IMPACT OF PROCESS-ORIENTED GUIDED INQUIRY LEARNING ON CHEMISTRY STUDENTS

by

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DEDICATION

I would like to dedicate this work to my loving wife, Danielle. Her unfailing support has made it possible for me to engage in this research and to complete the requirements of my degree.

TABLE OF CONTENTS

1. INTRODUCTION AND BACKGROUND 1

2. CONCEPTUAL FRAMEWORK 4

3. METHODOLOGY 18

4. DATA AND ANALYSIS 30

5. INTERPRETATION AND CONCLUSION 53

6. VALUE 57

REFERENCES CITED 60

APPENDICES 64

APPENDIX A IRB Exemption 65
APPENDIX B POGIL Classification of Matter 67
APPENDIX C Doing Science Inquiry Lab 73
APPENDIX D Lawson Classroom Test of Science Reasoning 76
APPENDIX E Sample Pretest/Posttest for Atomic Structure 87
APPENDIX F Sample Classroom Assessment for Atomic Structure 91
APPENDIX G Interview Questions 94

LIST OF TABLES

1. Data Triangulation Matrix 29

2. LCTSR Pretest Scores.....31

3. LCTSR Posttest Scores.....32

4. LCTSR Score Changes from Pretest to Posttest.....33

5. Classification of Matter Pretest and Posttest Indexed on LCTSR Pretest Score 37

6. Atomic Structure Pretest and Posttest Indexed on LCTSR Pretest Score 38

7. Average Atomic Mass Pretest and Posttest Indexed on LCTSR Pretest Score 40

8. Statistics for Classroom Assessments of Three Units and the Midterm Exam.....42

LIST OF FIGURES

1. Pretest Score for Each Reasoning Pattern.....34

2. Posttest Score for Each Reasoning Pattern 35

3. Plot of Pretest and Posttest Data for Classification of Matter 37

4. Average Scores on Unit Assessments.....38

5. Correlation Between the LCTSR Posttest Score and the Midterm.....44

ABSTRACT

Educating students in science using traditional methods such as lecture and demonstrations is not effective with the majority of students. Alternative methods such as the small-group work method of POGIL (Process Oriented Guided Inquiry Learning) and inquiry-based laboratory work have been shown to be more effective. In this classroom research study these techniques were employed with students in an effort to improve their understanding of science content. In addition, the reason why traditional methods may be less effective is explored through the lens of the work of Jean Piaget and Anton Lawson. Piaget (1972) enumerated several types of reasoning he collectively called 'formal thought'. This formal reasoning may emerge from concrete reasoning during adolescence. Whether it does or not depends in large part on an individual's experiences. The implications for teaching students who are at a concrete stage of cognitive development were explored through data collected regarding science content comprehension, the use of inquiry-based lab activities, and through interviews with students. Finally, prospects for having a direct impact on students' development of formal reasoning are discussed. The results of this study are that the majority of students in a college-preparatory chemistry classroom are in fact concrete thinkers, they require a specific, learning-cycle approach for effective instruction, and the use of such instruction does not in itself contribute directly to their development of formal reasoning abilities. As a result, the study points toward further work to incorporate elements of explicit instruction in formal reasoning skills. Previous research has demonstrated the value of such instruction both in the science classroom and beyond it and that it is in fact possible to aid most but not all students to attain this level of cognitive development.

INTRODUCTION AND BACKGROUND

I have been teaching now for over ten years. I began my career as a special education teacher with no formal training as an educator. I went back to school to earn a degree in chemistry and found a teaching job at Scarborough High School in Scarborough, Maine. I mainly developed my teaching philosophy and practices without the benefit of specific training in the field of education. To develop my teaching philosophy and practices I first looked to my own educational experiences for models. I emulated those teachers I saw as having provided me with the best, most educational courses. Second, I brought a reflective approach to everything I did (and do) in the classroom. I tried different techniques and adjusted from one unit to the next how I presented information and how I asked students to work. Most of these adjustments have necessarily been small but from one year to the next I am able to make deeper changes.

James N. Spencer describes my experience of learning how to teach with uncanny accuracy (1999). The stages of development of a teacher's career according to Spencer (1999) are as follows: First, a teacher sets expectations too high and only gradually begins to meet students at an appropriate level. Next, the teacher finds that even students who do well on assessments don't understand things as well as their scores might indicate. Frequently, students enact an algorithm without understanding why they are doing what they are doing. As a result of these experiences the teacher tries the obvious solutions: more homework problems, more examples in class, additional study periods, and supplemental handouts are all employed. But students do not learn problem solving from seeing problems solved by someone else. That only provides more material for them

to memorize. I can speak from my own experience that it is all too easy to conclude that "the students must be at fault; they are uninterested, don't work hard enough, or are less well prepared than they used to be" (Spencer, 1999, p. 566).

Moog, Creegan, and Hanson (2006) describe traditional teaching by providing the underlying assumptions that guide it. A teacher might expect good results if he or she clearly explains all the required material, organizes the course in a coherent fashion, and works to motivate and interest the students. If he or she also provides high-quality handouts and texts then all the better. Finally, I for one never questioned that if students work hard, take good notes, read the text in preparation for lecture, and practice by doing a lot of problems on their own, then they will surely do well. These assumptions may lead to a teacher-centered approach that encourages students to commit facts and algorithms to memory, whether or not they understand how things fit together or how to reason their way through a novel problem (Moog, 2006). It is clear from my own experience that this approach does not reach the majority of students. The majority struggle and blame themselves when they don't achieve the success they had aimed for.

It has been my experience that some students are very capable and succeed despite practices which leave most students struggling. The struggling students, when questioned on course content, display reasoning that is not relevant or which is turned around backwards. For example, when asked why mass is conserved in chemical changes they will say it is because the equation says so rather than giving a physical reason such as the non-destruction of atoms. They do not grasp seemingly clear concepts. They can follow solutions to problems but cannot solve a novel one, even if it is very similar to the

example. It is possible that these problems are due to differences in the development of reasoning capacity (Karplus, 1977). I am interested in exploring the effect that students' reasoning capacity has on their academic success in my classes. I am also interested in learning more about how I can have an impact on the further development of students' ability to go beyond concrete reasoning. One approach is to use Process-Oriented Guided Inquiry Learning (POGIL), a well-defined group-work approach to student-centered learning. To explore these ideas I have pursued the following action research question. How does my work with students, including an implementation of the POGIL teaching method and inquiry-based lab activities, contribute to their growth in developing from concrete thinkers toward formal reasoners? I have broken this question down into the following four sub-questions. First, *How does the use of POGIL and inquiry-based lab activities affect students' development of reasoning skills?* Second, *How does a student's initial measured level of reasoning skills affect comprehension of science content?* Third, *How does the use of POGIL affect students' own evaluation of their success in chemistry?* And finally, *How does my reflection on my practices with respect to the aim of developing students' formal reasoning affect my approach to teaching?*

School and Teaching Context

The course I am teaching is populated by students at Scarborough High School in Scarborough, Maine. There is little racial or ethnic diversity as Scarborough, like most of the state of Maine, has a predominantly white population. According to the National Center for Educational Statistics (https://nces.ed.gov/ccd/schoolsearch/school_detail.asp ?Search=1&DistrictID= 2310530&ID=231053000325) for the 2015-2016 school year the

high school had 998 students, of whom 59 were non-white. At the high school 105 students qualified for free and reduced lunch.

The course about which I am collecting data is called Chemistry-3 and is a college-preparatory course. It is the lowest expectation-level course in the subject at this school as there are an honors course (Chemistry-4) and an AP Chemistry course. Students who enroll in the course tend to be students who may struggle with math and/or reading but may also be students who are taking Chemistry-3 in order to allow them to focus on the more challenging courses in which they are enrolled. A slow pace in this course is required in order to ensure that most of the students have the time they need to process and comprehend the material. Chemistry is a naturally abstract subject and as such presents a particular challenge for students who have not developed formal reasoning skills.

CONCEPTUAL FRAMEWORK

The developmental theory of Jean Piaget is a relevant background for this research project: specifically, the idea of the difference between concrete thought and formal thought. “In general, reasoning that makes use of direct experience, concrete objects, and familiar actions is classified as a concrete reasoning pattern …. Reasoning that is based on abstractions and that transcends experience is classified as a formal reasoning pattern” (Karplus, 1977, p. 170). Concrete thought develops before formal thought though not in a linear, one-after-the-other fashion. It is not so much that as children grow they have the ability to reason concretely and then gradually acquire the

ability to reason formally. Rather, formal reasoning is a skill that can be developed through instruction and practice (Lawson, 1976).

Specific aspects of concrete and formal reasoning are outlined by Karplus (1977). Concrete reasoning is characterized by reference to immediate experience, physical materials and objects, and familiar actions. People who classify themselves as hands-on learners are a good example of individuals who rely upon this cognitive approach. If they are able to manipulate or imagine manipulating materials and objects then they are best able to understand. For concrete reasoners classifications are made based on directly observable features, the logic of conservation is respected, and related sets of can be placed in a serial order (Karplus, 1977).

By contrast individuals using formal reasoning are not only able to reason about immediate experience, etc., but also abstract properties, general rules, and theoretical constructs. Formal reasoning encompasses the ability to recognize and enumerate all possible combinations. For example, if asked to find ideal growing conditions for a garden, a formal reasoner would consider the possible combinations of amount and intensity of light, moisture, soil pH, availability of soil nutrients, and quality of seeds. Formal reasoners have the ability to apply mathematics to describe a functional relationship such as the fact that the pressure of a gas at a constant temperature is inversely proportional to its volume. Finally, formal reasoning includes the ability to decide which variables in an experiment are important, which need to be held constant, and which need to be varied in order to investigate a question. Formal reasoners are aware of and able to evaluate their own thought processes and actively check to see

whether their conclusions are correct. In contrast, concrete reasoners are not able to articulate their own thought process and as a result may make contradictory or inconsistent statements (Karplus, 1977).

The Lawson Classroom Test of Scientific Reasoning (LCTSR) investigates students' reasoning skills in several categories. To investigate concrete reasoning skills there are questions about the conservation of weight and about displaced volume. These are followed by questions regarding proportional thinking, identification and control of variables, probabilistic thinking, correlational thinking, and hypothetico-deductive reasoning. These are the different areas of formal (or scientific) reasoning examined in this test (Lawson, 1978). Proportional thinking and probabilistic thinking both incorporate mathematics as part of the reasoning pattern. If two measurements are related by a proportion then a change in one will result in an easily calculated change in the other. Probabilities for simple or compound events depend on considering the number of possible outcomes and how often one of them can occur. Hypothetico-deductive reasoning consists in applying the results or the practice of deductive reasoning to a hypothetical situation. For example, once a student understands how adding a second light bulb in series to a circuit causes the first to become dimmer, an example of hypothetio-deductive reasoning would be that he or she could correctly predict a similar dimming if another kind of resistor is introduced to the circuit, such as a fan motor.

Since the ability to engage in formal reasoning is not an inevitable result of growth, development, and traditional instruction, the question arises as to whether students can be assisted in gaining this ability. And if so, what are effective ways of

teaching that will aid them? Since students will most likely use concrete rather than formal reasoning, it makes sense for a teacher to meet them where they are and to start with the concrete before attempting to introduce the formal. This is exemplified in the "Learning Cycle", which consists of *exploration*, *concept introduction*, and *concept application*. Ideally, students encounter a new situation which raises questions in their minds which cannot be answered within their familiar reasoning patterns. I have heard this described in other contexts as a 'discrepant event'. Once students realize that there is something requiring further explanation before them, they are ready to be introduced to the scientific concept, which may still be concrete or which may lead toward the formal (or abstract) mode of reasoning. After this the teacher may assign tasks in which students must apply the new concept. This provides an opportunity for students to understand the broader applicability of the new idea and gives time for students for whom understanding comes more slowly (Karplus, 1977).

Some research has shown that students, who already have developed their formal reasoning ability so as to be late transitional or formal reasoners, benefit from traditional methods of instruction such as lectures and demonstrations. This stems from a study comparing concrete instruction, which followed the learning cycle, to formal instruction, which used traditional methods. The "inquiry-oriented instruction is more effective at producing reasoning gains for concrete students but for students with some expertise in formal reasoning, further progress is better attained by traditional methods" (Lawson, 1985, p. 604). Since the population of students in my classroom research is one in which

most students are concrete reasoners, this speaks strongly for adopting methods that will be effective in assisting them in gaining formal reasoning skills.

Some research has shown that explicit instruction in formal reasoning skills can result in improvements in students' scores on a test of those skills. Students not given such explicit instruction in their otherwise similar science courses showed no such improvement (Moore, 2012). In the referenced study one class of students was instructed in part using a process which guided them through forming hypotheses of the form "If…and…then". At first students struggled to formulate appropriate hypotheses. By having students evaluate the usefulness of inappropriate hypotheses, the students could learn how to better go about building their own.

In my mind the ideas presented so far provide sufficient motivation to reflect carefully on my practice and to look for ways to work toward improving students' formal reasoning skills. To do this one important approach is to incorporate the learning cycle as a central principle guiding the design and implementation of my curriculum. This research has focused on methods of cooperative learning and guided inquiry, which place a great deal of value on the construction of knowledge, rather than its transfer from teacher to student. This is the so-called POGIL method. In addition, lab activities designed to help students develop formal reasoning skills are also appropriate.

Cooperative Learning and Guided Inquiry

Traditional versus Student-centered Teaching

In order to understand student-centered learning which uses the learning cycle it will be helpful to contrast it with a traditional, teacher-centered approach. In this

approach the instructor's job is to lecture, explain ideas and provide definitive answers. Students expect the teacher to tell them whether they are wrong or right and to demonstrate step by step how to solve problems. Students in a traditional classroom tend to seek a single correct answer to questions and do not require any evidence before they accept an explanation. They not only memorize and reproduce the ideas in the book or from the lectures, but usually do so without really understanding them. Finally, in a traditional classroom students are isolated from one another (Spencer, 1999). It has been my experience that students tend to see teachers who work this way as being the ones who "really teach". If a teacher fails to meet these expectations, for whatever reason, students act as if they have been cheated. Some of my students have proven resistant to learning in any other way. The traditional approach is a cultural norm which needs to be overcome when I take a different approach.

