whether they did not recognize the observable evidence or if they simply did not answer the question.

Results/Evaluation

Measurement

All students involved in the study (n=48 with consent to participate) were given two separate measurements of content and process knowledge: a pre-test before receiving instruction and a post-test following instruction. Some students involved in the study (n=38) were also given a retention test several weeks following instruction. The tests were administered both to the control group and the experimental group.

The pre-test was given a few weeks before the study topic was introduced. In the intervening class time, students were introduced to the mole concept, which is prerequisite knowledge for the content material involved in the study. The post-test was administered immediately after the study topics were completed. The retention test was given approximately ten weeks after the instructional strategies were implemented.

The assessment (Appendix F) consisted of eight multiple-choice questions and seven constructed-response questions. The items were designed to assess at a variety of cognitive levels: eleven of the questions required direct use of an algorithm or recall of specific content; while four questions required explanations and/or identification of cause and effect. One of the constructed-response items required students to demonstrate the ability to plan and carry out an investigation.

Although the same questions were used for the retention test, the format was changed. All of the questions were converted to a constructed response style (Appendix G); therefore no multiple-choice items were included in the final (retention) administration of the assessment. This was done because the test was administered as part of the final exam and it was desired that students show how they arrived at their answers. In addition, only nineteen students from each group (n=38) took the retention test because it was given as part of the final exam. Six students from the experimental group and four students from the control group were unable to complete the exam in the allotted time period. These students ran out of time while completing the exam and were not given the portion of the final exam that entailed the retention test.

Data Collection and Analysis

In order to make sure that the two groups represented similar populations, a comparison was made of the students' first semester exam scores (Table 2).

Table 2. Comparison of semester exam scores.

	Control Group n=23	Experimental Group n=28
Average Exam Score	89.3%	86.6%
Range of Scores	81% - 100%	56% - 100%

The students took this exam after they each completed the same semester coursework and before participating in the instructional methods used for this study. Their scores were compared using an unpaired, two-tailed t-test. This t-test analysis returned a p-value of 0.20, which indicates that there is no significant difference between the exam scores for the two groups. This provides further evidence that the two sections are randomized and represent similar populations. It can be assumed the students in each group began the study at essentially the same academic level and ability.

Next, an analysis was done to see if guided-inquiry learning methods made a significant impact on students' performance on the science content knowledge assessment. A comparison was made of the difference in pre- and post- test scores (Table 3).

Table 3. Pre- and post- test assessment scores.

Control Group			Experimental Group		
Pretest (%)	Posttest (%)	Difference	Pretest (%)	Posttest (%)	Difference
39	74	35	13	78	65
43	78	35	39	78	39
35	87	52	22	78	56
30	78	48	30	78	48
48	100	52	35	87	52
22	83	61	30	78	48
39	96	57	43	83	40
52	96	44	35	91	56
35	87	52	17	91	74
26	78	52	35	100	65
22	74	52	35	96	61
35	87	52	26	78	52
22	83	61	30	78	48
26	91	65	30	96	66
22	57	35	35	70	35
39	91	52	43	96	53
17	65	48	30	91	61
17	61	44	35	96	61
26	74	48	35	91	56
39	96	57	17	83	66
35	70	35	17	87	70
26	74	48	26	83	57
35	70	35	30	70	40
Average = 31.7	Average = 80.4	Average = 48.7	13	83	70
			26	78	52
			Average = 29.1	Average = 84.7	Average = 55.6

The control group had an average pre-test score of 31.7%, with an average post-test score of 80.4%. This was a score improvement of 48.7%. The experimental group scored an average of 29.1% on the pre-test, with an average score of 84.6% on the post-test, leading to an average score increase of 55.6%. The percent gain values for the experimental group were compared to the percent gain values for the control group using an unpaired, two-tailed t-test. This analysis returned a p-value of 0.017. This means there is a 1.7% chance the same results would be obtained randomly. This shows that the increased gain in scores for the inquiry group is significantly different than the gain in scores experienced by the control group (the null hypothesis is rejected when the p-value is less than 0.05).

Finally, the retention scores were analyzed (Table 4). A subset of students in both groups retook the assessment ten weeks after the study. A comparison was made to determine if there was a significant difference between the post-test scores and the final retention scores of the two different groups. The experimental group received an average score that was 2.4% higher than the scores received on the post-test. The control group received an average score that was 3.8 % lower than the post-test. However, a t-test analysis (unpaired, two-tailed) of these scores gave a p-value of 0.071, indicating there was no significant difference between students' performances on retention tests. Examination of data shows that 14 out of 19 of students in the control group had negative differences in their retention score from their post test score, while only 5 out of 19 of the experimental group received lower scores.

Table 4. Comparison of post-test and retention scores.

	Control Scores (n=19)	Experimental Scores (n=19)
Range of score differences	-33 to +16	-16 to +16
# of *higher* retention scores than post-test	5	11
# of scores with no difference	0	3
# of *lower* retention scores than post-test	14	5

Student Surveys:

Students in the experimental group were given a survey on attitudes toward the guided-inquiry learning experience (Appendix I). They were asked to rate each of the guided inquiry lab activities on a scale of 1-5 (1=low, 5=high) according to the following four criteria: collaboration, thinking, interest, and learning. Table 5 shows the individual ratings for each laboratory activity and Table 6 compares the criteria by activity.

When ranking “collaboration,” students were asked to consider questions such as, “Was the activity structured in a way that made you work together? Were you actively participating throughout this activity?” When rating “thinking,” students were prompted, “How mentally engaging was this activity? Did you find yourself really thinking through the process as you performed the activity?” Under “interest,” they were asked, “How interesting did you find the activity? Did you enjoy the activity?” And, finally, the “learning” criterion asked the students to reflect on: “How much did you learn from the activity? Did you feel that it helped model the topic in a way that helped you learn?”

Additionally, after students selected their ratings for each activity, they were asked to provide general comments on their reaction to the labs, with the prompts: “Did you like doing [the lab activities]? Would you rather do something else in class? Was it frustrating to try to figure out how to do the lab without clear directions?”

