TRANSFER OF GRAPHING SKILLS FROM MATH TO CHEMISTRY

Brittany Danielle Busby

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TRANSFER OF GRAPHING SKILLS FROM MATH TO CHEMISTRY

By

BRITTANY DANIELLE BUSBY

BS, ACS Chemistry, University of River Falls-WI, River Falls, WI, 2008

Dissertation

presented in partial fulfillment of the requirements
for the degree of

Doctor of Philosophy
in Chemistry, Chemical Education

The University of Montana
Missoula, MT

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Approved by:

Scott Whittenburg, Dean of The Graduate School
Graduate School

Mark Cracolice, Chair
Department of Chemistry and Biochemistry

Chris Palmer, Co-Chair
Department of Chemistry and Biochemistry

Michael DeGrandpre
Department of Chemistry and Biochemistry

Daniel Denis
Department of Psychology

Tony Ward
School of Public and Community Health Sciences
TRANSFER OF GRAPHING SKILLS FROM MATH TO CHEMISTRY

Chairperson: Mark Cracolice
Co-Chairperson: Chris Palmer

Most students begin their university studies with adequate mathematical skills to succeed in general chemistry. However, students have a demonstrated difficulty with the application of math in a chemistry context. The ability to apply skills to new contexts is known as transfer, and understanding and enhancing transfer of graphing skills into the context of chemistry is the primary purpose of this investigation. Graphing skills were selected as the area of emphasis because they provide a strong conceptual link between math and chemistry.

This is a two-phase, sequential, quasi-experimental, mixed-methods study. In the first phase of the study, the quantitative research questions and hypotheses: (a) compare ability to transfer math-graphing skills to two other domains, (b) relate ability to transfer graphing skills to scientific accuracy of graphs constructed on chemistry exams, (c) relate scientific reasoning ability, prior content knowledge, intelligence, textbook reading, experience with story problems, and experience with inquiry labs, to ability to transfer math-graphing skills into science context, and (d) compare scientific accuracy of graphs constructed on exams based on instructional treatment. Results indicate that scientific reasoning and lack of chemical misconceptions, of all the predictor variables considered, have the greatest impact on ability to transfer, accounting for about 35% of variance ($R^2 = 0.350$, $F = 20.151$, $p < 0.001$). Also, instructional treatments did not appear to influence transfer, and even given all focused attention on graphing, students did not reach 50% capacity of transferring that knowledge into similar chemistry exam problems.

Information from the first phase was explored further in a second qualitative phase. In the second phase, qualitative interviews with purposefully selected participants probed students’ understanding of graphs and their ability to transfer graphing skills into science context. The qualitative research in the second phase was needed to ensure an accurate understanding and explanation of the quantitative results. It was found that, while understanding the time spend working with graphs in lab and being able to recognize graphical relationships and quantify those relationships, students demonstrated a lack of transfer from math context examples to chemistry context. They also exhibited a lack of taking in feedback concerning graphing construction and interpretation.

These results are generalizable because the relatively high drop/fail rate in college general chemistry observed here is prevalent in the United States today, and the students in the chemistry course studied are students who are representative of the general population. Thus, the results of the investigation are a definitive contribution to the research community’s understanding of math-to-chemistry transfer of graphing skills.
Acknowledgements

First, I would like to thank my advisor, Mark Cracolice, for offering a unique Chemical Education program that focuses on how students think and how we, as educators, can influence the development of students’ reasoning skills. I would like to thank him also for all his guidance and support throughout the years of this program. I am so grateful to have found a program that allows me to combine my interests of chemistry, math, and helping students learn. This program has taken me a long time to complete, but I have learned so much about leadership, teaching, presenting, the ins and outs of universities, and ultimately, balancing life. I would like to thank my co-chair, Chris Palmer, for his guidance and support not only in my analytical chemistry research project, but also throughout my time in this program. Thanks to my other committee members, Tony Ward and Mike DeGrandpre for their help with analytical chemistry and Brian Steele for his help with mathematical statistics early on. Special thanks to Daniel Denis, who graciously helped me with psychological statistics on all my projects for years and joined my committee toward the end of my time here. Thank you also to the faculty of the chemistry, psychology, curriculum and instruction, and math departments for their support and direction over the years.