A student-centered approach lies in stark contrast to the traditional one. First, the teacher's job takes on a different character. Instead of lecturing, the teacher consults with students as they construct their own knowledge. Instead of explaining ideas, the teacher asks probing questions of students so they develop their own understanding and explanations. The teacher works to get the students' take on the material and provides enough time for students to work out the solutions to problems on their own. Classroom methods include open-ended discussion, giving students opportunities to gauge the level of their own learning, referring students to data and models, and encouraging students to engage in dialog in which they put their fellow students' ideas in their own words. The students' role is also quite different. Instead of looking for a single correct answer the

student is expected to explain whatever solution is offered. Students are encouraged to try alternate explanations and to use the evidence they have to draw their conclusions. They interact more with their peers in order to explore other ways of looking at the topic under discussion and to test their own comprehension. Rather than accept an explanation which is simply provided for them, students are actively involved in making the connections between evidence and their experience to create an explanation for which they understand the justification. To construct their own knowledge students are expected to test their own hypotheses and use what they know or have been told to ask questions in order to expand their understanding (Spencer, 1999).

This is a very different situation and an uncomfortable one for students. Since they need to be active participants, it puts more demands on them. They must construct their understanding rather than memorize someone else's understanding. Memorization is difficult in its own right but requires no restructuring of the students' view of the material under study. In addition, they are expected to interact with one another, adding a social dimension in which students have to share their own thoughts. This can be hard for students who don't have confidence that their thoughts are valid. I asked students in the spring of 2016 how they felt about this type of work, having piloted it with them. The feedback I received acknowledged that giving them more responsibility for their learning was a good thing but this was salted heavily with a great deal of concern about fear of getting on the wrong track and building up an incorrect understanding. Several students insisted they would rather have a lecture.

Group Work

In organizing the class to be more student-centered it is natural to turn to having students work in small groups. Doing so has several benefits. First, there is a value in the social interactions between students who are focused on their work. They help one another. Second, by giving students prescribed roles, for which they have added responsibility, they have greater motivation to stay engaged (Farrell, 1999). Finally, the group dynamic forces students to give some thought not just to the material they are meant to learn but also to the process by which they learn it.

When students are passively listening to a lecture—or sitting and tuning it out—they do not interact with their peers. However, when they work in a group on a well-designed activity that follows the learning cycle, they must interact. Their roles help them to stay engaged. When they are not allowed to choose their own roles they have opportunities to grow in skill with process skills with which they are less comfortable. Students explain their work to one another. The listener benefits by having someone explain it when the material is also new to the explainer. The explainer benefits because when they are forced to put their understanding into words it brings a sharp focus to their understanding, deepening it (Farrell, 1999).

The goal of helping students to become independent lifelong learners is not well served by a traditional classroom. Some students do learn the appropriate process skills as a response to the demands of the course—as I know from my own experience as a student and from what I have observed in my own students. A focus on process as it is found in the implementation of POGIL (Process Oriented Guided Inquiry Learning) helps students

to develop “information processing, critical thinking, communication, [and] assessment” skills (Moog, Creegan, Hanson, Spencer & Harris, 2006, p. 45). This focus is brought about by the structure of the work given to students and by the way in which the teacher facilitates it.

The Structure of Cooperative Learning Inquiry Activities

Since my action research is based on my implementation of POGIL it is necessary to describe how it works. To begin, allow me to quote the simplest description of POGIL materials that I have found:

> 1. They are designed for use with self-managed teams that employ the instructor as a facilitator of learning rather than as a source of information.
> 2. They guide students through an exploration to construct understanding.
> 3. They use discipline content to facilitate the development of important process skills including higher-level thinking and the ability to learn and apply knowledge in new contexts (Moog, Creegan, Hanson, Spencer & Harris, 2006, p. 43).

The underlying philosophy for this structure is, of course, the learning cycle. Here is how worksheets are designed: First, students are presented with a figure, graph, picture, data or some combination of these. This provides material for the first phase of the learning cycle: exploration. Students work through questions designed to familiarize them with the information. The term introduction phase of the learning cycle is accomplished by setting a carefully crafted set of questions before students. These questions lead students to draw their own conclusions about the information and also introduce the terminology used to discuss it. In addition, the questions are similar to the kind of question a scientist might ask in order to understand something. Finally, after students have answered the questions that introduce the concept (or allow them to

'invent' it) they use their new understanding to solve additional problems in order to practice and apply their knowledge. This phase may be part of the in-class work or may in part be problems students do as homework (Farrell, 1999).

In order to be effective much thought must be given by the instructor to the implementation of the POGIL activity. First, students must be assigned to groups and must each take on specific roles. Second, the teacher does not lecture but instead guides students through the process of figuring things out for themselves (Moog, Creegan, Hanson, Spencer & Harris, 2006). Although it may seem that the teacher has less to do in a classroom run in this way,

> In reality, the instructor has a vital role to play—making decisions about when to intervene, what to say, when to leave a group alone, when (if at all) to deliver a mini-lecture, when (and how) to have groups interact, etc., all based on instructor observations of the progress and dynamics of the class and keeping in mind both the content and process goals for the course and for that day's activity (Moog, Creegan, Hanson, Spencer & Harris, p. 46, 2006).

Students who are the official recorder for the group may be required to submit their work for the teacher to review. This may also serve as the starting point for class discussions in which a spokesperson (often the same student who is the recorder) shares the group's answers to the questions and fields other probing questions from the teacher. At the end of the activity students may be asked to answer some questions in the manner of a formative assessment or classroom assessment technique (CAT). This allows the group to process what they've learned and to reflect on how well they worked together (Farrell, 1999).

Effectiveness Research

I find literature regarding POGIL very interesting and it has caused me to reflect on the things I do in the classroom. But I wonder just how effective are these techniques? Can it be proven that they are in fact capable of producing better results for students? 'Better results' here refers to outcomes such as reduced failure rates, higher achievement, and improved self-efficacy. I planned to use my classroom research project to investigate how my implementation of POGIL affects students' learning and attitudes towards learning and towards chemistry. In order to prepare myself for this work I read a few studies that have looked into the effectiveness of POGIL and cooperative learning more generally.

Lower Attrition and Lower Rate of Grades of D, F, or Withdrawal

According to a web page on the POGIL.org web site titled "Effectiveness" the expected results of using POGIL include a higher retention rate for students, a more thorough understanding of the material taught, and that students would rather use POGIL than a traditional approach (The POGIL Project, 2012-2016). The same page cited published results comparing four years in which strictly traditional methods were employed with a period of three years in which POGIL was employed. I have already referred to the theoretical background discussion from this same paper. The results showed that for the period when traditional methods were employed the percentage of students earning D, F, or withdrawing from the course was 21.9% (N = 420). For the following period, in which students were taught using Guided Inquiry techniques, the D,

F, W rate was 9.6% (n = 438). The rate at which students earned an A or a B also increased in the group which used Guided Inquiry (Farrell, 1999).

When measured based on attendance at the POGIL-based discussion sections, a study at the Univ. of Nebraska, Lincoln showed that students attended 1.47 more sessions (out of 12) than students who were assigned to discussion groups at which POGIL was not employed. This same study did not find a significant difference in the rate of grades of D, F or withdrawals (Chase, 2013).

It seems that there may be factors besides whether or not POGIL is employed that affect these outcomes. In fact, the Chase study was based on the investigation of whether the adaptations made to the basic POGIL idea had made the method more or less effective than anticipated.

Higher Achievement

Some studies have found no significant improvement in achievement with the use of POGIL. This may have been due to the manner in which POGIL was implemented. (Chase, 2013) Other studies have shown significant differences between the achievement of students who were in a POGIL-based section of a course compared with those who were in a traditionally taught section. A meta-analysis of studies investigating cooperative learning (more broadly) found that the median student performance in a cooperative learning group would be at the 75^{th} percentile compared with a student taught by traditional methods who would earn a score at the 50^{th} percentile (Warfa, 2016). Final scores for a general chemistry course included a rate of 64.8% of students in a POGIL

section earning an A or a B as compared with only 52.4% earning A or B in sections taught in a traditional manner (Farrell, 1999).

Since the scope of my classroom research goes beyond just the use of POGIL it is worth looking at how students fare when they have better-developed formal reasoning skills. It is a common finding that students who enter college in a STEM field tend to test as either late transitional or formal reasoners. These students perform better academically in science courses, as evidenced by the higher-level courses these self-selected students enroll and succeed in (Moore, 2012). Students who are concrete reasoners have a harder time learning science content and students who perform well on a test of scientific reasoning (the LCTSR) perform better on standardized tests of physics which require abstract and theoretical understanding (Moore & Rubbo, 2012). Moore and Rubbo go on to suggest that in a population of students consisting mainly of concrete thinkers it is important to provide explicit instruction in formal reasoning often throughout the course.

Improved Self-efficacy

In descriptions of the POGIL method it is often claimed that students will learn to be more confident in their ability to learn chemistry. This is meant to come about by their learning the process skills which are central to the philosophy behind the method. For example, one student was quoted as follows: “I have learned (and can remember what I’ve learned) significantly more this semester than last and I feel the group learning method is an *excellent* method of learning” (Farrell, 1999, p. 573). This is a piece of qualitative data that was described as a typical comment. This, combined with the fact that students in the study preferred to reenroll in a Guided Inquiry section for the next

semester seems like a strong indicator that an improvement in self-efficacy may in fact be a consequence of using this teaching approach.

On the other hand, in a study using proven valid and reliable surveys, the researchers found no statistically significant difference in students' self-efficacy between two groups, one of which experienced a traditional instructional approach while the other used POGIL activities (Chase, 2013). The focus of this study was on whether the method used to implement POGIL in the classroom for the first time would be effective when adaptations were made so that it would fit into the framework of the authors' particular institution and department. Indeed, the authors conclude that adaptations may change how the use of POGIL affects students and that the prescribed approach given by the organizers of the POGIL project (at pogil.org) should be carefully followed. In addition, they advise readers that the first time POGIL is put into practice it may not immediately provide the anticipated results. Finally, the data they collected was adequate to show that using POGIL did not have a negative impact on students' grades. They cautiously suggest that it may have the potential to enhance student achievement (Chase, 2013).

Because the effects of one or two uses of the POGIL approach are not expected to have a large impact on students, my study looked at data and information from early in the school year and compared it to information gathered later in the year. This classroom research considered my work holistically in order to investigate how my practice broadly affected students' success in chemistry and their development of formal reasoning skills.

Inquiry Laboratory Activities

POGIL and small-group work generally is one useful approach when using the learning cycle to help students to comprehend science content and to aid their development of scientific reasoning skills. Another approach is to use hands-on, open-ended activities in which students literally explore a phenomenon with their own hands and senses. In response to student progress this year I developed an activity I called Doing Science. In this activity I intended to help students to explicitly develop their skills in the identification and control of variables, correlational thinking, and hypothetico-deductive reasoning.

Conclusion

This classroom research project is concerned with exploring alternative methods of instruction, including POGIL and inquiry-based laboratory activities. These have been shown to be effective means of instruction. In addition, the effects of the level of students' cognitive development on their performance in comprehending science content are explored. Finally, the consideration of methods by which students may be aided in their cognitive development are explored.

METHODOLOGY

The purpose of this classroom research project was to explore the use of methods intended to improve the formal reasoning capabilities of students. In order to do this I have taken certain steps in the classroom to learn how to use these methods and to investigate their effects on students. I wanted to find out whether the interventions I take with students have an impact on their formal reasoning ability and if so, what that impact

is. I planned to do this by using the POGIL method and by introducing simple inquiry-based lab activities which draw on students' skills in forming hypotheses and coming up with valid ways to test them. Science teaching is concerned both with process skills, such as formal reasoning, but also with helping students to master content. I wanted also to find out whether the process skills identified as formal reasoning ability had an effect on students' comprehension of course materials. Were students with a more developed set of formal reasoning skills more adept at learning the content or did they show more improvement from unit pretests to posttests? And since student perceptions play a large role in the success of any classroom intervention, I wanted to know how these methods affected students' sense of their success in learning science.

Participants

In two sections of the same course there were 37 participants, 22 male and 19 female. The demographics of the participants matches the demographics of the school with most students classified as white and with approximately 10% qualifying for free or reduced lunch. The course is a college-preparatory chemistry course. This course is selected mainly by students who wish to continue their work in science with a challenging course but who are not yet ready for an honors or college level course. The majority of students in the course would likely not describe themselves as mainly interested in science. In addition, this population of students has a history of difficulty in their math and science classes.

I did not separate students into different groups in order to compare how students fared with or without the interventions. Since I intended my classroom research as a way

to explore new methods, and because scientific control was unlikely to be possible, I decided that it was better to have a larger pool of students with which to use the interventions.

The research methodology for this project received an exemption by Montana State University's Institutional Review Board and compliance for working with human subjects was maintained, Appendix A.

Interventions

The interventions I used in the classroom came in two main categories. First, I used the POGIL method as a part of many lessons, and especially with the three I focus on in this paper. An example POGIL lesson is included as Appendix B. Second, partway through the year I wrote a new lab activity which I intended to serve as a way to put students in the position of needing to exercise formal reasoning skills. I called this activity “Doing Science”. It was written in a generalized way so that I can use it for a variety of simple experiments. I have included the handout as Appendix C. I will describe two such experiments and then analyze my observations of students and their written responses.

I implemented the Process Oriented Guided Inquiry Learning activities in the following way. Before I used this approach I tried to help students understand the idea behind this type of work. They are responsible for solving the problems and figuring things out on their own, and I served as a facilitator and a last line of defense in case they got stuck. The expectation was that they work together until they were all convinced they

have figured it out correctly. It was not acceptable to go along with another's answer until every member could honestly say they understand it.

There were four group member roles: manager, reader, recorder/spokesperson, and quality control. After students assign these roles to group members I walked around and recorded who is performing which role so that they will be sure to rotate roles each time they do an activity like this. The manager's task was to do the work and to get people back on task if they become distracted. The manager was also the member of the group who asked questions of me if necessary. The recorder's job was to produce a clean copy for me to collect and review in order to provide feedback. The recorder was also responsible for reporting out to the whole class about their group's responses. The reader was responsible for reading the text of the activity aloud for the group. The reader's job seems simplest but was in fact vital because it provided a way to re-focus for every question and every new model. Finally, the quality control member was responsible for giving the group feedback about how well their work was serving the goal of learning the material. As the teacher I also checked in with this student.

I reviewed the recorders' papers so that I could focus on just the trouble-spots in the class-discussion portion of the work. By using this information to inform my discussion with students, I hoped to consolidate what they did understand and to correct any misunderstandings. After reviewing each group's work with them specifically I called the class together for a class discussion. We went over the key points of the activity and ensured that everyone had everything correctly. I then asked students to work together in their groups to write down summary statements about what skills, ideas, and

important concepts they were supposed to learn by doing the group work activity. After they completed this work, I led a class discussion in which I wrote down all of the summary statements from all of the groups so that students could in turn add them to their class notes.