Table 5. Summary of student survey results (n= 27) for each inquiry lab activity. Rating on a scale of 1-5 (1=low, 5=high)

Lab 1: Determining an Activity Series	1-3	4-5
Collaboration	3	24
Thinking	5	22
Interest	5	22
Learning	6	21
Lab 2: What happens when iron is burned?	**1-3**	**4-5**
Collaboration	7	20
Thinking	9	18
Interest	9	18
Learning	8	19
Lab 3: Changing Baking Soda into Table Salt	**1-3**	**4-5**
Collaboration	2	25
Thinking	7	20
Interest	11	16
Learning	3	24
Lab 4: Air Bag Experiment	**1-3**	**4-5**
Collaboration	3	24
Thinking	11	16
Interest	6	21
Learning	9	18
Lab 5: Foiled Again!	**1-3**	**4-5**
Collaboration	7	20
Thinking	11	16
Interest	8	19
Learning	7	20

Table 6. Comparison of average student criterion rating (1-5) for each guided inquiry lab activity. (n=27)

	Collaboration	Thinking	Interest	Learning
Determining an Activity Series	4.5	4.2	4.3	4.1
What happens when iron is burned?	4.1	3.9	4.1	4.0
Changing Baking Soda into Salt	4.5	4.1	3.9	4.1
Air Bag Experiment	4.5	3.7	4.1	3.9
Foiled Again	4.3	3.7	4.0	4.1

On a scale of 1-5, all criteria received an average rank higher than "3" for every inquiry investigations. *Determining an Activity Series* received the highest average ratings among all four criteria. This was the first inquiry activity the students participated in, so it makes sense that they would consider it the one that required the most thinking, as they were unaccustomed to developing their own procedure and making decisions about data collection. Collaboration was the criterion that received the highest overall ratings among all the lab activities; in fact, it was the only criterion that never received a "1" rating. The average rating for collaboration in each lab activity ranged between 4.1 and 4.5. Evidently, most students felt these activities required them to work together and actively participate in the investigation. Students rated the *Air Bag* activity and *Foiled Again* as the lowest for thinking. And along with *Determining an Activity Series*, they considered *Changing Baking Soda into Salt* as requiring the highest level of thinking. Again, this makes sense because the students had the most difficulty and "false starts" when performing these two activities.

Figure 1 presents excerpts from student replies to the survey prompt: “Please comment on your reaction to the labs in general.” Only two students did not specifically reply that they liked doing the labs: one student provided no comment and one wrote the nonsense comment: “I like burning substances.” The remaining comments were positive about participation in the laboratory investigations. Approximately 35% of the students indicated that it was sometimes frustrating to try to figure out the lab procedure on their own, but they added that they eventually were able to complete the task. In addition, they expressed satisfaction that they could “figure it out.” A few students indicated that they felt like “real scientists” and several stated that the labs made them think, or as one student put it, “the experiments…required more brainpower.” The contrast between inquiry and cookbook-style labs was summed up by one student’s comment from the inquiry group, “I like how we had to think and do it ourselves instead of being robots.”

I like doin labs in class. They make me feel like we are actually doing science. It was a great opener to the day.

I liked the labs a lot. I like having a hands on learning situation because it really makes me think.

I enjoy labs, it was sometimes quite frustrating to figure out the procedure ourselves, but rewarding once we figured it out.

I like having to figure out what exactly to do because it makes me feel smart.

Labs are fun, i like doing them. they were very frusturating at times but it made us think hard and do it on our own. The labs we do are very interesting and i enjoy them a lot.

Figure 1. Excerpts from student survey replies.

Discussion and Conclusion

The implementation of this study was motivated by the desire to determine whether the integration of guided inquiry learning activities had an effect on students' achievement on stoichiometry content knowledge. When students were provided with the opportunity to engage in scientific practices that required the planning and implementation of data collection strategies, did this result in a deeper conceptual understanding of the abstract concept of stoichiometry? The results (Table 3) indicate that this learning method did, indeed, have an effect on student achievement. The significant increase between pre- and post- test scores for the experimental group as opposed to the score increase for the control group suggests that achievement was correlated with guided inquiry instruction methods.

Although a significant difference was not found between posttest and retention scores relating the control and experimental group (Table 4), a notable trend can be observed. Examination of data shows that 74% (14 out of 19) of students in the control group had negative differences in their retention score from their post test score, while only 26% (5 out of 19) of the experimental group scored lower after the same ten week period. This trend implies there is a positive effect on retention of material in the group receiving guided-inquiry instruction.

These results support the findings of Geier, et al. (2008) in their study showing significantly higher pass rates on standardized exams for students engaged in inquiry-based learning. They also found significant gains in long-term retention of material following inquiry instruction; this study shows a trend that may support those observations.

The significance of the retention results for this study may have been affected by the fact that not all forty-eight students in the initial study were able to take the final retention test due to time constraints. Because ten students did not take the retention test, the sample size was reduced by 21%. The p-value for the sample size in the retention study (n=38) was 0.07, not far from the significant result of <0.05. Nevertheless, it is interesting to note that the experimental group obtained an overall average improvement from their post-test scores of 2.4%, while the control group received an average score that was lower than the post-test by 3.8%.

Additionally, according to the results of the student survey conducted in this study, students' attitude toward guided inquiry instruction developed in a positive manner. Several students had comments such as, "I love doing labs. I think they are very awesome" and " I did like doing the labs, it gets me thinking a lot." This correlates with findings by other researchers (Bopegedera, 2011; Palmer, 2009; Taraban et al., 2007) who maintain that inquiry instruction increases motivation, engagement, and attitude.

Another benefit highlighted by the student survey was the use of collaboration by the students in the experimental group. As noted earlier, students gave "collaboration" an average rating of 4.5 (on a scale from 1 to 5) on three of the five labs (Table 8). In addition to the student survey ratings, classroom observation showed students engaged in collaborative problem-solving discussions while providing mutual encouragement, as evidenced by the excitement when planning a procedure and the shared congratulations upon successful completion. This agrees with studies that show students working collaboratively have been found to obtain benefits such as becoming more actively engaged in the learning process and retaining the information for a longer period of time, along with engaging in justifications and reflections and giving each other mutual support (Kirschner, Paas, and Kirschner, 2009; Morgan, Whorton, and Gunsalas, 2000).

Overall, the laboratory activities were successful. The experimental group found *Determining an Activity Series* to be the most challenging. As noted earlier, this was their first experience without specific lab instructions; their unfamiliarity with planning and implementing their own data collection may have contributed to their perception of difficulty. One issue with this lab investigation was that students had trouble observing whether a reaction had occurred with solid iron. Iron filings were used in this experiment and the surface reaction was difficult to detect because of the small particle size. In the future, it is advised that a larger piece of solid iron, such as a polished nail, is used as the iron metal sample.