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Chapter 1: Introduction

1.1 Chemistry is challenging

College general chemistry is a difficult course. The fundamental reason for this is that the central concepts of chemistry—concepts like the electron—are not directly observable to human senses. When "there is no immediate sensory way to get at" concepts such as an electron (Johnstone, 1991, p. 78), chemistry concepts can only exist in the mind. The closest students may get to sensory connection to chemical concepts is through experimental observations they make. From these experimental observations, the students must deduce, with the aid of instruction, the real indicators of chemical occurrences from all the other distractions during experiments (Johnstone, 1991). Outside of experimentation, students must consider the central concepts of chemistry without relying on sensory experience. This is extremely challenging for many students.

Throughout the process of learning chemistry concepts, students must also learn the language of science itself. This is also difficult. There are numerous technical words, as well as non-technical terms, that students think they understand, but the words are often used differently in science from everyday life (Johnstone, 1991). Scientific language is meant to be concise. To accomplish this, each word bears significant meaning, so the processing load is much higher than what many students have previously experienced (Snow, 2010).

The way chemistry is taught may also compound the difficulty (Johnstone, 1991; Nakhleh, 1992; Tai, Sadler, & Loehr, 2005). The combination of high enrollment and a large quantity of challenging material that must be covered in a relatively limited period combine to make general chemistry an infamous course at almost every university. Chemistry is also one of the first science courses many college students take. This makes it a gatekeeper course that determines access to future science courses (Tai et al., 2005).

In this chapter, the challenges of the general chemistry course will be presented along with proven tools that instructors can leverage to provide the best opportunities for students to succeed in general chemistry. Among the challenges that must be overcome is chemistry’s reliance on skill sets that are learned elsewhere. Chief among these are mathematical skills that are commonly learned in a purely mathematical context and must be transferred into the context of chemistry by students.

The investigation reported here will explore students’ transfer of math skills from the mathematical context in which they are learned to the chemistry context in which they must be applied. This is undertaken by specifically using mathematical graphing skills.

Mathematical graphing skills are the ideal marker for researching the interface between math and chemistry, and skill transfer between the two, because graphing sits at the interface between conception of a physical relationship and its mathematical representation. Thus, the proximity of graphing to conceptual understanding reduces potential interference from the complex network of factors that may influence a student’s ability to transfer a skill between math and chemistry.
1.1.1 Course demographics.

The difficulty of general chemistry is "exacerbated by the fact that most students in general chemistry courses are neither chemistry nor biochemistry majors" (Cracolice & Busby, 2015, p. 1790). General chemistry is a gatekeeper course for any college student pursuing a degree in biology, geology, pharmacy, pre–medical sciences, and many more. For example, in the autumn of 2014, only 4% of students enrolled in general chemistry at the University of Montana were declared chemistry majors (Figure 1).

![Composition of a general chemistry class by declared major. These data are from first-semester general chemistry in fall 2015 at the University of Montana.](image)

The consequence of this is that many students in the course may not regard general chemistry as central, or relevant, to their declared major (Gillespie, 1991). This perception can significantly impair their engagement in the course.

General chemistry courses changed greatly in the 1960s (Gillespie, 1991; Johnstone, 1991). Chemistry went from largely macroscopic explorations to "a much expanded treatment of 'principles,'" such as gas laws, atomic structure and orbitals, bonding, electrochemistry, and thermodynamics (Gillespie, 1991, p. 192). The large amount of material presented with these principles can be overwhelming for students. Students often avoid the need to conceptualize these principles by memorizing perceived essential facts, theories, and equations to pass the course.