I assigned students to heterogeneous groups. I hoped that by doing so I would be able to encourage students to work together in such a way as to help the students who struggle with the material. I changed groups once a month so that students could make new connections and benefit from different perspectives. I determined group membership by testing students with the Lawson Classroom Test of Scientific Reasoning (more about which, below), which assigns students to different levels of development between concrete thinkers and formal operational thinkers. I used the test to identify students who were likely to find chemistry difficult and also to identify students likely to be able to learn the material more readily. As much as possible I kept one or more students in each group who scored more highly than his or her peers on the test of reasoning.

The POGIL teaching method has been found to encourage students to develop independence, self-constructed knowledge, and "information processing, critical thinking, communication, [and] assessment" skills (Moog, Creegan, Hanson, Spencer & Harris, 2006, p. 45). While these are related to the formal reasoning skills which the Lawson Classroom Test of Scientific Reasoning (LCTSR) evaluates, they are not identical. As such, they are not expected to have a direct impact on student scores on this test.

The second type of intervention I used in my classroom research was the inquiry-based lab activity I wrote called “Doing Science”. I performed a demonstration to illustrate a problem or a question and then students in turn attempted to re-create the demonstration. Following this, they were asked to devise experiments to help them to create an explanation for what they observe. The handout guides students through the process of generating and testing hypotheses. By interacting with the pairs of students working on the problem I could find out where they are in the process of learning formal reasoning skills. I asked probing questions to help them to develop those skills.

The first Doing Science activity I did with students focused on the simple experiment of filling a narrow-necked flask with water, covering the top with a plastic disk, and then turning it upside-down without spilling the water. I extended the experiment by providing students with small pieces of plastic window screen. By attaching this to the opening of the flask the water can still be observed not to fall out when the flask is turned upside-down. At first students did not know what to vary in order to investigate the phenomenon further. By pointing out the small drops of water that always leak out I was able to get some students to focus on appropriate experiments. As the hour-long activity drew to a close I came to each group and demonstrated crucial experiments that provided the observations necessary to build the correct explanation. Namely, the ‘molecular stickiness’ of the water makes the disk stick to the glass and the small amount of water that escapes when the flask is turned over leads to a small decrease in the pressure inside the flask, allowing external air pressure to push up the disk against the flask’s rim.

The second Doing Science activity that I did with students involved buoyancy. I weighed a brass 100 g weight. Next I weighed a beaker full of water. Then I suspended the brass weight in the water using a string and measured the total weight. By subtracting the weight of the beaker and water I demonstrated that only 11.8 g had been added. I asked students to figure out why the suspended mass of an object has its particular value. In other words, what is the rule that relates a feature of the suspended object to its suspended weight in water? To follow up I asked students who didn't know how to begin to determine whether it was the weight or the volume of the suspended object that mattered. As needed, I gave hints or pointed out materials that would allow students to keep one variable constant while varying the other. The correct explanation is simply that the weight held up by the string is less by exactly the weight of the water which would occupy the volume of the object. The water supports just that much weight and this is what gives rise to buoyancy.

After the activity was complete I asked students to write up their explanations giving evidence and to answer these questions:

1. Imagine a string supports a cylinder suspended in water. The cylinder has a mass of 100 g. The balance reads 10 g after the mass of the beaker and water is subtracted. How much weight does the string support? Write one sentence justifying your answer.
2. A rubber stopper has a mass of 10 g. When placed under water in a graduated cylinder it is found that its volume is 8.0 mL. Next, the stopper is suspended from a string into a beaker full of water set up on a balance. What mass will the balance read after the mass of the beaker and the water is subtracted out?
3. What if it wasn't just plain water? Take an object that has a suspended mass of 10 g in water. What would its suspended mass be in salt water, with a density of 1.1 g/mL? Explain your answer.

My hope in using these interventions was to influence students' development of formal reasoning skills. As I learned more about this topic in the course of my research this year I came to realize that POGIL and academic achievement are not necessarily tied to fostering student development of formal reasoning. I wrote the Doing Science activity in order to address this lack. In this classroom research project I reported only two instances of the use of this intervention, but I think I will be able to make the case that if used many times over the course of a school year it could have a positive impact on students' formal reasoning skills.

Data Collection Instruments

Lawson Classroom Test of Scientific Reasoning

In order to gauge formal reasoning skills, I used the Lawson Classroom Test of Scientific Reasoning (LCTSR). This test is given in its entirety in Appendix D. This survey has been validated in several ways. First, the author of the survey sought face validity from a panel of six judges, who are considered experts in Piagetan research. All agreed about the questions with respect to whether they address concrete or formal reasoning. In addition, the author compared results on the survey with a large group of students to results from a different test of formal reasoning and found that they correlated strongly (Lawson, 1978).

The test is scored so that for questions 1 – 22 the student receives one point for each correct pair of answers. The questions follow a pattern of asking about a situation and then inquiring as to the student's reasoning for their choice. A point is scored only when both answers are correct. Questions 23 and 24 are independent and so there are a

total of 13 points on the test. The test examines students in a variety of ways. First, there is a question about the conservation of weight and another about displaced volume. Then there are questions regarding proportional thinking, identification and control of variables, probabilistic thinking, correlational thinking, and hypothetico-deductive reasoning. These are the different areas of formal (or scientific) reasoning examined in this test (Lawson, 1978).

Though Piaget (1972) originally considered formal reasoning to be a unitary capability it is now understood that it consists of separate skills. Students will not necessarily generalize formal reasoning from one area into another. For example, it was not found that students who performed well with proportional reasoning also performed well with the control of variables or vice versa (Karplus, 1977).

There are four categories, based on the writings of Jean Piaget, into which students can be grouped according to their scores. For a score of up to 4 out of 13 students are classified as concrete (C). Concrete thinkers focus on observable criteria and are able to apply the logic of conservation—the amount of something does not change when it is put into a new container. This type of thinker typically is not aware his or her own reasoning, nor of inconsistencies in statements he or she has made, nor of contradictions with known facts. Typically, this type of student needs to refer new things to familiar actions, objects, and properties. Students with a score of 11 – 13 are considered formal (F) reasoners. These students can reason in all of the ways a concrete reasoner does but can also reason with concepts, axioms, theories and abstract ideas and uses symbols to represent ideas. In addition, the formal reasoner is aware of his or her

own reasoning process and actively seeks to evaluate his or her conclusions in light of other known facts. In between these scores (5 – 10) are students who are classed as transitional between these two reasoning patterns. For scores from 5 – 7 students are considered early transitional (ET) and from 8 – 10 they are considered late transitional (LT). Students in these categories may show formal reasoning ability on the test in some areas but not others (Kaplus, 1977). The development of formal reasoning is not inevitable and though it is related to age it will not normally develop without training or appropriate experiences.

I administered the test once in mid-October, 2016 and again in late March, 2017. I collected the data using a printed-out test and an online form which only has the letters for the multiple-choice answers. I discuss the results in the next section.

The POGIL intervention may or may not have had an impact on students' development of formal reasoning skills. The new Doing Science activity which I created specifically to attempt to address the development of these skills may not have been used over a long-enough period of time to have a significant effect. Still, a connection may be made between academic achievement and formal reasoning ability. In summarizing research relating to intelligence, mental capacity, and formal reasoning, Lawson had this to say: "It would appear that…the ability to utilize formal reasoning patterns is an ability of considerable importance to achievement in a variety of disciplines. This result is important for it makes plausible the hypothesis that teaching formal reasoning patterns may produce widespread gains in academic achievement" (Lawson, 1985, p. 595). As a result, I used pretests and posttests and classroom assessments to judge the impact of

formal reasoning skills on academic achievement. To be clear, I looked at the effect of students' existing formal reasoning skills on their academic achievement. The data are not suited to making a direct connection between my interventions and changes in students' tested formal reasoning ability.

Pretests and Posttests

I gave a simple multiple-choice test covering the content of three units both before and after instruction. In these units I used the POGIL method as described above. In addition, I gave class notes, assigned homework, and reviewed homework and sample questions and problems with the class. In collecting these data I intended to address my research question regarding the impact of students' reasoning skills on their academic achievement. The instruments I used include questions which require factual recall but also questions which require application of concepts, where appropriate. I have included a sample quiz as Appendix E.

Classroom Assessments

I gave pencil-and-paper assessments which allowed me to do two things that multiple-choice tests do not enable. First, I could ask open-ended questions to probe students' knowledge and their ability to explain their reasoning. Second, I could judge students' understanding in a more nuanced way than with a binary right or wrong answer. These test and quiz scores were useful for exploring whether reasoning skills had an impact on student comprehension of the course material. Also, they could be compared with pretest and posttest data for the units I studied. I have included a sample classroom assessment (for atomic structure) as Appendix F.

Interviews

I interviewed students in small groups to find out how they felt about the instructional methods and their own learning. My classes were small and so I interviewed all students. The full list of questions is given in Appendix G. By asking these questions I hoped to find out whether students were aware of what I was trying to accomplish and to find out how they felt about their work in my class. Most importantly, I needed the information from the interviews in order to speak most directly to the question of how their work with POGIL, particularly, affected their own evaluation of their success in the course.

In Table 1 I have connected all of my instruments to the relevant questions.

Table 1

Data Triangulation Matrix

	DATA COLLECTION METHODOLOGIES				
DATA COLLECTION MATRIX	LCTSR*	Pretests/ Posttests	Inquiry Lab Scoring	Classroom Assessments	Interviews
RESEARCH QUESTIONS					
Main Topic ❖ How does my work with students, including implementation of the POGIL teaching method and inquiry-based lab activities, contribute to growth in developing from concrete thinkers toward formal reasoners?	❁	❁	❁	❁	❁
Sub question #1 ❖ How does the use of POGIL and inquiry-based lab activities affect students' development of reasoning skills?	❁	❁	❁	❁	❁
Sub question #2 ❖ How does a student's initial measured level of reasoning skills affect comprehension of science content?	❁	❁		❁	
Sub question #3 ❖ How does the use of POGIL affect students' own evaluation of their success in chemistry?		❁			❁
Sub question #4 ❖ How does reflection on my practices with respect to the aim of developing students' formal reasoning affect approach to teaching?	❁	❁	❁	❁	❁

* *Note:* LCTSR is the Lawson Classroom Test of Scientific Reasoning

DATA AND ANALYSIS

In order to answer my research questions I needed to measure my students' reasoning ability. As described above, I did this using the LCTSR. Other results, including unit pretest/posttests, classroom assessments, and Doing Science labs were interpreted with reference to the results from the LCTSR. Changes in students' reasoning skills were small but at least for some students, significant. Interviews with focus groups provided useful qualitative data to validate the teaching methods I employed.

Lawson Classroom Test of Scientific Reasoning

I asked my students to take the Lawson Classroom Test of Scientific Reasoning (LCTSR) in the third week of October, 2016. Students were informed that I wanted to use the results to refine my teaching practice in general and inform my work with them specifically. I described the test as one which will evaluate their skills with respect to solving problems in science and that it would not count as a grade. Students participated willingly and appeared to take the questions seriously. This valid and reliable test should, at this early point in the year, provide information about students' reasoning capabilities prior to the bulk of the instruction provided in the course. Generally, this population of students was likely to score in the concrete to early transitional range given that many of them have a history of difficulty in math and science. This was in fact what I found.

Results indicated that no students in these courses scored in the Formal-operational range and that a large minority scored in the Early Transitional range (see Table 2).

Table 2
LCTSR Pretest Scores, (N = 37)

Piaget Level	No. of Students	Percentage of Students
Concrete (0-4)	17	46%
Early Transitional (5-7)	15	41%
Late Transitional (8-10)	5	14%
Formal (11-12)	0	0%

By far the majority of my 11th grade students scored in the Concrete and Early Transitional ranges: 87% or a total of 32 out of the 37 taking the survey. The average score for the entire group of students was 4.8 with a standard deviation of 2.2, which is just beyond the Concrete range. According to the developer of the survey, a typical result for 10th graders is an average score close to 8 with a standard deviation of 4, which is in the Late Transitional range. (Lawson 1978) This group of students is well below that average showing that most of them had not yet developed skills in formal reasoning.

By way of comparison, I also gave the survey to the students in my AP Chemistry course. The average score for that group of 24 students was 9.5, with a standard deviation of 2.5. This places nearly all of the students in the Late Transitional to Formal Operational categories. This is to be expected for a population of students who have selected a college level course in an abstract science such as chemistry. This result underscores the validity of the test with respect to reasoning abilities as the scores matched my expectations about these two groups of students.

These pretest results provided an important baseline in order to put other data into context. In order to address students' development of reasoning skills I needed to have a

reliable and valid measure of those skills. I wished to also address the question of the relevance of students' reasoning skills to their success on academic tests—my second research sub-question. Do these reasoning skills show any connection with students' comprehension of science content? Does it correlate to the improvement shown between a pretest and a posttest for a given lesson? I will explore this in a later section.

In order to be able to gauge any changes in scientific reasoning skills after five months of instruction using POGIL and the learning cycle I gave the LCTSR to the college-prep students again in late March, 2017. Due to absences and students who dropped the course there are only 31 students who participated in the posttest. The scores indicated that the same number of students could be identified as concrete thinkers (see Table 3).

Table 3
LCTSR Posttest Scores, (N =31)

Piaget Level	No. of Students	Percentage of Students
Concrete (0-4)	17	55%
Early Transitional (5-7)	7	23%
Late Transitional (8-10)	6	19%
Formal (11-12)	1	3%

Two students previously identified as concrete did not take the posttest so this is actually an increase in the number of students in that category. Thirteen students stayed in the concrete category and four students previously identified as early transitional joined them to give the total of 17.

Three students who did not take the posttest were identified as early transitional on the pretest. Four students dropped from early transitional to concrete, four remained in

the early transitional category, and one student who had a late transitional score on the pretest scored in the early transitional range on the posttest. Four students originally in the early transitional range moved into the late transitional range on the posttest. Of those scoring in the late transitional range on the pretest one dropped to early transitional, two remained where they were and one moved up to the formal operational range (see Table 4).