Another matter was brought up by the results from the single replacement lab (*Foiled Again!*). Even after performing the reaction, it was notable that some students continued to have difficulty using observational evidence to support claims regarding limiting reactants. This implies that these students do not have a concrete interpretation of the meaning of a balanced equation. For example, the control group was specifically given information as follows: “Copper(II) chloride is blue. If the solution remains blue after the reaction occurs, this indicates some copper(II) chloride remains unreacted and therefore must be in excess." Yet, it is noteworthy that 57% of the students in the control group could not use these same physical observations to explain how they could tell copper(II) chloride was in excess, even after hearing the explanation. This mirrors conclusions made by Spencer (2006): "Certain conceptual difficulties are not overcome by traditional instruction." He points out that instructor-guided inquiry is more effective in promoting learning than lectures. In support of this idea, the experimental group performed better than the lecture group; yet 19% of these students still did not use observational evidence to explain how they could tell that copper(II) chloride was the limiting reactant. As a result of the students' unsatisfactory explanations, this laboratory investigation will be adapted in the future to include more inquiry-based planning of the experimental procedure. Rather than simply having the students perform and observe the experiment, they will be asked to design an experiment that gives observational evidence showing the limiting and excess reactants. Hopefully, this will require students to focus more on the macroscopic meaning of the balanced equation.

A possible influence on this study was the timing of the implementation. Although this unit was designed to require two weeks of class time, the period of time over which it was taught was stretched out to a time period of five weeks, with gaps between instructional days. The unit instruction was interrupted by the testing week for the administration of the MME/ACT. Additionally, there were other gaps of time between instruction due to ACT preparation, snow days and teacher absence while attending a conference. It is not known whether the interruptions in the delivery of the inquiry instruction had an impact on the results of the study.

Future studies might explore the effects of inquiry-based instruction on lower achieving students. For example, the studies done by Geier, et al. (2010) and Hickey, et al. (2000) indicated a positive effect on achievement when inquiry-based instruction was used with students from at-risk populations. The participants in the study described in this document were higher-achieving students who are generally more motivated to learn. It would be constructive to investigate the impact on a different population of students, such as a group with lower academic motivation.

In conclusion, this study provides evidence that guided-inquiry instruction has a positive impact on students' concrete and conceptual knowledge. As educators approach the implementation of the *Framework for K-12 Science Education* (NRC, 2011) and the *Next Generation Science Standards*, these findings support the goal in science education to engage in scientific inquiry. This method not only involves students in the practice of science, but also enhances student performance on tests of content knowledge. Continued research on the inclusion of inquiry practices should lead to the benefit of improved science teaching and learning.

APPENDICES

APPENDIX A

Determining the Activity Series for Metals

A-1 Cookbook Version

LAB: Determining an Activity Series for Metals

In this experiment, you will test some metals to find their relative reactivity.

Purpose: To create an activity series that ranks metals from most to least reactive.

Materials:

=Samples of four metals:
zinc, copper, iron, and magnesium
=Samples (in pipets) of four metallic salt solutions
zinc nitrate, $Zn(NO_3)_2$
copper(II) nitrate, $Cu(NO_3)_2$
iron(II) nitrate, $Fe(NO_3)_2$
magnesium nitrate, $Mg(NO_3)_2$
=One well-plate (for performing reactions)

Procedure:
Using the well plate, test each of the solid metals with each of the nitrate solutions. Place the sample of metal in the well plate. Add enough solution from the pipet to cover the metal completely. Let each sit for at least 5 minutes. Record which combinations react in the data table provided. Be sure to include observations. Discard of the waste in the appropriate labeled container. Wash your equipment and clean up your lab area. Wash your hands before leaving the lab.

Data/Observations:

	$Zn(NO_3)_2$	$Cu(NO_3)_2$	$Fe(NO_3)_2$	$Mg(NO_3)_2$
Zn	-NR-			
Cu		-NR-		
Fe			-NR-	
Mg				-NR-

Conclusion Questions:

1. Which metal reacted with the most solutions? Which reacted with the fewest?

2. Using the data above, create an activity series that ranks these metals from most to least reactive.

3. How does your activity series compare to the standard activity series found in your textbook? Explain.

4. List 2 signs that indicate a chemical reaction occurred.

A-2 Inquiry Version

LAB: Determining an Activity Series for Metals

Materials:

=Samples of four metals:
zinc, copper, iron, and magnesium

=Samples (in pipets) of four metallic salt solutions
zinc nitrate, $Zn(NO_3)_2$
copper(II) nitrate, $Cu(NO_3)_2$
iron(II) nitrate, $Fe(NO_3)_2$
magnesium nitrate, $Mg(NO_3)_2$

=One well-plate (for performing reactions)

Your task:

Design a procedure to test the metals for their relative activities. From your data, you should rank the four metals so that you end up with a list of the metals in order of decreasing activity (most active first).
SAFETY: You must wear goggles during this investigation!

Use a **separate sheet of paper**. Your final lab write-up should follow this format:

1. Title
2. Purpose
3. Procedure
4. Data $^{and}/_{or}$ Observations
5. Conclusions (This is where you will list your experimental activity series for the metals you tested.)
6. Discussion of Theory (This is where you will explain your reasoning. In paragraph form, you should explain how you made your conclusions. For example, how did you know that *Metal A* was more active than *Metal B*? Discuss the thought process that led to your conclusion.)
7. How does your activity series compare to the standard activity series found in your textbook? Explain.
8. List 2 signs that indicate a chemical reaction occurred.

APPENDIX B

What happens when iron is burned?

B-1 Cookbook Version

What happens when iron is burned? NAME______________________

Part A:

Pre-lab question: After burning, do you expect the mass of the product to be greater, less than, or equal to the mass of the original iron? Write your hypothesis and explain why you think this is true.

Use the following procedure to test your hypothesis.

> ***Safety notes**: Wear goggles! Remove all combustible materials from your lab area. Use caution handling the Bunsen burner and heated iron. Note that the iron will continue to glow as long as the reaction is occurring*.

1. Obtain about 1 g of iron wool. Record the exact mass.
2. Hold the steel wool with crucible tongs directly in the flame of a Bunsen burner. The wool will glow as it burns. Rotate the wool and change the position of the tongs so that every part of the iron wool has reacted. Record your observations.
3. After the reaction is complete, allow the product to cool. Find the final mass. Record.

Data:

Initial mass of iron wool ___________

Observations:____

____

Final mass of burned product ______________

Discussion: Did your data support your hypothesis? Use results from your experiment to explain.

Part B:
The process of burning is called **combustion**. What substance is required for combustion to occur?_____________

Iron can form either Fe^{2+} or Fe^{3+} in compounds. In the following space, write the formula for the oxide that would form with each:

Fe^{2+} oxide = _______________

Fe^{3+} oxide = _______________

Calculations:
1. Write out the formulas and balance each of the equations in the box provided:

$Fe + O_2 \rightarrow$ iron(II) oxide

$Fe + O_2 \rightarrow$ iron(III) oxide

2. If iron(II) oxide were formed, what mass would be expected from the original amount of iron? Show your calculations.

3. If iron(III) oxide were formed, what mass would be expected from the original amount of iron? Show your calculations.

4. Based on your data, which oxide of iron was formed? Discuss your reasoning.

B-2 Inquiry Version

What happens when iron is burned? NAME______________________

Part A:

Pre-lab question: After burning, do you expect the mass of the product to be greater, less than, or equal to the mass of the original iron? Write your hypothesis and explain why you think this is true.

Explain the procedure you will use to test your hypothesis. Be sure to include the type of data you will need to collect.

> ***Safety notes**: Wear goggles! Remove all combustible materials from your lab area. Use caution handling the Bunsen burner and heated iron. Note that the iron will continue to glow as long as the reaction is occurring.*
>
> **Obtain teacher permission before beginning your experiment.**

Perform your experiment. Record data here (show all calculations):

Discussion: Did your data support your hypothesis? Use results from your experiment to explain.

List 2 signs that indicate a chemical reaction occurred.

Part B:

The process of burning is called **combustion**. What substance is required for combustion to occur?_____________

Iron can form either Fe^{2+} or Fe^{3+}. In the following space, write the formula for the oxide that would form with each:

Fe^{2+} oxide = _______________

Fe^{3+} oxide = _______________

Write each of the balanced equations in the box provided:

$Fe + O_2 \rightarrow$ iron(II) oxide

$Fe + O_2 \rightarrow$ iron(III) oxide

Use your data from Part A to determine which oxide of iron formed when you combusted the iron. (Alternately, you may repeat the experiment if you wish to collect new data.)

Which oxide of iron was produced? Show your calculations and discuss your reasoning:

APPENDIX C

How can you change baking soda into table salt?

C-1 Cookbook Version

How can you change baking soda into table salt?

Purposes:

1. Calculate theoretical mass of NaCl based on a known mass of $NaHCO_3$.
2. Experimentally determine the actual mass of NaCl produced.
3. Calculate the percent yield for your experiment.

Reaction Equation: $NaHCO_3(s) + HCl(aq) \rightarrow NaCl(s) + CO_2(g) + H_2O(l)$

Materials:

safety goggles
50 or 100 mL beaker
hot plate
beaker tongs
baking soda ($NaHCO_3$)
pipet containing 6.0 M HCl

Procedure: **Wear Safety Goggles!**

Day One:

1. Find the mass of a small beaker.
2. Record this mass in the Data Table.
3. Add about $^1/_2$ of a teaspoon of baking soda to the beaker. Record the total mass in the Data Table.
4. Use the pipet to drip HCl into the beaker. Add HCl ***until the fizzing ceases***. Gently swirl the beaker so that all of the solid contacts the acid. ***Safety note***: Do NOT add excess hydrochloric acid! Use only the amount needed to complete the reaction.
5. Gently heat the beaker and contents on a hot plate until the sodium chloride solution just begins to boil. This will begin the evaporation process.
6. Using beaker tongs, place the beaker in a drying oven to complete the evaporation.

Day Two:

1. Weigh the beaker and contents (now crystalline NaCl). Record the mass.
2. Clean, rinse, and dry the beaker. The NaCl can be washed down the drain.

Data Table:

A	Mass of empty beaker	
B	Mass of beaker + $NaHCO_3$	
C	Mass of $NaHCO_3$ (B-A)	

D	Mass of beaker + NaCl	
E	Mass of NaCl (D-A)	

Calculations:

1. From your initial mass of $NaHCO_3$, calculate the theoretical mass of NaCl you expected to obtain. Show your work.

2. Use the actual mass of NaCl from your experiment to calculate the percent yield you obtained.

3. Discuss reasons your yield was not 100%. You should give specific sources of error that can explain why your yield was higher or lower than expected.

C-2 Inquiry Version

How can you change baking soda into table salt?

Your kitchen cupboard probably contains both baking soda and table salt. Consider the following reaction:

$$NaHCO_3\ (s) + HCl(aq) \rightarrow CO_2(g) + H_2O(l) + NaCl(aq)$$

What is the chemical formula for baking soda? _______________

What is the chemical formula for table salt? _______________

Design an experiment to produce and recover 1 gram of NaCl from the reaction between solid sodium bicarbonate and 1.0 M hydrochloric acid. Include answers to the following in your experimental design:

Determine the stoichiometric amount of $NaHCO_3$ required. Show your set-up.
How could you ensure you add enough HCl without using an excess of HCl?
How will you recover the solid NaCl?

Write your experimental procedure here: (obtain teacher approval before proceeding)

Record all relevant data and discuss your results here. Be sure to calculate your percent yield.

APPENDIX D

Air Bag Experiment

D-1 Cookbook Version

Air Bag Experiment

The basic idea of an automobile air bag is simple: in the event of a collision, a plastic bag rapidly inflates with a gas, preventing the occupant from hitting the dashboard or the steering column.

Your task: Construct a model air bag using a Ziploc bag, baking soda (sodium bicarbonate, $NaHCO_3$), and 1.0 M hydrochloric acid. The carbon dioxide produced in the reaction inflates the bag. The ideal result will be to fill the bag to plumpness, not to overinflate or underinflate the bag. The bag may also contain unreacted HCl and/or products of the reaction. Make sure you write your names on the bag you will be handing in.

Reaction: $NaHCO_3 + HCl \rightarrow NaCl + H_2O + CO_2$

Procedure:

1. Use water and a graduated cylinder to determine the volume of the bag. This is the volume of gas you wish to produce.

   Volume of bag =

2. Calculate the mass of sodium bicarbonate needed to produce the volume of gas desired. (You can make an assumption that conditions are at STP, therefore, 1 mol = 22.4 Liters)

3. For each trial, use 50. mL of the 1.0 M HCl. This is more HCl than you will need, but this will ensure that HCl is in excess.

4. Devise a way to add both the acid and the baking soda to the bag without making contact until you want the reaction to proceed. (Think about some method to fold the bag with one of the contents in the bag before adding the second). Make sure your names are on the bag before you begin.

5. Allow the bag to fill with CO_2 gas. You must turn in your sealed bag at the end of the experiment for evaluation. The degree of "plumpness" will be part of your score.

D-2 Inquiry Version

Air Bag Experiment **Name____________________**

The basic idea of an automobile air bag is simple: in the event of a collision, a plastic bag rapidly inflates with a gas, preventing the occupant from hitting the dashboard or the steering column.

Your task: Construct a model air bag using a Ziploc bag, baking soda (sodium bicarbonate, $NaHCO_3$), and 1.0 M hydrochloric acid. The carbon dioxide produced in the reaction inflates the bag. The ideal result will be to fill the bag to plumpness, not to overinflate or underinflate the bag. The bag may also contain unreacted HCl and/or products of the reaction. Make sure you write your name *and* your partner's name on the bag you will be handing in.