Table 4
LCTSR Score Changes from Pretest to Posttest, (N = 31)

	No. of Students	Percentage of Students	Average Normalized Gain
Moved to the next category down	5	16%	-0.26
Remained in the same category	19	61%	-0.01
Moved up to the next category	7	23%	+0.33

In Table 4 the normalized gain compares the actual change in score from the pretest to the posttest to the largest possible change in score. These are calculated based on the percentage scores, rather than raw points. The formula used for this calculation is as follows:

$$G = \frac{postscore\% - prescore\%}{100 - prescore\%}$$

Only seven students improved their performance when measured based on their assigned Piaget level. Just eleven students had a positive normalized gain in their score when it is measured as a percentage of the total points on the test. Of the 19 who remained in the same category six had negative normalized gains, nine showed zero gain, and four showed small gains. All of the seven students who moved up to the next category showed positive normalized gains and these ranged from 0.11 to 0.57. These results do not speak well for the hope that the use of POGIL and inquiry-based lab activities would lead to improvements in students' reasoning abilities.

Two or three students who had high scores on the LCTSR did well on every assessment. These are the kind of students that are easy to teach because they learn well even when I don't teach well. Interestingly, there were also a few students who scored in the concrete range on the LCTSR but who still did well on classroom assessments. This is interesting because it supports an idea I have long thought to be true: at least for some students hard work and dedication can make up for a lower level of aptitude. Unfortunately, some students scored in the concrete range and scored poorly on just about every assessment. It is these students who most need attention and who will benefit most from a program which successfully improves their reasoning skills.

These disappointing results aside, there is some reason for optimism. Figure 1 and Figure 2 show the average scores earned by students for each of the formal reasoning patterns which the LCTSR examines.

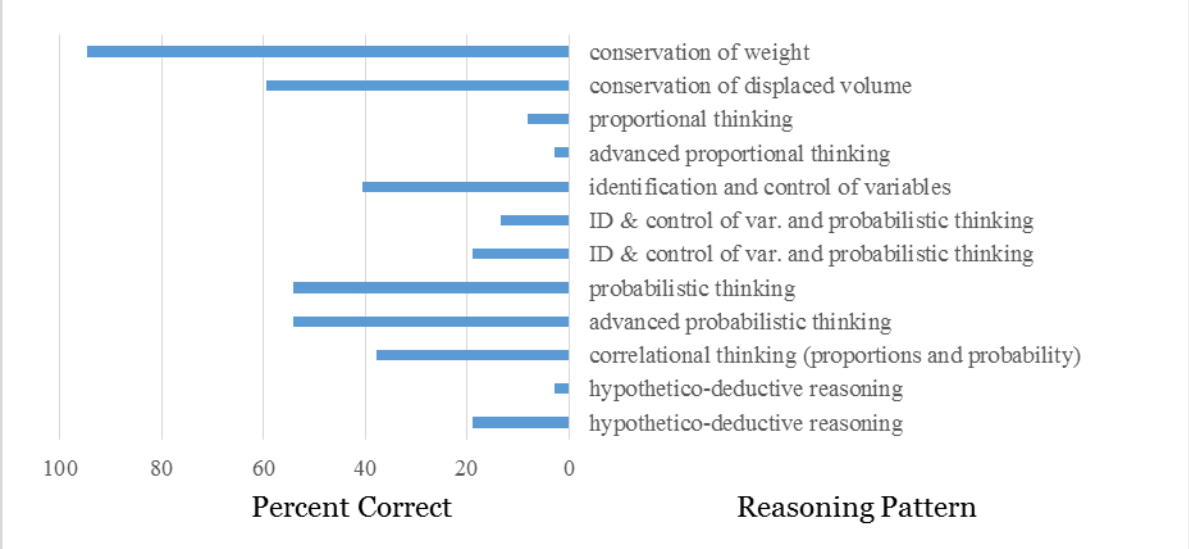


Figure 1. Pretest score for each reasoning pattern, (*N*=37).

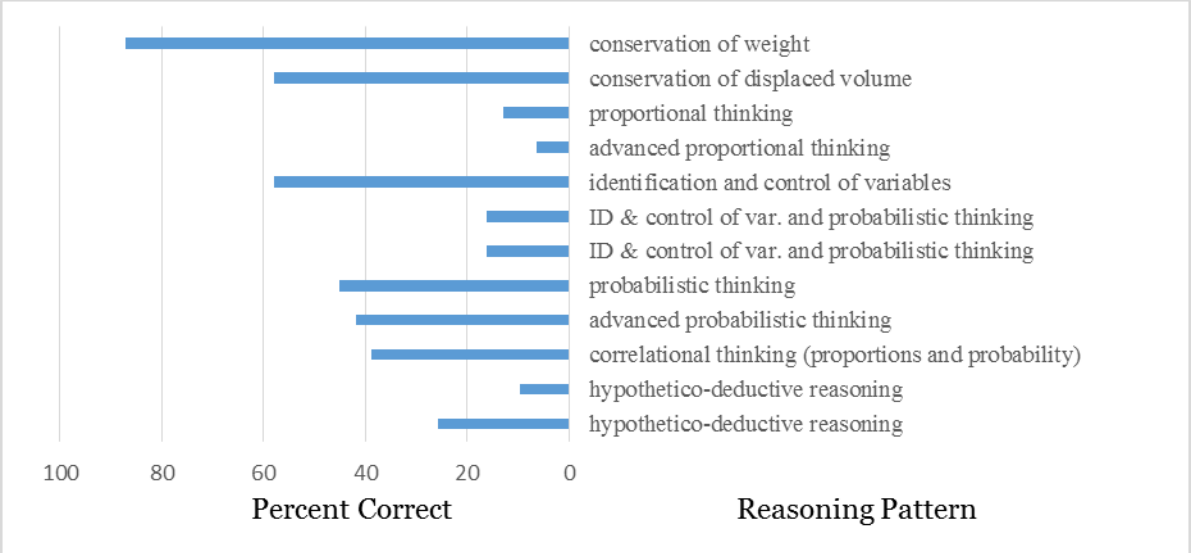


Figure 2. Posttest score for each reasoning pattern, (*N*=31).

In these graphs it is clear that the highest average scores on both the pretest and the posttest are in the concrete reasoning patterns represented by the conservation of weight and volume. Proportional thinking and hypothetico-deductive reasoning are areas where scores were lowest. In between are the reasoning patterns having to do with probabilistic thinking and the identification and control of variables.

For most of the reasoning patterns students show little or no change from the pretest to the posttest in the average scores of the class within each pattern. Some improve a little and some have lower scores. POGIL and the use of the learning cycle help concrete thinkers to access content otherwise incomprehensible. However, since they do not involve direct instruction in formal reasoning patterns they are likely to contribute little if at all to students' improvements with these skills. Achievement in the course is still primarily tied to the ability to remember facts and apply simple skills. Since these do not require formal reasoning students cannot be expected to improve much.

The one positive result concerns the reasoning pattern identified as “identification and control of variables”. This reasoning pattern shows an improved average score on the posttest. The pretest average score was 41% and the posttest is 58%. This is a gain of 17 percentage points which is a normalized gain of 0.29. No other reasoning pattern shows this large of a change. It is possible that the implementation of the inquiry-based lab activities had some effect in assisting students to improve in the skill represented by this reasoning pattern. I will discuss this further in a later section dealing specifically with the qualitative data I collected about the two activities I did with students.

Science Content Pretests and Posttests

For three different units I taught this year I gave a pretest and a posttest using a simple multiple-choice format in an electronic Google form. The atomic structure unit pretest/posttest is included as Appendix E. I used the quiz feature so students would receive immediate feedback about their score and which questions they answered incorrectly and what the correct answer was. These data were collected so that I could look at whether the reasoning level of students had an impact on students’ comprehension of content. I also wanted to know whether students at different Piaget levels had different outcomes with respect to how much they were able to improve their scores. To be clear, I intended these data to address my classroom research sub-question two, regarding how reasoning ability impacts science content comprehension.

The first unit for which I collected pretest and posttest data was about the classification of matter. That is, the distinctions among elements and compounds, and homogeneous and heterogeneous mixtures. The average score on the pretest in

classification of matter unit for all students was 46% and the average posttest score was 64%. I have broken down the average scores based on the Piaget level of the students based on the results of the LCTSR (see Table 5).

Table 5
Classification of Matter Pretest and Posttest Indexed on LCTSR Pretest Score

Piaget Level	Average Pretest Score	Standard Deviation Pretest	Average Posttest Score	Standard Deviation Posttest	Average Normalized Gain	N
C	37%	13%	58%	15%	0.38	16
ET	48%	16%	65%	12%	0.33	15
LT	67%	18%	80%	5%	0.29	5
All	46%	18%	64%	14%	0.35	36

It is clear from these results that there is a connection between the higher scores on both the pretest and the posttest and the Piaget reasoning level. The sample isn't large enough to be able to perform a reliable statistical analysis of this connection but it seems that if students do better on the LCTSR they will do better on unrelated academic tests. This is supported by the visual representation data as in Figure 3. The concrete learners started low and though their normalized gain was as large as the other groups', their median score did not rise above 60%. One outlier student in the concrete category earned a posttest score of 92%. He was an unusual student who appeared to have other areas of intelligence that made up for his poor showing on the LCTSR. Another interesting case is of a student who scored in the early transitional range but who found the subject of chemistry very challenging. Although he showed evidence of better formal reasoning skills than his peers, his score on the posttest was actually lower than it was on the

pretest. This shows how a student's particular circumstances can be more important for academic success than reasoning skills alone.

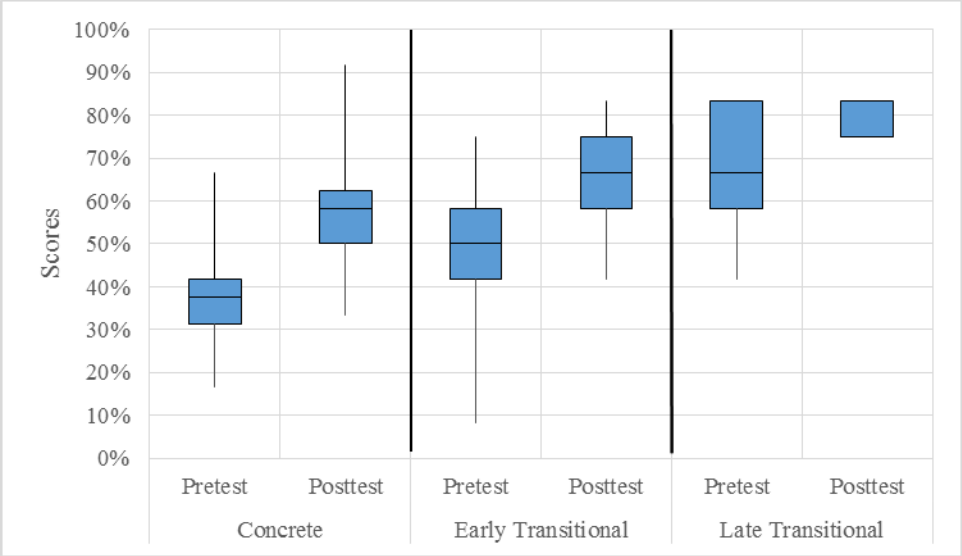


Figure 3. Plot of pretest and posttest data for Classification of Matter, (*N* =36).

The next unit for which I collected this kind of data was one about atomic structure. It covers ions and isotopes and requires simple calculations to find the number of protons, neutrons, and electrons in an atom. The average score on the pretest in the atomic structure unit for all students was 40% and the average posttest score was 69%. I have broken down the average scores based on the Piaget level of the students based on the results of the LCTSR (see Table 6).

Table 6
Atomic Structure Pretest and Posttest Indexed on LCTSR Pretest Score

Piaget Level	Average Pretest Score	Standard Deviation Pretest	Average Posttest Score	Standard Deviation Posttest	Average Normalized Gain	N
C	46%	19%	65%	28%	0.23	16
ET	30%	21%	67%	23%	0.54	15
LT	62%	19%	83%	16%	0.66	5
All	40%	23%	69%	25%	0.43	36

Scores on the pretest do seem to follow a pattern with students with better reasoning abilities achieving higher scores on the pretest. This may simply be due to the fact that these students are better at figuring out the intended response for a question by carefully reading the answer choices. Of course, it's possible that students with higher reasoning abilities remember more from previous experiences with this material. Higher reasoning abilities probably mean that a student has higher success in lessons requiring those skills. It appears that the reasoning skills measured by the LCTSR are in fact predictive of the ability of a student to succeed on a quiz such as the one given here.

In Table 6 (above) I have calculated the normalized gain on the basis of individual students and then averaged these results. Students who are classified as Early Transitional did more poorly than the students in the Concrete category. This is unexpected. The posttest scores show a pattern that is more like what I would have expected: the average score is higher for students with more highly developed reasoning skills. Also, the normalized gains are greatest for students in the highest Piaget category.

It is also interesting to note that the amount of variation in the posttest score is highest for students in the Concrete category. The standard deviation is high for this set of scores showing that there is a wider range of scores earned by students in this category. Some of the students in this category actually earned lower scores on the posttest than on their pretest while three of them earned perfect scores.

The third and final unit for which I collected pretest and posttest data concerned average atomic mass. Atoms of an element are differentiated based on the number of protons. Neutrons also make up part of almost every atomic nucleus but the number of

neutrons in a nucleus can vary without altering the element. Each variation is called an isotope. Each isotope of an element has the same number of protons but different numbers of neutrons and each isotope has its own specific mass. By performing a weighted average calculation based on the weights and natural abundances of the isotopes it is possible to calculate the average atomic mass of an element. It is this number that is given as the mass of an element in the periodic table. The results of data collection for this unit are given here in Table 7.

Table 7
Average Atomic Mass Pretest and Posttest Indexed on LCTSR Pretest Score

Piaget Level	Average Pretest Score	Standard Deviation Pretest	Average Posttest Score	Standard Deviation Posttest	Average Normalized Gain	N
C	53%	24%	69%	27%	0.28	16
ET	44%	32%	79%	18%	0.64	15
LT	68%	30%	75%	26%	0.31	5
All	51%	30%	75%	23%	0.42	36

One notable result is the low average pretest score for students in the early transitional category. The reason might have to do with the nature of the material. The questions here are more mathematical in nature and students' mathematical skills may (or may not) be separate from their reasoning skills. As a result those with slightly better reasoning skills, but lagging mathematical skills, may have initially done more poorly on the pretest.

The students in the concrete category did better on this pretest than either of the other two lessons. However, their performance on the posttest shows a large standard deviation. This is due in part to five of these students earning a lower score on the

posttest for this lesson than on the pretest. None of the early transitional and only one of the late transitional students had a poorer posttest than pretest. On the other hand, seven of the concrete thinkers missed none or just one or two questions on the posttest. One student even earned 92% on the posttest after earning only 33% on the pretest. She is an English language learner and it's possible that her low LCTSR score was due to difficulties with language rather than deficits in reasoning ability. Then again, it seems fair to say that the improvements, some of them dramatic, seen by concrete thinkers indicates that the LCTSR does not uniquely identify the only important variable in a student's success with academic content.