Reaction: $NaHCO_3 + HCl \rightarrow NaCl + H_2O + CO_2$

Materials Provided:

Ziploc bags	Baking soda ($NaHCO_3$)
Graduated cylinders	Hydrochloric acid (HCl)
Tap water	Electronic balance

Some specific instructions and hints:

1. For each trial, use 50. mL of the 1.0 M HCl. This is more HCl than you will need, but this will ensure that HCl is in excess.

2. Reminder: You must turn in your sealed bag at the end of the experiment for evaluation. The degree of "plumpness" will be part of your score.

3. Record the minimum amount of baking soda needed to fill the bag: _______g
   Show your calculation:

When you have successfully completed the task, write a paragraph on the back of this page→ explaining your experimental design, including the reasoning you used to arrive at your end result. In addition, list **2 signs** that indicate a chemical reaction occurred.

APPENDIX E

Lab: Foiled Again!

Lab: Foiled Again!

Purpose:

In this activity, you will relate mass, moles, stoichiometric coefficients and limiting reactants to one another by observation of the reaction between copper(II) chloride and aluminum foil.

Safety: Wear goggles during this experiment. Avoid skin contact with $CuCl_2$.

1) Balance the equation for this reaction:

_____$CuCl_2$ *(aq)* + _____Al*(s)*   _____Cu*(s)* + ____$AlCl_3$*(aq)*

2) Mass out approximately 0.10 g of aluminum using a clean, dry 250 mL beaker. Record the exact mass below:

mass of aluminum_______________

3) Using a graduated cylinder, measure out exactly 20. mL of copper(II) chloride. Note the color of the solution below:

initial color of $CuCl_2$ _____________________

4) Carefully add the copper(II) chloride to the aluminum. Stir gently, then allow the beaker to sit undisturbed for 5-10 minutes. Record observations below:

5) a) Determine the mass of Cu that can be formed from your starting mass of aluminum:

b) Determine the mass of Cu that can be formed given the initial 20. mL of 1.0 M $CuCl_2$

6) Based on your *calculations in Step 5 on the previous page*:

Identify your limiting reactant______________

Identify your excess reactant__________________

7) Based on your *observations*, what substance appeared to be the limiting reactant? Did this agree with what you expected from your calculations? Explain your reasoning.

8) Based on your *observations*, what substance appeared to be in excess? Did this agree with what you expected from your calculations? Explain your reasoning (discuss the color of solution as part of your answer).

E-2 Inquiry Version

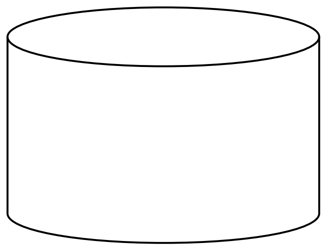
Lab: Foiled Again!

Purpose:

In this activity, you will relate mass, moles, stoichiometric coefficients and limiting reactants to one another by observation of the reaction between copper(II) chloride and aluminum foil.

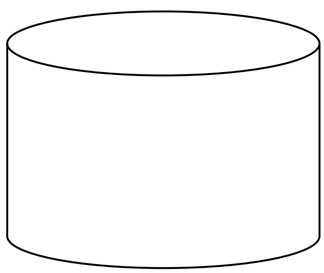
Think about this:

Draw the ions in a solution of $CuCl_2$ *(aq)* (*be sure to include the charge on the ions*)



← this solution is **blue**

Draw the ions in a solution of $AlCl_3$*(aq)* (*be sure to include the charge on the ions*)



← this solution is **colorless**

Based on the above information, determine the color of the following ions in solution:

Cu^{2+} is________________ Cl^- is_________________ Al^{3+} is_________________

Balance the equation for this reaction:

_____Al + _____$CuCl_2$ → _____Cu + _____$AlCl_3$

If you combined stoichiometric amounts of aluminum and copper(II) chloride and they reacted completely (with neither reactant left over), what would be the color of the final solution after the reaction was complete?____________

Calculation/Observation:

1) If you add 0.10 g of Al to 20.0 mL of 1.0 M $CuCl_2$ *(aq)*, predict which will be the limiting reactant. Use the balanced equation from the previous page. Show your calculations below.

Prediction: _______________ is limiting

2) Now, carry out the reaction to test your prediction. Measure 20.0 ml of $CuCl_2$ with a graduated cylinder and pour it into a beaker. Add 0.10 g aluminum. Stir gently. Allow the beaker to sit undisturbed for 5-10 minutes. ***Reminder: Wear goggles***!

= Cite at least three examples that indicate a chemical reaction has occurred:

= What is the chemical identity of the brown solid?_____________

3) Based on your *observations*, which reactant, aluminum or copper(II) chloride, appeared to be the limiting reactant? ____________
Did this agree with what you expected from your calculation in Question #1? Explain your reasoning.

4) Based on your *observations*, what substance appeared to be in excess?_____ How can you tell? Explain your reasoning (You should comment on the color of the solution as part of your answer).

Consider the same reaction (reminder: this equation has not been balanced)

_____Al + _____$CuCl_2$ → _____Cu + _____$AlCl_3$

5) What mass of aluminum would you need to add to 20. mL of 1.0 M $CuCl_2$ solution to ensure that the reaction goes to completion with neither reactant left over? (Show calculations)

6) Look back at your answer to question #5. If you used 2.0 grams of Al instead of the amount of Al you calculated in #5 (with the same 20 mL of 1.0 M $CuCl_2$), could you produce a greater amount of copper? Why or why not?

In addition, describe what you would see in the beaker if you used 2.0 g of Al (without actually performing the experiment!)

APPENDIX F

Pre- and Post- Assessment

Reactions and Stoichiometry **NAME**________________________

Refer to the following reaction for questions (**1-3)**

$$2\ Al(s) + 6\ HCl(aq) \rightarrow 2\ AlCl_3(aq) + 3\ H_2\ (g)$$

_____1. If 4 mol of Al is reacted with excess HCl, how many moles of H_2 will be produced?

a. 2
b. 3
c. 4
d. 5
e. 6

_____2. If you wish to produce 1 mol H_2, how many moles of HCl are required to react with excess Al?

a. 2
b. 3
c. 4
d. 5
e. 6

_____3. Calculate the mass of Al required to react completely with 30.g HCl.

a. 2.2 g Al
b. 7.4 g Al
c. 27 g Al
d. 73 g Al
e. 90. g Al

_____4. Consider the following balanced equation:

$$NaHCO_3 + HCl \rightarrow NaCl + H_2O + CO_2$$

What volume of CO_2 gas will be produced (at STP) from the reaction of 2.0 g $NaHCO_2$ with excess HCl?

a. 0.44 L
b. 0.53 L
c. 1.00 L
d. 1.22 L
e. 2.24 L

______5. What is the coefficient for Na when the following equation is balanced?

$Na(s) + Cl_2(g) \rightarrow NaCl(s)$

a. 1
b. 2
c. 3
d. 4
e. 5

______6. What is the coefficient for HBr when the following equation is balanced?

$HBr(aq) + Li_2S(s) \rightarrow LiBr(aq) + H_2S(g)$

a. 1
b. 2
c. 3
d. 4
e. 5

______7. What is the coefficient for F_2 when the following equation is balanced?

$Fe(s) + F_2(g) \rightarrow FeF_3(s)$

a. 1
b. 2
c. 3
d. 4
e. 5

______8. A gas collected in the lab is tested with a burning wood splint. A popping sound is heard. What is the identity of the gas?

a. oxygen
b. helium
c. carbon dioxide
d. hydrogen
e. nitrogen

9. List 3 observations that could indicate a chemical change has occurred.

10. What is meant by the term limiting reactant?

11. Calcium reacts spontaneously with water to produce calcium hydroxide and hydrogen gas.

a. Balance the equation for the reaction:

____ Ca + _____ $H_2O \rightarrow$ _____ $Ca(OH)_2$ + _____ H_2

b. If 25.0 g of calcium and 25.0 g of water are present initially, determine the limiting reactant. Show the calculations you use to arrive at your answer.

12. T or F: In a chemical reaction, all reactants are used up to form the product.

Explain your reasoning.

13. T or F: Adding more reactant always results in the formation of more product.

Explain your reasoning.

14. Use the activity series to predict the products of each reaction. Balance the equation.
If there is no reaction, write "No Rxn".

Li *More active*
K
Ba
Sr
Ca
Na
Al
Ni
Pb
Cu
Ag *Less Active*

a. Al(*s*) + NaBr(*aq*) →

b. Ca(*s*) + $Ni(NO_3)_2$(*aq*) →

c. Ba(*s*) + $SrCl_2$ (*aq*) →

15. Describe a procedure you would use to produce 1.0 g of solid copper from the reaction between aluminum and copper(II) chloride as shown by the equation below:

$$2\ Al(s) + 3\ CuCl_2\ (aq) \rightarrow 3\ Cu(s) + 2\ AlCl_3(aq)$$

APPENDIX G

Retention Assessment

Semester 2 EXAM NAME________________________
Reactions and Stoichiometry

Refer to the following reaction for questions (**1-3)**

$$2\ Al(s) + 6\ HCl(aq) \rightarrow 2\ AlCl_3(aq) + 3\ H_2\ (g)$$

1. If 4 mol of Al is reacted with excess HCl, how many moles of H_2 will be produced?

2. If you wish to produce 1 mol H_2, how many moles of HCl are required to react with excess Al?

3. Calculate the mass of Al required to react completely with 30.g HCl.

4. Consider the following balanced equation:

$$NaHCO_3 + HCl \rightarrow NaCl + H_2O + CO_2$$

What volume of CO_2 gas will be produced (at STP) from the reaction of 2.0 g $NaHCO_3$ with excess HCl? (at STP, 1 mole= 22.4 L)

5. Balance the following equation:

______Na(*s*) + ______Cl_2 (*g*) → ______NaCl(*s*)

6. Balance the following equation:

_____HBr(*aq*) + _____Li_2S(*s*) → _____LiBr(*aq*) + _____H_2S(*g*)

7. Balance the following equation:

______Fe(*s*) + ______F_2 (g) → ______FeF_3(s)

8. A gas collected in the lab is tested with a burning wood splint. A popping sound is heard. What is the identity of the gas? (circle the correct answer)
   a. oxygen
   b. helium
   c. carbon dioxide
   d. hydrogen
   e. nitrogen

9. List 3 observations that could indicate a chemical change has occurred.

10. What is meant by the term limiting reactant?

11. Calcium reacts spontaneously with water to produce calcium hydroxide and hydrogen gas.
   a. Balance the equation for the reaction:

   ____Ca + _____ H_2O → _____ $Ca(OH)_2$ + _____ H_2

   b. If 25.0 g of calcium and 25.0 g of water are present initially, determine the limiting reactant. Show the calculations you use to arrive at your answer.

12. *(circle one →)* T or F: In a chemical reaction, all reactants are used up to form the product.
   Explain your reasoning:

13. *(circle one →)* T or F: Adding more reactant always results in the formation of more product.
   Explain your reasoning:

14. Use the activity series to predict the products of each reaction. Balance the equation.
If there is no reaction, write "No Rxn".

Li *More active*
K
Ba
Sr
Ca
Na
Al
Ni
Pb
Cu
Ag *Less Active*

a. Al(*s*) + NaBr(*aq*) →

b. Ca(*s*) + $Ni(NO_3)_2$ (*aq*) →

c. Ba(*s*) + $SrCl_2$ (*aq*) →

15. Describe a procedure you would use to produce 1.0 g of solid copper from the reaction between aluminum and copper(II) chloride as shown by the equation below:

$$2\ Al(s) + 3\ CuCl_2\ (aq) \rightarrow 3\ Cu(s) + 2\ AlCl_3(aq)$$

APPENDIX H

Individual Student Retention Data

Table 7. Retention Data

	Control Group			Experimental Group		
	Posttest	Retention	Difference	Posttest	Retention	Difference
	74	67	-7	78	67	-11
	78	72	-6	78	89	11
	87	78	-9	78	83	5
	78	67	-11	78	78	0
	100	89	-11	78	78	0
	83	50	-33	83	94	11
	96	94	-2	91	89	-2
	96	94	-2	96	100	4
	87	83	-4	78	94	16
	78	94	16	96	100	4
	74	67	-7	70	83	13
	87	83	-4	91	94	3
	83	67	-16	96	83	-13
	91	89	-2	91	100	9
	57	67	10	87	78	-9
	65	72	7	70	83	13
	61	72	11	83	67	-16
	74	67	-7	78	83	5
	96	100	4	96	96	0
Average	81.3	77.5	**-3.8**	83.3	85.7	**2.4**

APPENDIX I

Student Survey

SURVEY

Activity Rating:
In the table below, rate each of the activities on a scale of 1-5 (1=low, 5=high) according to the following criteria.

Collaboration. Did you work with others on this activity? Was the activity structured in a way that made you work together? Were you actively participating throughout this activity?

Thinking. How mentally engaging was this activity? Did you find yourself really thinking through the process as you performed the activity?

Interest. How interesting did you find the activity? Did you enjoy the activity?

Learning. How much did you learn from the activity? Did you feel that it helped model the topic in a way that helped you learn?