One student who did particularly well on the both the pretest and the posttest was grouped with the concrete thinkers. However, the evidence of clear reasoning that he gives in conversation indicates that this may be a misleading characterization. His work and his contributions in class seem to indicate strong reasoning skills. Students like him likely bring the average scores for the concrete group higher. On the other hand, there is another boy who is in the late transitional group. He asks many questions in class, which is good, but his questions are of a nature that indicates poor reasoning ability. He was the one student in the late transitional group whose posttest score for this lesson was lower than his pretest score. Tellingly, he is the one late transitional student whose posttest score for the LCTSR indicated that he should be in the early transitional group.

In summary, there is some indication that students who do better on the LCTSR do better on tests of content knowledge, both prior to and after instruction. This indicates that it is likely a good practice to work toward improving students' reasoning skills as

doing so may positively impact their ability to learn new science content. But other results point in a slightly different direction. Some students in the concrete or early transitional groups do much better than their peers in the same group. This may be because the LCTSR is not adequately measuring their reasoning ability. Or it may be that there are habits, skills, or other aspects of intelligence that have an equal or greater impact on achievement on tests of academic content knowledge. For example, a student with good study habits who takes it upon herself to seek out individual instruction with the teacher may learn more and earn a higher score than a student who has better formal reasoning skills but who did not take any time to study. This is not to say that reasoning skills are therefore less important but it is valuable to acknowledge that this is a complex area of study.

Classroom Assessments

For every unit I gave a summative assessment in the form of a short quiz. At the end of each quarter I gave an assessment which covers the content in the quizzes given during that quarter. Finally, I gave a midterm exam and a final exam at the end of each semester. The assessments build on one another and give students a chance to revisit material and make an effort to correct mistakes and misunderstandings. I have tabulated some assessment data for the units I have included in this present classroom research project in Table 8.

Table 8
Statistics for Classroom Assessments of Three Units and the Midterm Exam, (N=31)

	Classification of Matter	Atomic Structure	Average Atomic Mass	Midterm
Average	82	89	82	71
Std. Deviation	10	11	16	12

All three units show similar statistics without much variation in the average score from one to the next. The standard deviation for the average atomic mass unit quiz is larger than for the other two, probably because the mathematical skills required made it a more challenging quiz for some students. The midterm data are typical for midterms I have given for the past six years. The interesting question about these data concerns whether or not it can inform about the usefulness of incorporating POGIL methods into my teaching. To address this question I looked at the data I have collected over the past several years for these same units. In all cases the student population is similar in demographics and general composition. In my subjective judgement in each year there was about the same proportion of very capable students and students who struggle. The units are much the same from year to year, and the quizzes themselves have only been slightly modified. I did not teach this course in 2011. I only have data for classification of matter for two years.

As can be seen in Figure 4, the quiz grades for each unit have remained much the same over the past several years. I began using POGIL instruction intentionally in the 2014-2015 school year. This change in my instructional practice does not reveal itself in changes to the classroom assessment scores earned by my students. I have been refining and improving my implementation of POGIL during the current and the prior academic year. Optimistically, this may have played a part in the improvement in student scores on the atomic structure assessment. As there are so many other factors which may have played a part in determining those scores, this is doubtful, however.

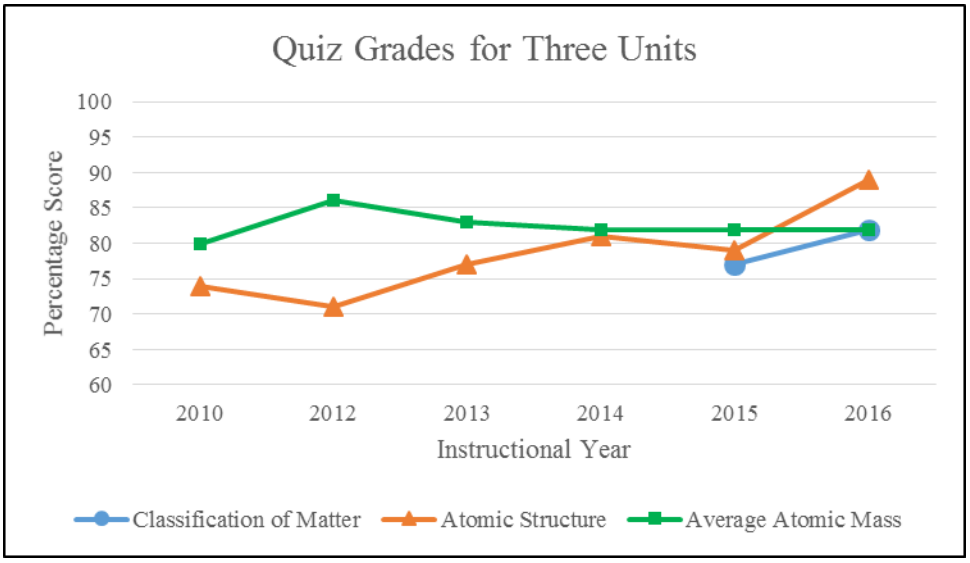


Figure 4. Average scores on unit assessments (*N* = 34 – 58).

Another important question that classroom assessment data may be used to address is the extent to which a student's measured reasoning skills contributes to their scores on important summative assessments such as a midterm exam.

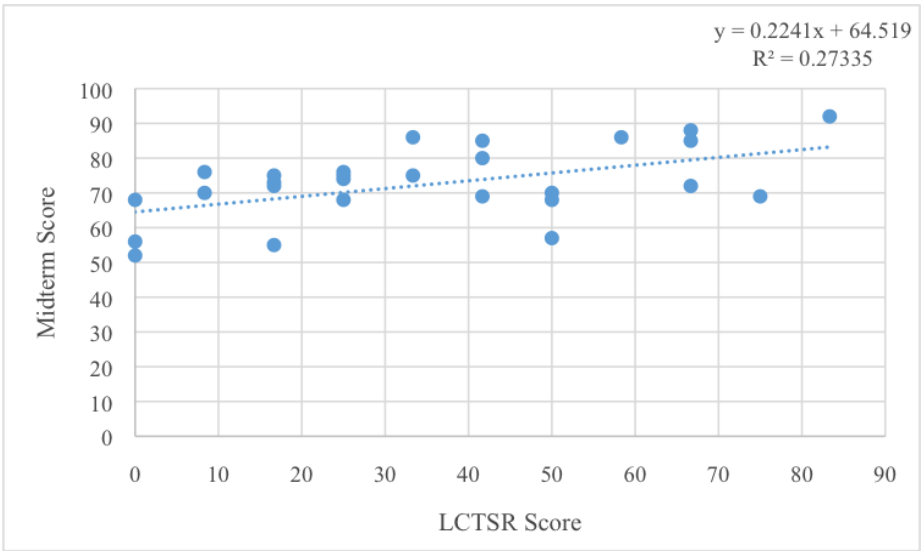


Figure 5. Correlation between the LCTSR posttest score and the midterm score, (*N*=31).

I plotted data (see Figure 5) to determine the relationship between a student's posttest score on the LCTSR and their midterm grade. The data displayed in Figure 5 show a modest positive association between the LCTSR posttest score and the midterm

score. According to the R^2 value the LCTSR explains about 27% of the variation in the midterm scores. This is not a large amount but does seem important. With data concerning human behavior such a correlation is at least strong enough to warrant further investigation. The rest of the variation of the midterm scores is due to factors other than scientific reasoning. These include, but are not limited to, extent of student preparation, support of family, peer group, and the student's cumulative educational experience. Exploration of the relative influence of these or other factors is beyond the scope of the present classroom research project.

Inquiry Lab Scoring

I had initially intended my classroom research project to be concerned entirely with changes in students' reasoning skills as a result of the use of the POGIL method. POGIL demands a certain baseline level of scientific reasoning ability and if students have not yet developed that ability then they pose a more serious challenge. I believe, as does Lawson, that students need to be challenged appropriately using a learning cycle in order to help them to learn scientific reasoning. As he said, "it would appear that, although some students do not need our help, and some may be beyond our help, the majority of students can and should be assisted in their acquisition of formal reasoning patterns" (1985, p. 607). With this idea in mind I thought that POGIL would be an appropriate intervention. In practice I found that my students required a large amount of support to get through the work. I also found that unless I reinforced the themes of the work in a POGIL activity by the use of direct instruction and focused practice they

neither recalled the underlying concepts nor could they demonstrate even a rote level of skill.

After observing how students struggled with these activities I realized that they alone were unlikely to assist students very much in developing scientific reasoning skills. As a result I developed the "Doing Science" inquiry lab activity, which I intended as a direct attempt to engage students in a learning cycle of exploration, concept introduction, and concept application. As mentioned previously, a copy of this activity is included as Appendix C. This has been shown to be an effective way of helping concrete students develop formal reasoning skills. Research has shown that a concrete method of teaching in which students follow this learning cycle is more effective with concrete thinkers than more formal methods of teaching (such as lecture and paper-and-pencil practice). (Lawson, 1985) This had to do both with content comprehension and with bringing about an improvement in students' ability to reason formally.

I was able to fit in two of these activities, and the qualitative data I gathered through classroom observations and by scoring students' papers is useful in addressing my second and third classroom research sub-questions. That is, my questions about how reasoning ability affects science content comprehension and about how work in the classroom affects students' own evaluation of their understanding of the content.

The first activity I did with students regarded a flask which, when covered with a thin piece of plastic, would not allow water to fall out even when the flask was overturned. I asked students to perform this demonstration and then to devise and carry out experiments that would allow them to write an explanation of how it was possible. I

have identified a few themes from their written responses to the activity. First, many students could not cite evidence for the explanations they wrote. All except for one of the late transitional students (according to the LCTSR) failed to connect their experiments and observations to the explanations they gave. At least one student classified as concrete was able to cite evidence for both parts of the correct explanation: 'molecular stickiness' and the difference in pressure. This is one indication that the LCTSR may not be a complete inventory of students' formal reasoning capacity.

Second, many students described their experiments (as they were asked to do) but most did not give any indication that their resulting observations were in any way relevant to building or supporting an explanation. This was true for the majority of students regardless of their score on the LCTSR. A third theme is that students did one of two related things: either they cited naïve explanations such as 'suction' without understanding or supporting them or they used abstractions which they had heard about (such as hydrogen bonding) but without experimental support. To me this means that students know they are supposed to be using abstract ideas in their explanations. The problem is that at least some of them don't really understand these ideas. This can lead to the classic problem of persistent incorrect preconceptions which is a central challenge of science teaching.

Another important observation that I can make about student writing in this activity concerns the effect of direct intervention on my part in the students' experiments. As time ran out I demonstrated the crucial experiments and drew their attention to the important observations about those experiments. Even after seeing this, most students did

not remember both parts of the explanation and could not cite evidence for whatever part of the explanation they could articulate.

Students had a tendency to use ‘scientific’ language, rather than describe their own experience, even when making statements that were simply wrong. Concept invention, or term introduction, is the second step in the learning cycle. Since students come to a class with pre-existing ideas, concepts, and terms (including terms which they do not fully understand) this step in the learning cycle is particularly challenging.

The words students already know effectively form a barrier to synthesis of new understanding because the words, as meaningless as they may be to the student, are difficult to dislodge. For example, one student wrote,

> If the flask and material were wet with water then they would stick because of hydrogen bonding. I know this is true because when I tested to see if they would stick when they were both dry they didn't stick. With this evidence you can conclude that the plastic and screen were able to stick due to hydrogen bonding.

Hydrogen bonding is an abstract concept best used to explain the anomalously high melting and boiling points of water, though it is the most important intermolecular force of attraction in water. In this context, however, there is no direct evidence for it and instead a generalized ‘molecular stickiness’ is a more appropriate term to use because it is more concrete and because it is almost directly observable. And though I used this more concrete term exclusively during this activity this student, responding presumably to an internal sense that science requires the use of obscure terminology, persisted in the use of the abstract term.

The second Doing Science activity had to do with the buoyancy of objects suspended in water by a string. Here a significant barrier to being able to build up evidence from which to draw conclusions was the difficulty of setting up and taking measurements. If students could get the measurement set up they often did not carry it out with enough care for the data to be useful in building a quantitative understanding of what they were investigating. Controlling variables is a central scientific reasoning skill and my students needed a significant amount of support in order to generate appropriate data. Some students were quite competent and quickly devised and carried out convincing experiments. For the others, with a lot of coaching and an additional hour of class time, most students were able to collect data indicating that it was the volume of the object that was important. In their writing, however, it was clear that most students could not turn this correct explanation into a quantitative statement about how the apparent weight depended on the weight of the water displaced by the object. As with the other activity, prior experiences led students to think that using the word ‘displacement’ would be sufficient to explain their observations. When asked, however, most could not articulate what displacement means.

Though some of the deficits in student reasoning were the same, there was some improvement in the writing of students for this second activity. Generally, more students were able to connect some experimental evidence to their explanation. For example, one student wrote, “We hypothesized that it wasn't the weight of the object, it was the size. To test this, we took a smaller object and measured the volume. The volume of the object was 10.6 mL. We then suspended the object in the water and the weight went up 10.6

grams. This proved our hypothesis." This is a good sign and shows that practice with setting up, carrying out, and interpreting experiments can bring about improvements in reasoning. As a result I have some evidence to support continuing to do work of this kind as it may ultimately help more students to improve their reasoning skills.

The final theme that I wish to discuss concerns the fact that I asked students to extend their understanding to similar circumstances not explored directly in the lab. The ideas were concrete (suspending objects in denser salt water, for example) but the connection between their work in the lab and the other situation was one based on abstract reasoning. In order to predict the apparent weight of an object in salt water the student would need to reason with the abstract property of density. More than two-thirds of students could not correctly predict the effects of suspending a mass in salt water as compared with plain water. This group included all of the students in the concrete group and most of the students in the early or late transitional groups.

This result concerns a different reasoning pattern from the primary pattern of hypothesis generation and testing and the control of variables. Namely, the reasoning pattern concerned with the drawing of conclusions using abstract concepts. The discouraging result shows that most students could not demonstrate this reasoning pattern, at least in this context. It indicates that future activities should include prompts to reason in this way and should be followed up by in-class discussion to model it.

Interviews

I asked students a few questions (see Appendix G) about our work together this year in a small-group setting. This was a whole-class discussion in which I asked the

questions, we discussed them as a class, and students wrote down their own responses. I did it this way so that I could collect as many student perspectives as possible.