Activity	Collaboration	Thinking	Interest	Learning
Air Bag Experiment				
Determining an Activity Series for Metals				
Turning Baking Soda into Salt				
What Happens When Iron is Burned?				
Foiled Again				

Please comment on your reaction to the labs in general. (Did you like doing them? Would you rather do something else in class? Was it frustrating to try to figure out how to do the lab without clear directions?)

APPENDIX J

Parental Consent and Student Asset Form

PARENTAL CONSENT AND STUDENT ASSENT FORM

Dear Students and Parent/Guardian:
I would like to take this opportunity to welcome you back to school and invite you or your child, hereafter referred to as "you", to participate in a research project. For the past three summers I have been involved in completing my Master's degree at Michigan State University. I have been working on effective ways to teach reactions and stoichiometry in chemistry and I plan to study the results of this teaching approach on student comprehension and retention of the material. The results of this research will contribute to teachers' understandings about the best way to teach about science topics. Completion of this research project will also help me to earn my master's degree in Michigan State University's Division of Math and Science Education (DSME).
What will students do? You will participate in the instructional unit about reaction and stoichiometry. You will complete the usual assignments, laboratory experiments and activities, surveys, and pretests/posttests just as you do for any other unit of instruction. Participation in this study will not increase or decrease the amount of work that students do. Depending on which group you are randomly assigned to, your directions for conducting the lab activities will be different. One group will have more detailed instructions that the other, and a separate group will randomly have either the detailed or the less explicit directions. You will not know which group you are in. I will simply use scores from student work for my research purposes. At no time will a student's name be attached to any work or score included in the thesis.
Please complete the attached consent form and return it by September 9, 2011. Please seal it in the provided envelope. The envelopes will not be opened until after the school year ends. You should bring your forms to Mrs. Libby, F-section, and she will store the envelopes in a locked file cabinet that will not be opened until after I have assigned the grades for this unit of instruction. That way I will not know who agrees to participate in the research until after grades are issued. In the meantime, I will save all of your written work. Later I will analyze the written work only for students who have agreed to participate in the study and whose parents/guardians have consented. There are no penalties for saying "no" or choosing to withdraw. Participation is voluntary and you can withdraw at any time. If you choose to withdraw at any time during the school year, simply write a note stating that you wish to withdraw permission to use your scores for research, and give the note to Mrs. Libby. She will place the note in the locked cabinet and when the consent forms are opened, your permission to participate will be withdrawn. Again, there will be no penalty for withdrawing.

Who can you contact with questions and concerns? If you have concerns or questions, please contact me (Mrs. Lynn Thomas) at Escanaba High School, 786-6521 x500, lthomas@eskymos.com. You may also contact Dr. Merle Heidemann: 118 North Kedzie Lab , Michigan State University, East Lansing, MI 48824; heidema2@msu.edu; 517-432-2152 x 107].
If you have questions or concerns about your role and rights as a research participant, would like to obtain information or offer input, or would like to register a complaint about this study, you may contact, anonymously if you wish, the Michigan State University's

Human Research Protection Program at 517-355-2180, Fax 517-432-4503, or e-mail irb@msu.edu or regular mail at 207 Olds Hall, MSU, East Lansing, MI 48824.

How should I submit this consent form? Whether or not you agree to participate in this study, please complete the attached form. Both the student and parent/guardian must sign the form.

Chemistry
Mrs. Thomas
Escanaba High School

A parent/guardian should complete this following consent information:

I voluntarily agree to have ____ participate in this study.

(print student name)

Please check one:
Data:
___________ I give Mrs. Lynn Thomas permission to use data generated from my child's work in this class for her thesis project. All data from my child shall remain confidential.
___________ I do not wish to have my child's work used in this thesis project. I acknowledge that my child's work will be graded in the same manner regardless of his/her participation in this research.

Signature:

____ ________
(Parent/Guardian Signature) (Date)

Student: I voluntarily agree to participate in this thesis project.

____ ______
(Student Signature) (Date)

*****Important*****
Return this form to Mrs. Libby (F-section) by September 9 in the envelope provided.

REFERENCES

REFERENCES

American Association for the Advancement of Science. (1993). *Benchmarks for Science Literacy*. New York, NY: Oxford University Press.

Anderson, R.D. (2002). Reforming science teaching: What research says about inquiry. *Journal of Science Teacher Education*, *13*(1), 1-12.

AP Chemistry Curriculum Framework. 2011. The College Board.

Atkinson, R., & Shiffrin, R. (1968). Human memory: A proposed system and its control processes. In K. Spence & J. Spence (Eds.), *The psychology of learning and motivation* (Vol. 2, pp. 89–195). New York: Academic.

Banchi, H., Bell, R. (2008). The many levels of inquiry. *Science and Children*. *46*(2), 26-29.

Banerjee, A. (2010) Teaching science using guided inquiry as the central theme: A professional development model for high school science teachers. *Science Educator*, *19*(2), 1-9.

Basaga H, Geban O, Tekkaya C (1994). The effect of the inquiry teaching method on biochemistry and science process skills achievements. *Biochemical Education*, *22*(1), 29-32.

Bell, R.L., Smetana, L., Binns, I. (2005). Simplifying inquiry instruction. *The Science Teacher*, *72*(7), 30-33.

Berg, C.A.R., Bergendahl, V.C.B., Lundberg, B.K.S., Tibell, L.A.E. (2003). Benefiting from an open-ended experiment? A comparison of attitudes to, and outcomes of, an expository versus an open-inquiry version of the same experiment. *International Journal of Science Education*, *25*(3), 351-372.

Bilgin, I. (2009). The effects of guided inquiry instruction incorporating a cooperative learning approach on university students' achievement of acid and bases concepts and attitude toward guided inquiry instruction. *Scientific Research and Essay*, *4*(10), 1038-1046

Bopegedera, A.M.R.P. (2011). Putting the laboratory at the center of teaching chemistry. *Journal of Chemical Education*, *88*(4), 443-448.

Bybee, R. W. (2012). Scientific and engineering practices in K-12 classrooms. In H. Pratt, *The NSTA reader's guide to a framework for K-12 science education* (pp. 35-42). Arlington, VA: NSTA Press.

Cakir, M. (2008). Constructivist approaches to learning in science and their implication for science pedagogy: A literature review. *International Journal of Environmental and Science Education*, *3*(4), 193–206.

Cohen, J., Kennedy-Justice, M., Pai, S., Torres, C., Toomey, R., DePierro, E., Garafalo, F. (2000). Encouraging meaningful quantitative problem solving. *Journal of Chemical Education*, *77*(9), 1166-1173.