Some themes emerged in student responses. Generally, students gave good descriptions both of traditional teaching methods and the POGIL approach. There were mixed responses about whether POGIL led to more learning on their part. Students reported that they liked being given responsibility for figuring out the material on their own. They appreciated the idea that in order to learn they would have to make an effort and that they could not depend on the teacher to do all the work. For example, one students commented, “Not all classes but I’ve noticed in some classes, you don’t really have to apply yourself and can still get a decent grade but in this class, you have to completely apply yourself and commit if you want to succeed.” I attribute this at least in part to the use of small-group activities in which students make progress commensurate with their efforts.

Some particularly reflective students were able to articulate clearly what they appreciated about the POGIL work in small groups. One student said, “With lecture and notes you get less out of it because it’s not interactive.” Another said, “Without the group you have less help understanding.” This perspective was made more nuanced by students who felt challenged by the group-work approach. One student tellingly said, “If I get it right then I learn more from POGIL but it makes me feel very uncertain.” The student who made the comment is a very capable student who has done very well in my class this year. I don’t think she was just trying to say something positive: she expressed her

sincere belief that she learned more with the POGIL method but also that the independence was intimidating.

In that same vein, several students commented that they had trouble with the approach. A student told me that he didn't like the process very much and that he would rather have notes and practice. This was in part because he felt that he learned more from direct instruction (though he didn't use that phrase). He felt that he was not able to learn very well from reading as compared with having me explain things. For example, he said, "Trying to figure it out on my own from reading is harder. I like doing notes." Doing something new, especially when it is demanding, can be a negative experience for some students. As a result of comments like these, I have incorporated more whole-class discussion or lectures prior to, during, and after the activity is complete.

As to the impact of this type of work on students' own evaluation of their competence in the subject of chemistry the interviews left little doubt that students appreciated how being challenged helps them to understand the subject and to be better students generally. One student commented, "This class has challenged me to make me more observant and driven. With everything not always explained it forces me to apply myself to solve problems." This is a typical response and shows that there are positive impacts of using POGIL and other learning-cycle approaches beyond measurable changes in scores on a test of reasoning like the LCTSR. If students carry this attitude forward into other classes and their future academic work, then it can perhaps serve as a starting point for further development of formal scientific reasoning.

In addition to helping students to see how the challenge of working through material in small groups with minimal instruction is good for them, I have also noted that students appreciate the content more for its own sake. For example, one student said, "This class has helped me as a student by wanting to know how things work and to become more curious and think deeper about things that look like they have an easy solution." This comment demonstrates the acquisition of an abiding curiosity about the natural world which I certainly hope will lead to deeper thought and eventually to the development of formal reasoning as a necessity for that pursuit.

INTERPRETATION AND CONCLUSION

My first research sub-question concerned how POGIL and inquiry-based lab activities affected students' development of reasoning skills. The first major finding after carrying out this classroom research is that the techniques I attempted did not have a large measurable and positive effect on students' scores on the LCTSR. In other words, POGIL and Doing Science activities were not enough on their own to aid students in their development of formal reasoning skills. It is possible that development of these skills is a slow process and that significant improvement will require many repetitions. Additional teaching strategies may also be required, such as guiding students through practice in recognizing and evaluating their own reasoning process.

Students did improve in their response on the LCTSR to the questions about the identification and control of variables. Also, their work on the second Doing Science activity already showed evidence of improvements in students' ability to perform and interpret experiments relevant to solving a problem. It is possible that further work in this

area will help students to become more aware of their own reasoning process and to otherwise improve their formal reasoning skills.

The implications for my teaching practice are clear if my goal is to improve students' reasoning abilities. I will need to incorporate more explicit instruction in formal reasoning skills. Moore (2012) was able to significantly increase student scores on the LCTSR through the explicit instruction in formal reasoning patterns. As he says, "Through the incorporation of context-rich activities, authentic research experiences, and explicit interventions on reasoning patterns, we have been able to increase gains in student scientific reasoning abilities as well as transition students from transitional reasoners to more formal operational reasoners" (p. 10).

Arons (1976) gives a variety of approaches which can be used to specifically cultivate formal reasoning. He advocates the use of a learning cycle in which students explore and ask questions before being introduced to concepts and names. This is further developed by the notion that students can be brought to an idea first, which then necessitates a name. In the buoyancy activity I did with students, I endeavored for them to discover that it was the volume of the suspended object that mattered and that the volume could be used to predict the mass measurement they would make. Only after all of this did I use the term 'displacement'. This is exactly the sort of thing I will need to find ways to do more often.

Another valuable suggestion is to avoid teaching science 'backwards'. Rather than giving an explanation for a phenomenon prior to observing it, give a student the facts of the case (or better yet, let him or her find out the facts themselves). First, a

student must know there is something worth explaining. If the explanation is provided before the phenomenon then science will appear to be nothing more than a body of facts that someone else has already found out. In that case, there is no reason to engage in formal thought in order to find things out for oneself (Arons, 1976).

Clearly, if I wish to improve students' formal reasoning skills then I, too, will need to provide activities rich in context and authentic experience with the use of experiments to perform an investigation. Most importantly, I need to provide direct instruction in formal reasoning patterns. In Moore's paper (2012) this is done through instruction in the syntax of a good hypothesis followed by scaffolded activities beginning with guided and ending with independent activities. I believe I can incorporate this into my Doing Science activity. I can start with simple activities in which students can learn good syntax for hypotheses in which they can design an experiment which tests the hypothesis without an appeal to authority or the use of previously learned jargon.

Another major finding concerns the predictive power that a student's reasoning skills had for performance in understanding and mastering science content. This addresses my second classroom research sub-question about how students' reasoning ability affects their comprehension of academic content. It was clear from the results of pretests and posttests that a student's score on the LCTSR was connected with their performance on those tests. Students with a higher LCTSR score also had higher scores on both the pretest and the posttest. If I wish to give students the best possible preparation for college then helping them to learn formal reasoning skills must be an important part of my work with my students.

There is much discussion of methods for teaching science which are better than the traditional lecture and demonstration approach (Chase, Pakhira, & Stains, 2013; Chatterjee, Williamson, McCann, & Peck, 2009; Cooper, 1995; Farrell, Moog, & Spencer, 1999; Gosser & Roth, 1998; Hanson & Wolfskill, 2000; Hinde and Kovac, 2001; Lewis & Lewis, 2005; Linn & Their, 1975; McDonnell, 2013; Spencer, 1999; & Warfa, 2016). My perspective on this work is that the reason these methods (POGIL, inquiry, five Es, the learning cycle, etc.) are helpful in teaching science is that so many of the students taking science courses are in fact concrete thinkers. What all of these methods have in common is that they use an approach which starts in the concrete and moves toward the abstract. My belief is that by consciously focusing on helping students to develop a greater proficiency with formal reasoning, I will best be able to help them learn science.

My third research sub-question concerned students' own evaluation of their learning. I evaluated this through interviews with students and I found that although the testing was not showing a marked improvement in students' reasoning ability, they were conscious of the fact that the course was structured in such a way as to help them to learn to think for themselves. They connected up the extent to which they were able to work things out for themselves with their success in learning new material. Ultimately, I would like to turn this consciousness into a bigger asset by more deliberate attention to the instruction of reasoning skills.

VALUE

Results measured by classroom assessments and student writing indicate that students are improving little if at all in their formal reasoning ability. However, interviews with students tell a different story. The range of student responses from all ability levels show that there are other benefits to making the effort to improve their reasoning skills. For one, they appreciate how reasoning things through on their own is more effective than simply trying to remember how the teacher explained things. Instead of simply learning by rote students are aware that they can and should make the effort to reason things through themselves. This is a strong step forward on the road to developing formal reasoning skills.

Another benefit is that students are reflecting on the kind of learning they are doing in the classroom. They compared their work in my room with work they have done in other classes and came to their own conclusions about what approaches worked well for them. And these thoughts were more insightful than discussions of 'learning styles'. Students did not simply say that they learn best 'hands-on' but recognized that sometimes they need things explained to them and that sometimes they can work things out on their own. It is a sign of growth that they consciously recognize the value of working things out on their own.

Finally, students are seeing the benefit of being curious. By wanting to know about the content students are engaged and can therefore be led into new reasoning patterns. By giving students work that requires formal reasoning, they see that they will have to go beyond their existing patterns of thought. One student said that, "A way this

class has helped me because it is challenging is because it makes me problem solve to find the best answer." And when a student sees the applicability of this way of learning to their other academic work, then it is a positive step toward improving their reasoning skills, even if that is not accomplished in a single course over a span of a few months.

My final research sub-question addressed how this work has affected my thinking and my teaching practice. Using the whole of my experience doing this research I have concluded that the value of this work lies in the fact that I have learned a lot about concrete thinking and formal reasoning skills and that it has changed my thought process when it comes to the goals of my teaching. In the past I looked at 'new' teaching techniques such as Engage, Explore, Extend, Explain, and Evaluate (the five Es) as the means by which I would help students to learn science content. Now I view them differently. If I have students explore a topic before introducing the abstract concepts and then follow up by having them apply the new concept, then it will no longer be simply because I have been told that this is an effective way of helping students to learn new content. Now I will be using this approach with the deliberate goal of helping students to develop their formal reasoning skills. In the past I have used these approaches on faith that they will be more effective than other methods of instruction. Knowing why they may be more effective will provide me with an important lens to use when I plan instruction and design curriculum.

For example, rather than simply using POGIL and the learning cycle I will be looking for ways to include instruction in reasoning skills as part of the lesson. In the classification of matter lesson I will engage students in the process of categorizing matter

using formal definitions but I will do so using a lab activity in which students can concretely interact with the materials they are categorizing. This will be followed by activities and questions. One example question could be, “In a chemical change, how do you know when a compound has formed from two elements?” In this question the formal categories are applied to a situation students experienced in the lab.

This research raises interesting questions that deserve further investigation. How can I use this information to help me to improve my work with concrete learners? Also, what effective approaches have researchers developed which have a demonstrable effect on students’ reasoning abilities? And how can I work with colleagues to make our school’s curriculum one in which teaching to improve reasoning ability plays a larger role?

To answer these questions I intend to take some specific actions. I plan to further develop my Doing Science activity using the ideas I have learned through the reading I have done. I will examine my curriculum and look for ways I can incorporate explicit instruction in formal reasoning skills such as proportional thinking, identification and control of variables, correlational thinking, probabilistic thinking, and hypothetico-deductive reasoning. I will also engage in the work outlined in the interpretation section above. Specifically, I would like to follow the model provided by Moore (2012) in which he used simple demonstrations and questions to model scientific reasoning and then to examine that reasoning. Ultimately, my more deliberate focus on these aspects of my students’ growth will, I hope, have far-reaching effects on their success in science and in their academic work generally.

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APPENDICES

APPENDIX A

IRB EXEMPTION

MONTANA
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For the Protection of Human Subjects
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MEMORANDUM

TO: Aaron Keller and Walt Woolbaugh

FROM: Mark Quinn Mark Quinn

DATE: October 26, 2016

SUBJECT: "*Impact of Process-oriented Guided Inquiry Learning on Chemistry Students*" [AK102616-EX]

The above research, described in your submission of October 26, 2016, is exempt from the requirement of review by the Institutional Review Board in accordance with the Code of Federal regulations, Part 46, section 101. The specific paragraph which applies to your research is:

__X__ (b) (1) Research conducted in established or commonly accepted educational settings, involving normal educational practices such as (i) research on regular and special education instructional strategies, or (ii) research on the effectiveness of or the comparison among instructional techniques, curricula, or classroom management methods.

__X__ (b) (2) Research involving the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures or observation of public behavior, unless: (i) information obtained is recorded in such a manner that human subjects can be identified, directly or through identifiers linked to the subjects; and (ii) any disclosure of the human subjects' responses outside the research could reasonably place the subjects at risk of criminal or civil liability, or be damaging to the subjects' financial standing, employability, or reputation.

____ (b) (3) Research involving the use of educational tests (cognitive, diagnostic, aptitude, achievement}, survey procedures, interview procedures, or observation of public behavior that is not exempt under paragraph (b)(2) of this section, if: (i) the human subjects are elected or appointed public officials or candidates for public office; or (ii) federal statute(s) without exception that the confidentiality of the personally identifiable information will be maintained throughout the research and thereafter.

____ (b) (4) Research involving the collection or study of existing data, documents, records, pathological specimens, or diagnostic specimens, if these sources are publicly available, or if the information is recorded by the investigator in such a manner that the subjects cannot be identified, directly or through identifiers linked to the subjects.

____ (b) (5) Research and demonstration projects, which are conducted by or subject to the approval of department or agency heads, and which are designed to study, evaluate, or otherwise examine: (i) public benefit or service programs; (ii) procedures for obtaining benefits or services under those programs; (iii) possible changes in or alternatives to those programs or procedures; or (iv) possible changes in methods or levels of payment for benefits or services under those programs.

____ (b) (6) Taste and food quality evaluation and consumer acceptance studies, (i) if wholesome foods without additives are consumed, or (ii) if a food is consumed that contains a food ingredient at or below the level and for a use found to be safe, or agricultural chemical or environmental contaminant at or below the level found to be safe, by the FDA, or approved by the EPA, or the Food Safety and Inspection Service of the USDA.

Although review by the Institutional Review Board is not required for the above research, the Committee will be glad to review it. If you wish a review and committee approval, please submit 3 copies of the usual application form and it will be processed by expedited review.

APPENDIX B

POGIL: CLASSIFICATION OF MATTER

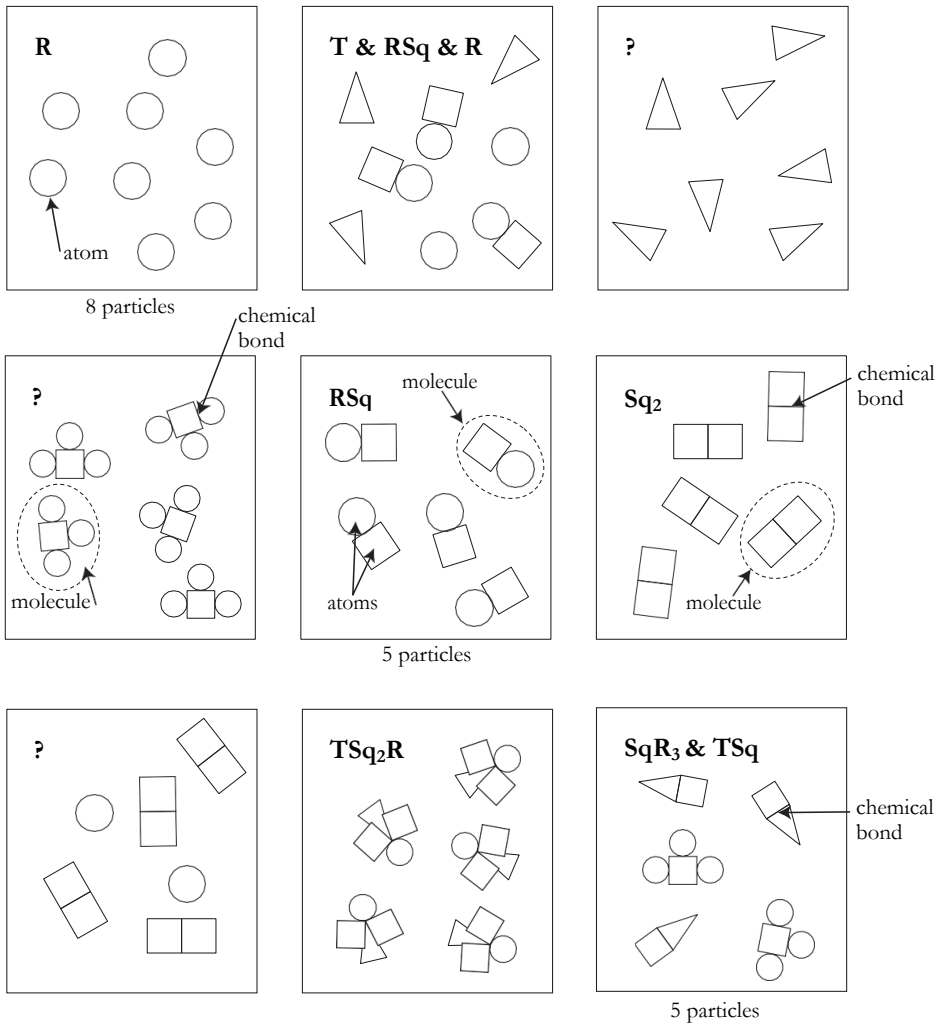
Classification of Matter

How do atoms combine to make different types of matter?

Why?

Look at the things in this room. They are all matter. That matter may be pure or it may be a mixture. Can you tell by looking at it? What if you looked at it under a microscope? Then could you tell? Something that looks pure may not really be pure. It depends on what type of particles an object or substance is made of. In this activity we will explore how the smallest chemical units of matter determine whether something is classified as an element, a compound, or a mixture.

Model 1 — Atoms, Particles, and Molecules



1. Locate the circled molecule of **RSq** in Model 1.
   a. Find a second **RSq** molecule and circle it.
   b. How many atoms are in a molecule of **RSq**?

2. Find and circle a molecule of $\mathbf{TSq_2R}$ in Model 1.
   a. How many different types of atoms are found in a molecule of $\mathbf{TSq_2R}$?

   b. How many Sq atoms are in a molecule of $\mathbf{TSq_2R}$?

3. Locate the drawing labeled $\mathbf{SqR_3}$ **&** **TSq** in Model 1.
   a. How many different types of atoms are found in the sample of $\mathbf{SqR_3}$ **&** **TSq**?

   b. How many different types of molecules are found in the sample of $\mathbf{SqR_3}$ **&** **TSq**?

4. When two atoms are touching in the drawings of Model 1, what is holding the atoms together?

5. As a group, discuss the following questions and record your answers:
   a. Can a *particle* be a single atom?

   b. Can a *particle* be a molecule?

   c. How many particles are in the drawing representing **T & RSq & R** in Model 1?

   d. What is your group's definition of the word "particle" as it is used in chemistry?



6. Compare the codes listed at the top of each drawing in Model 1 with the shapes in that box.
   a. What do the letters **R**, **Sq,** and **T** in the codes represent?

   b. What do the small numbers (subscripts) in the codes represent?

   c. When atoms are touching, how is that communicated in the code?

   d. What is the common characteristic of the samples in which an ampersand (&) is used?

e. In Model 1 there are three drawings that are labeled with a question mark. Write codes to properly label these drawings. 7. Appoint one group member to cut apart Model 1 to separate the nine drawings. As a team, sort the drawings into two groups—one group where all the particles in the drawing are identical, and a second group in which the drawings contain more than one type of particle.

READ THIS!

Matter is classified as a **pure substance** when all of the particles are identical. Matter is classified as a **mixture** if there are different types of particles present.



8. Identify which drawings from Question 7 are pure substances and which are mixtures. List the codes for the drawings in the appropriate places below.

Pure Substances		Mixtures
_____	_____	_____
_____	_____	_____
_____	_____	_____

9. How are the codes (chemical formulas) for pure substances different from those for mixtures?

10. As a team, take the set of pure substances drawings from Question 8 and sort them into two new groups, those containing only one type of atom and those with two or more types of atoms.

READ THIS!

Elements are defined as pure substances made from only one type of atom. **Compounds** are defined as pure substances made from two or more types of atoms.



11. Identify which drawings from Question 10 are elements and which are compounds. List the codes for the drawings in the appropriate places below.

Elements	Compounds
_____	_____
_____	_____
_____	_____

12. How are the codes (chemical formulas) for elements different from those for compounds?

13. Use what you have just learned about chemical formulas to identify each of the following as an element, a compound or a mixture.

a. Br_2 *b.* $NaHCO_3$ *c.* $C_6H_{12}O_6$ & H_2O

d. Cu & Zn *e.* CO_2 *f.* AlExplain the difference between:

b. An atom and an element.

c. A molecule and a compound.



EXTENSION QUESTIONS

14. It is often useful to separate matter. Physical methods of separation (filtering, distillation) do not require a chemical change. In other words, no chemical bonds are broken or formed during the separation. Chemical methods of separation (decomposition, electrolysis) require a chemical change. In other words, chemical bonds are broken and/or formed during the separation.

a. Is straining cooked pasta from water a physical or chemical separation?

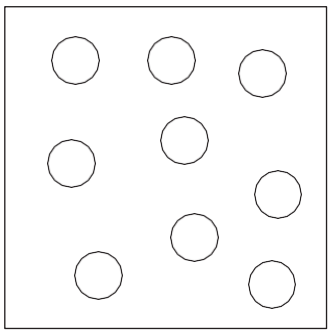
b. Is using a fuel cell to separate water into hydrogen and oxygen a physical or chemical separation?

c. Which type(s) of matter (mixtures/compounds/elements) could be separated by physical methods?

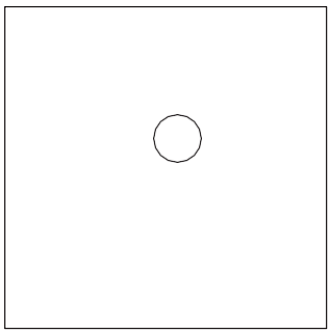
d. Which type(s) of matter (mixtures/compounds/elements) would need to be separated by chemical methods?

15. Students in a chemistry course were asked the following question on a unit exam: "Draw a dia- gram representing an element using circles as atoms."

a. The following diagrams represent two typical answers given by students. Which drawing is the best representation of an element? Explain.



Drawing A



Drawing B

b. Imagine that the atom in Drawing B had been removed by physical separation from one of the substances in Model 1. What substances could have been the source of the atom in Drawing B?

APPENDIX C

DOING SCIENCE INQUIRY LAB

DOING SCIENCE

Learning science is more than just learning the facts of science and learning the skills and concepts necessary to understand those facts. Science is also about investigating nature to find out how things work. The nature of science is that no conclusion that we draw can be trusted unless it can be verified by experiment. But coming up with just the right experiment to perform, and having the skills necessary to perform it, can be a challenge. This is science at its most creative: how do we write a testable, possible explanation (a hypothesis) and then test it conclusively? In this activity you will practice and extend your skills as a scientist.

Your teacher will demonstrate an experiment in which something interesting and/or unexpected happens. You will discuss the experiment as a class and perhaps witness it again with additional instructions. Then you will attempt to re-create the demonstration. After you do this you will work with a partner to come up with possible explanations. First, anything will do but you will ultimately need to narrow down your choices to just those you can test and rule out by observation and experimentation. Follow the procedure below and keep careful notes in your lab notebook of your procedures, hypotheses, and conclusions. Check in frequently with your teacher to be sure you're on track.

Procedure

1. Watch the demonstration. Carefully note details of the procedure. Carefully observe what happens. Discuss with the whole class and share your observations. Write down others' observations when they add to what you know. Ask questions of your teacher. You are no longer a student but a scientist about to commence an investigation. Try to think like one.
2. Work with a partner to write (each in your own lab notebook) what is happening in the demonstration and identify the variables that affect the outcome.
3. Perform the demonstration yourself. Have your partner do it, too. Try some variations and in general play with the materials to see what you can find out. Your teacher may provide you with an extension activity which expands upon the basic demonstration. Investigate this along with the original demonstration. Write down additional observations and ideas that you have about what's going on.
4. Discuss what you've seen so far with your teacher and your partner. Brainstorm and be creative. Identify the variables that matter. Write them down. Design experiments to determine what effect changing your variables will have.
5. After performing several experiments, propose an explanation. Write it out used well-formed, complete sentences. Include one or more if-then statements which would be true if the explanation is true, and false if your explanation is false. Share with your teacher to get feedback.
6. In order to support your explanation, and rule out other possible explanations, you need observations and measurements. What experimental results would provide strong support for your proposed explanation? Design and carry them out. Consult with your teacher to get feedback about your ideas.
7. In your lab notebook record your **actual procedure**: not what you planned to do but what you actually did. Also, record your results. What did you observe? Do your observations help to provide support for your proposed explanation? If so, how? If not, what new experiments could you do? Answer these questions in your lab notebook and then get feedback from your teacher before proceeding.
8. Based on teacher feedback decide whether you need to propose a new explanation. If so, write it down along with appropriate if-then statements that are testable using the materials you have. If not, then write a brief paragraph in your lab notebook which explains the demonstration, and its extension, using the physical evidence you have gathered by making observations.
9. Perform any necessary new experiments and check in again with your teacher. Repeat the steps above if your explanation and experiments are still inconclusive.

Report

Write a short informal report of your work. Include the following as separate paragraphs:

1. Describe the demonstration you investigated. Include the extension activity, if appropriate. Give enough detail that a reader could perform the demonstration given the right materials.
2. What experiments did you perform? Describe them in terms of the physical actions taken. Also, interpret your observations: what do they mean when it comes to writing an explanation of the demonstration?
3. Give your final hypothesis as an if-then statement. For each part of the hypothesis provide the observational evidence that it is true.
4. Include one or more *original* drawings or photographs which illustrate your work in the lab and/or how you came to your conclusions. Your written work should refer to your drawing/photo at least once.

APPENDIX D

THE LAWSON CLASSROOM TEST OF SCIENTIFIC REASONING

CLASSROOM TEST OF

SCIENTIFIC REASONING

Multiple Choice Version

Directions to Students:

This is a test of your ability to apply aspects of scientific and mathematical reasoning to analyze a situation to make a prediction or solve a problem. Make a dark mark on the answer sheet for the best answer for each item. If you do not fully understand what is being asked in an item, please ask the test administrator for clarification.

DO NOT OPEN THIS BOOKLET UNTIL YOU ARE TOLD TO DO SO

Revised Edition: August 2000 by Anton E. Lawson, Arizona State University. Based on: Lawson, A.E. 1978. Development and validation of the classroom test of formal reasoning. *Journal of Research in Science Teaching*, 15(1): 11-24.

1. Suppose you are given two clay balls of equal size and shape. The two clay balls also weigh the same. One ball is flattened into a pancake-shaped piece. *Which of these statements is correct?*

   a. The pancake-shaped piece weighs more than the ball
   b. The two pieces still weigh the same
   c. The ball weighs more than the pancake-shaped piece

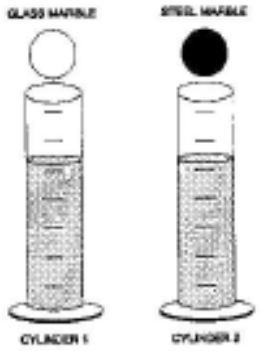
2. *because*

   a. the flattened piece covers a larger area.
   b. the ball pushes down more on one spot.
   c. when something is flattened it loses weight.
   d. clay has not been added or taken away.
   e. when something is flattened it gains weight.

3. To the right are drawings of two cylinders filled to the same level with water. The cylinders are identical in size and shape.

   Also shown at the right are two marbles, one glass and one steel. The marbles are the same size but the steel one is much heavier than the glass one.

   When the glass marble is put into Cylinder 1 it sinks to the bottom and the water level rises to the 6th mark. *If we put the steel marble into Cylinder 2, the water will rise*

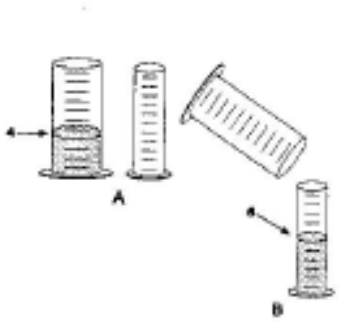


   a. to the same level as it did in Cylinder 1
   b. to a higher level than it did in Cylinder 1
   c. to a lower level than it did in Cylinder 1

4. *because*

   a. the steel marble will sink faster.
   b. the marbles are made of different materials.
   c. the steel marble is heavier than the glass marble.
   d. the glass marble creates less pressure.
   e. the marbles are the same size.

5. To the right are drawings of a wide and a narrow cylinder. The cylinders have equally spaced marks on them. Water is poured into the wide cylinder up to the 4th mark (see A). This water rises to the 6th mark when poured into the narrow cylinder (see B).



Both cylinders are emptied (not shown) and water is poured into the wide cylinder up to the 6th mark. *How high would this water rise if it were poured into the empty narrow cylinder?*

a. to about 8
b. to about 9
c. to about 10
d. to about 12
e. none of these answers is correct

6. *because*

a. the answer can not be determined with the information given.
b. it went up 2 more before, so it will go up 2 more again.
c. it goes up 3 in the narrow for every 2 in the wide.
d. the second cylinder is narrower.
e. one must actually pour the water and observe to find out.

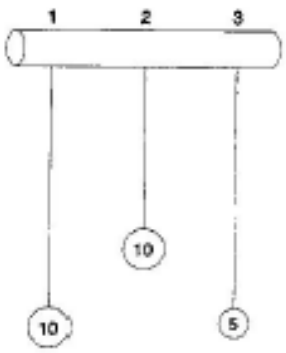
7. Water is now poured into the narrow cylinder (described in Item 5 above) up to the 11th mark. *How high would this water rise if it were poured into the empty wide cylinder?*

a. to about 7 1/2
b. to about 9
c. to about 8
d. to about 7 1/3
e. none of these answers is correct

8. *because*

a. the ratios must stay the same.
b. one must actually pour the water and observe to find out.
c. the answer can not be determined with the information given.
d. it was 2 less before so it will be 2 less again.
e. you subtract 2 from the wide for every 3 from the narrow.