Colburn, A. (2000). Constructivism: Science education's grand unifying theory. *The Clearing House*. *74*(1), 9-12

Davidowitz, B., Chittleborough, G., Murray, E. (2010). Student-generated submicro diagrams: A useful tool for teaching and learning chemical equations and stoichiometry. *Chemistry Education Research and Practice*, *11*(3), 154-164

Davis, E.A. (2000). Scaffolding students' knowledge integration: prompts for reflection in KIE, *International Journal of Science Education*, *22*(8), 819-837

Deters, K.M. (2003). What should we teach in high school chemistry? *Journal of Chemical Education*, *80*(10), 1153-1155.

Felder, R.M., (1990). Stoichiometry without tears. *Chemical Engineering Education*, *24*(4), 188–196.

Gabel, D. (1999). Improving teaching and learning through chemistry education research: A look to the future. *Journal of Chemical Education*, *76*(4), 548-554.

Geier, R., Blumenfield, P.C., Marx, R.W., Krajcik, J.S., Fishman, B., Soloway, E., Clay-Chambers, J. (2008). Standardized test outcomes for students engaged in inquiry-based science curricula in the context of urban reform. *Journal of Research in Science Teaching*, 45(8), 922-939.

Haim, L.,Corton, E., Kocmur, S., Galagovsky, L. (2003) Learning stoichiometry with hamburger sandwiches. *Journal of Chemical Education*, *80*(9), 1021-1022

Hanson, A.L. (1982). You don't have to think in the lab! *Journal of Chemical Education*, *59*(8), 671.

Hickey, D.T., Wolfe, E.W., Kindfeld, A.C.H. (2000). Assessing learning in a technology-supported genetics environment: Evidential and systemic validity issues. *Educational Assessment*. *6*(3), 155-196.

Hmelo-Silver, C.E., Duncan, R.G., Chinn, C.A. (2007). Scaffolding and achievement in problem-based and inquiry learning: A response to Kirschner, Sweller, and Clark. *Educational Psychologist*, *42*, 99–107.

Hudson, S.B., McMahon, K.C., & Overstreet, C.M. (2002). The 2000 national survey of science and mathematics education: Compendium of tables. Chapel Hill, NC: Horizon Research.

Kirschner, F., Paas, F., Kirschner, P.A. (2009). A cognitive load approach to collaborative learning: United brains for complex tasks. *Educational Psychology Review*. *21*(1), 31-42.

Kirschner, P. A., Sweller, J., & Clark, R. E. (2006). Why minimal guidance during instruction does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching. *Educational Psychologist*, *41*(2), 75–86.

Klahr, D., & Nigam, M. (2004). The equivalence of learning paths in early science instruction: Effects of direct instruction and discovery learning. *Psychological Science*, *15*(10), 661–667.

Lewis, S.E. and Lewis, J.E. (2005). Departing from lectures: An evaluation of a peer-led guided inquiry alternative. *Journal of Chemical Education*, *82*(1), 135-139.

Mayer, R. (2004). Should there be a three-strikes rule against pure discovery learning? The case for guided methods of instruction. *American Psychologist*, *59*(1), 14–19.

Minner, D.D., Levy, A.J., Century, J. (2010). Inquiry-based science instruction - what is it and does it matter? Results from a research synthesis years 1984 to 2002. *Journal of Research in Science Teaching*. *47*(4), 474-496.

Moreno, R. (2004). Decreasing cognitive load in novice students: Effects of explanatory versus corrective feedback in discovery-based multimedia. *Instructional Science*, *32*, 99–113.

Morgan, R. L., Whorton, J. E., & Gunsalus, C. (2000). A comparison of short-term and long-term retention: Lecture combined with discussion versus cooperative learning. *Journal of Instructional Psychology*, *27*, 53–58.

Nakhleh, M. B. (1992). Why some students don't learn chemistry. *Journal of Chemical Education*, *69*(3), 191-196.

National Research Council. (1996). *National science education standards*. Washington, DC: The National Academies Press.

National Research Council. (2000). *Inquiry and the National Science Education Standards*. Washington, DC: The National Academies Press.

National Research Council. (2011). *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*. Washington, DC: The National Academies Press.

Paas, F., Renkl, A. & Sweller, J. (2003). Cognitive load theory and instructional design: Recent developments, *Educational Psychologist* 38: 1–4.

Palmer, D. (2009). Student interest generated during an inquiry skills lesson. *Journal of Research in Science Teaching*, *46*(2), 147–165.

Pine, J., Aschbacher, P., Roth, E., Jones, M., McPhee, C., Martin, C., Phelps, S., Kyle, T., & Foley, B. (2006). Fifth graders' science inquiry abilities: A comparative study of students in hands-on and textbook curricula. *Journal of Research in Science Teaching*, *43*(5), 467–484.

Rhee, F. (2009, November 23). Obama highlights science education. *The Boston Globe*. Retrieved from http://www.boston.com

Rudd, J.A., Greenbowe, T.J., Hand, B.M., Legg, M.J. (2001). Using the science writing heuristic to move toward an inquiry-based laboratory curriculum: An example from physical equilibrium. *Journal of Chemical Education*, *78*(12), 1680-1686.

Rutherford, F.J., & Ahlgren, A. (1990). *Science for all Americans*. New York, NY: Oxford University Press.

Spencer, J.N. (2006). New approaches to chemistry teaching. *Journal of Chemical Education*, *83*(4), 528-533.

Taraban, T., Box, C., Myers, R., Pollard, R., Bowen, C.W. (2007). Effects of active-learning experiences on achievement, attitudes, and behaviors in high school biology. *Journal of Research in Science Teaching*. *44*(7): 960-979.

Tuovinen, J.E. & Sweller, J. (1999) A comparison of cognitive load associated with discovery learning and worked examples, *Journal of Educational Psychology*, *91*: 334–341.

U.S. Census Bureau: State and County QuickFacts. Last Revised: Tuesday, 31-Jan-2012

Walker, J.P., Sampson, V., Zimmerman, C.O. (2011). Argument-driven inquiry: An introduction to a new instructional model for use in undergraduate chemistry labs. *Journal of Chemical Education*, *88*(8), 1048-1056.

Weiss, I.R., Pasley, J.D., Smith, P.S., Banilower, E.R., & Heck, D.J. (2003). Looking inside the classroom: A study of K-12 mathematics and science education in the U.S. Chapel Hill, NC: Horizon Research.

Wilson, C.D., Taylor, J.A., Kowlaski, S.M., Carlson, J. (2010). The relative effects and equity of inquiry-based and commonplace science teaching on students' knowledge, reasoning, and argumentation. *Journal of Research in Science Teaching*, *47*(3): 276-301

Witzig, S.B., Zhao, N., Abell, S.K., Weaver, J.C., Adams, J.E., Schmidt, F.J. (2010). Achievable inquiry in the college laboratory: The mini-journal. *Journal of College Science Teaching*, *39*(6), 14-23.