9. At the right are drawings of three strings hanging from a bar. The three strings have metal weights attached to their ends. String 1 and String 3 are the same length. String 2 is shorter. A 10 unit weight is attached to the end of String 1. A 10 unit weight is also attached to the end of String 2. A 5 unit weight is attached to the end of String 3. The strings (and attached weights) can be swung back and forth and the time it takes to make a swing can be timed.



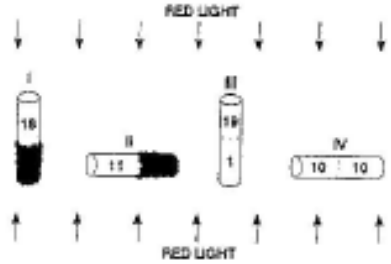
Suppose you want to find out whether the length of the string has an effect on the time it takes to swing back and forth. *Which strings would you use to find out?*

a. only one string
b. all three strings
c. 2 and 3
d. 1 and 3
e. 1 and 2

10. *because*

a. you must use the longest strings.
b. you must compare strings with both light and heavy weights.
c. only the lengths differ.
d. to make all possible comparisons.
e. the weights differ.

11. Twenty fruit flies are placed in each of four glass tubes. The tubes are sealed. Tubes I and II are partially covered with black paper; Tubes III and IV are not covered. The tubes are placed as shown. Then they are exposed to red light for five minutes. The number of flies in the uncovered part of each tube is shown in the drawing.



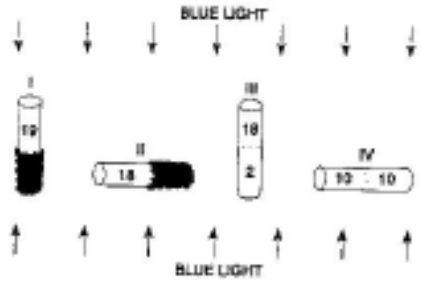
This experiment shows that flies respond to (respond means move to or away from):

a. red light but not gravity
b. gravity but not red light
c. both red light and gravity
d. neither red light nor gravity

12. *because*

a. most flies are in the upper end of Tube III but spread about evenly in Tube II.
b. most flies did not go to the bottom of Tubes I and III.
c. the flies need light to see and must fly against gravity.
d. the majority of flies are in the upper ends and in the lighted ends of the tubes.
e. some flies are in both ends of each tube.

13. In a second experiment, a different kind of fly and blue light was used. The results are shown in the drawing.



These data show that these flies respond to (respond means move to or away from):

a. blue light but not gravity
b. gravity but not blue light
c. both blue light and gravity
d. neither blue light nor gravity

14. *because*

a. some flies are in both ends of each tube.
b. the flies need light to see and must fly against gravity.
c. the flies are spread about evenly in Tube IV and in the upper end of Tube III.
d. most flies are in the lighted end of Tube II but do not go down in Tubes I and III.
e. most flies are in the upper end of Tube I and the lighted end of Tube II.

15. Six square pieces of wood are put into a cloth bag and mixed about. The six pieces are identical in size and shape, however, three pieces are red and three are yellow. Suppose someone reaches into the bag (without looking) and pulls out one piece. *What are the chances that the piece is red?*

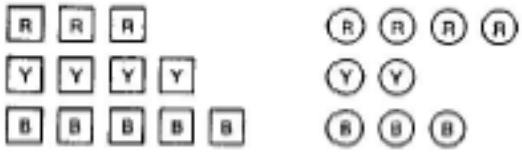


a. 1 chance out of 6
b. 1 chance out of 3
c. 1 chance out of 2
d. 1 chance out of 1
e. cannot be determined

16. *because*

    a. 3 out of 6 pieces are red.
    b. there is no way to tell which piece will be picked.
    c. only 1 piece of the 6 in the bag is picked.
    d. all 6 pieces are identical in size and shape.
    e. only 1 red piece can be picked out of the 3 red pieces.

17. Three red square pieces of wood, four yellow square pieces, and five blue square pieces are put into a cloth bag. Four red round pieces, two yellow round pieces, and three blue round pieces are also put into the bag. All the pieces are then mixed about. Suppose someone reaches into the bag (without looking and without feeling for a particular shape piece) and pulls out one piece.



What are the chances that the piece is a red round or blue round piece?

    a. cannot be determined
    b. 1 chance out of 3
    c. 1 chance out of 21
    d. 15 chances out of 21
    e. 1 chance out of 2

18. *because*

    a. 1 of the 2 shapes is round.
    b. 15 of the 21 pieces are red or blue.
    c. there is no way to tell which piece will be picked.
    d. only 1 of the 21 pieces is picked out of the bag.
    e. 1 of every 3 pieces is a red or blue round piece.

19. Farmer Brown was observing the mice that live in his field. He discovered that all of them were either fat or thin. Also, all of them had either black tails or white tails. This made him wonder if there might be a link between the size of the mice and the color of their tails. So he captured all of the mice in one part of his field and observed them. Below are the mice that he captured.



Do you think there is a link between the size of the mice and the color of their tails?

a. appears to be a link
b. appears not to be a link
c. cannot make a reasonable guess

20. *because*

a. there are some of each kind of mouse.
b. there may be a genetic link between mouse size and tail color.
c. there were not enough mice captured.
d. most of the fat mice have black tails while most of the thin mice have white tails.
e. as the mice grew fatter, their tails became darker.

21. The figure below at the left shows a drinking glass and a burning birthday candle stuck in a small piece of clay standing in a pan of water. When the glass is turned upside down, put over the candle, and placed in the water, the candle quickly goes out and water rushes up into the glass (as shown at the right).



This observation raises an interesting question: Why does the water rush up into the glass?

Here is a possible explanation. The flame converts oxygen into carbon dioxide. Because oxygen does not dissolve rapidly into water but carbon dioxide does, the newly formed carbon dioxide dissolves rapidly into the water, lowering the air pressure inside the glass.

Suppose you have the materials mentioned above plus some matches and some dry ice (dry ice is frozen carbon dioxide). *Using some or all of the materials, how could you test this possible explanation?*

a. Saturate the water with carbon dioxide and redo the experiment noting the amount of water rise.
b. The water rises because oxygen is consumed, so redo the experiment in exactly the same way to show water rise due to oxygen loss.
c. Conduct a controlled experiment varying only the number of candles to see if that makes a difference.
d. Suction is responsible for the water rise, so put a balloon over the top of an open-ended cylinder and place the cylinder over the burning candle.
e. Redo the experiment, but make sure it is controlled by holding all independent variables constant; then measure the amount of water rise.

22. What result of your test (mentioned in #21 above) would show that your explanation is probably wrong?

a. The water rises the same as it did before.
b. The water rises less than it did before.
c. The balloon expands out.
d. The balloon is sucked in.

23. A student put a drop of blood on a microscope slide and then looked at the blood under a microscope. As you can see in the diagram below, the magnified red blood cells look like little round balls. After adding a few drops of salt water to the drop of blood, the student noticed that the cells appeared to become smaller.



Magnified Red Blood Cells After Adding Salt Water

This observation raises an interesting question: Why do the red blood cells appear smaller?

Here are two possible explanations: I. Salt ions (Na+ and Cl-) push on the cell membranes and make the cells appear smaller. II. Water molecules are attracted to the salt ions so the water molecules move out of the cells and leave the cells smaller.

To test these explanations, the student used some salt water, a very accurate weighing device, and some water-filled plastic bags, and assumed the plastic behaves just like red-blood-cell membranes. The experiment involved carefully weighing a water-filled bag, placing it in a salt solution for ten minutes and then reweighing the bag.

What result of the experiment would best show that explanation I is probably wrong?

a. the bag loses weight
b. the bag weighs the same
c. the bag appears smaller

24. *What result of the experiment would best show that explanation II is probably wrong?*

a. the bag loses weight
b. the bag weighs the same
c. the bag appears smaller

APPENDIX E

SAMPLE PRETEST/POSTTEST FOR ATOMIC STRUCTURE

Atomic Structure

How well do you understand atomic structure, isotopes and ions? A self-assessment.

You may only answer the questions once and you may not change your answers once you submit them. You may NOT work together with a partner to answer the questions.

When you complete the self-assessment be sure to choose to have your responses sent to you. You will receive them in your school email account.

When you finish this assessment click the "DONE" button on the Google classroom page.

This assessment will not be given a grade and nothing will be entered into the gradebook. It is for informational purposes only.

Your email address (**example@scarboroughschools.org**) will be recorded when you submit this form. Not you? Sign out

* Required

What is your last name? *

What is your first name? *

What is your class period? *

1. Atoms are made of smaller particles known as... *
    a. Protons, Isotopes, and Ions
    b. Protons, Neutrons and Electrons
    c. Neutrons, Electrons, and Positrons
    d. Nucleus, Protons, and Electrons

2. The nucleus of an atom contains... *
    a. electrons and protons.
    b. electrons and neutrons.
    c. neutrons and protons.
    d. neutrons and electrons.

3. The atomic number of an atom tells you... *
    a. the number of electrons in an atom.
    b. the number of protons in the nucleus of an atom.
    c. the number of neutrons in the nucleus of an atom.
    d. the number of electrons in the nucleus of an atom.

4. Atoms of different elements are distinguished based on...
    a. the number of electrons they have.
    b. the number of protons they have.
    c. the number of neutrons they have.
    d. their ionic charge.

5. The atomic mass number tells you... *
    a. the number of neutrons in an atom.
    b. the value of the mass given on the periodic table.

c. the average mass of an element.
d. the total number of protons and neutrons in an atom.

6. Isotopes of an element have... *
   a. the same number of neutrons but different numbers of protons.
   b. the same mass number but different atomic numbers.
   c. the same number of protons but different numbers of neutrons.
   d. the same atomic number but different numbers of electrons.

7. An atom has 6 protons and 7 neutrons. What element is this? What is its atomic number? What is its atomic mass number? *
   a. Carbon. Atomic number is 6. Atomic mass number is 7.
   b. Carbon. Atomic number is 6. Atomic mass number is 13.
   c. Nitrogen. Atomic number is 7. Atomic mass number is 13.
   d. Nitrogen. Atomic number is 7. Atomic mass number is 6.

8. Ions of elements have...
   a. the same number of protons but different numbers of neutrons.
   b. the same atomic number but different mass numbers.
   c. the same number of protons but different numbers of electrons.
   d. the same number of neutrons but different numbers of electrons.

9. An atom has 26 protons and 23 electrons. What element is this? What is its atomic number? What is the ionic charge?
   a. Iron. Atomic number is 26. Ionic charge is +3.
   b. Vanadium. Atomic number is 23. Ionic charge is -3.
   c. Iron. Atomic number is 26. Ionic charge is -3.
   d. Vanadium. Atomic number is 23. Ionic charge is +3.

10. Isotopes of an element have... *
    a. the same atomic mass number but different atomic numbers.
    b. the same atomic number but different numbers of electrons.
    c. the same atomic number but different atomic mass numbers.
    d. the same number of electrons but different atomic numbers.

11. In the name "Helium-4" the numeral "4" stands for... *
    a. the atomic number of helium.
    b. the number of protons plus electrons in an atom of helium.
    c. the number of protons in an atom of helium.
    d. the total number of protons plus the total number of neutrons in a particular atom of helium.

12. Besides the atomic number, the box for each element on the periodic table also contains a number that... *
    a. is equal to the average atomic mass of the element's isotopes.
    b. is equal to the atomic mass number of the element.

c. is equal to one of the atomic mass numbers that are possible for that element.
d. is equal, when rounded off, to the atomic mass number of the element.

A copy of your responses will be emailed to you.

APPENDIX F

SAMPLE CLASSROOM ASSESSMENT FOR ATOMIC STRUCTURE

Quiz

Atomic Structure

Instructions: Where answers can be written using complete sentences, **use complete sentences**. Points will be deducted for partial answers. You may use your periodic table. For five percentage points extra credit, write down what the difference is between the average atomic mass of an element and the atomic mass number of an isotope. All questions are worth 10 points unless otherwise noted. This quiz has 100 points.

1. Fill in the following table with the mass expressed in atomic mass units (amu).

	Mass	Symbol	Charge
proton			
neutron			
electron			

2. What structural feature of an atom determines which *element* it is?

3. What feature of an atom based on the subatomic particles that it is made from makes *isotopes* of an element different from each other?

4. What feature of an atom based on the subatomic particles that it is made from determines whether it has an electric charge or not?

5. What is the expression used to calculate charge? Show work for the calculation of the ionic charge of an atom with 8 protons, 9 neutrons, and 10 electrons.

6. What is the difference between *mass number (A)* and *atomic number (Z)*?

turn over

7. Give the atomic number and atomic mass number for each of the following isotopes *based on the information in the table*:

	Atomic Number (Z)	Mass Number (A)
lithium-6		
^{42}Ca		
uranium-235		
^{62}Cu		
gold-195		

8. Fill in the following table (atoms may or may not be neutral). Include the charge, if any, in the symbol you write. (20 pts)

Isotope Name	**Isotope Symbol incl. Charge**	**No. of p^+**	**No. of n^0**	**Mass Number**	**No. of e^-**	**Charge**
		30		68		+2
			74	124	48	
		50		112	46	
	$^{182}_{74}W^{4+}$			182	70	+4
radon-222					85	

9. Draw a picture of a neutral atom of fluorine-17. In your picture clearly indicate the parts of the atom and show the number and kind of each subatomic particle. Your atom must be accurate in every detail to earn full credit.

APPENDIX G

INTERVIEW QUESTIONS

1. Now that you have done a few POGIL lessons tell me about what it is and how it works.

2. Compare this group work approach to how you've done things in the past. What is the way things are usually done when it comes to basic instruction?

3. Which teaching approach leads to more learning for you individually? Why?

4. If you could change something or add something to the way we do group work to make it better, what would you add? Why?

5. Do you think working with your peers to learn new material helps you to improve your comprehension of the material? Why or why not? What works best for you?

6. Do you think that your work in this class this year has helped you to develop your critical thinking skills? (For example, your ability to identify a problem and propose solutions for it). Why or why not?

7. What is your opinion of the class motto, FIO (Figure It Out)? Do you think it's an attitude that will lead to deeper, more successful learning? Do you feel challenged by it? Is that challenge a positive or a negative thing?