Some students can get through a semester or two of general chemistry using algorithms and memorization but are unable to solve questions that deviate from a general algorithmic structure. Algorithmic problems can be solved from a memorized set of procedures, whereas conceptual problems require students to solve the problem based on an understanding of the concept without use of memorized procedures (Cracolice, Deming, & Ehlert, 2008).

1.1.2 Fail rates.

Actual measurement of failure rates supports students’ perceptions of chemistry being a difficult course. A meta-analysis of 225 studies in undergraduate science, technology, engineering, and mathematics (STEM) courses reported that students earned a D or F grade, or withdrew from the course, at a rate of 33.4% across STEM courses (Freeman et al., 2014). Historically, failure rates
of over 50% have been reported (Gafney, 2001). In their first semester general chemistry course, Chambers and Blake (2008) reported failure rates of 58%. Gellene and Bentley (2005) state that, of students beginning their first semester general chemistry course, over 70% fail to complete the course with a C or better. In the Fall of 2015, there was a 54% fail rate in first semester general chemistry at the University of Montana.

So, what differentiates the minority of students who excel in chemistry from the majority who fail? A fundamental difference is that successful students develop a conceptual understanding of chemistry (Cracolice & Busby, 2015; Tai et al., 2005; Vass, Schiller, & Nappi, 2000), possess a solid mathematical foundation in arithmetic and algebra ( Nicoll & Francisco, 2001; Potgieter, Harding, & Engelbrecht, 2008; Sinapuelas & Stacy, 2015), and have a high quality of scientific reasoning (Cracolice & Busby, 2015). These fundamental cognitive abilities and need for conceptual understanding are examined in detail in the following sections.

1.1.3 Conceptual understanding.

Science, chemistry included, is represented on three conceptual levels: macroscopic, particulate, and symbolic (Johnstone, 1982). Most of chemistry is taught and understood at the particulate and symbolic levels, and the abstract nature of these concepts can make chemistry difficult to understand. Gabel (1999) states: “students live in a macroscopic world of matter, things that have mass and occupy space. Unfortunately, however, students do not perceive chemistry as related to their surroundings” (p. 550). Skills and knowledge of macroscopic concepts need to be transferred into particulate contexts. Most topics in chemistry involve abstract—unseen—entities, so students must be able to mentally conceptualize these entities and develop conceptual understanding from those mental representations.

Conceptualization is the ability to visualize a concept underlying an observation, calculation, or description. It is crucial for students to be able to utilize symbolic representations to transfer between macroscopic and particulate levels to conceptualize material. Conceptualization is a fundamental skill in chemistry. It is needed to comprehend abstract concepts such as atoms, pressure-volume relationships, and kinetics. When students are more conceptual in their thinking they are “more experienced in problem solving, more situational in their knowledge orientation, and more verbal in their reasoning” (Pushkin, 1998, p. 809).

The concepts that students must conceptualize are well represented in The Science Content Standards for California Public Schools: Kindergarten Through Grade Twelve. These require high school chemistry courses to include the following topics (California State Board of Education, 1988):

- Atomic and molecular structure
- Chemical bonds
- Conservation of matter and stoichiometry
- Gases and their properties
- Acids and bases
- Solutions
- Chemical thermodynamics
- Reaction rates
- Chemical equilibrium
- Organic chemistry and biochemistry
- Nuclear processes
Every one of these topics is based on abstract, unobservable causal entities. It is essential for such material to be understood conceptually to advance to higher levels. The ability to reason with unobservable, abstract entities is known as formal thinking and is required for conceptualization. To reason with observable, concrete, entities is known as concrete thinking. These will be described in greater detail under constructivism in Section 2.2 Constructivism.

### 1.1.3.1 Scientific Reasoning

A large percentage of students entering college lack the ability to reason through concepts that involve unobservable entities rather than observable entities, i.e., abstract rather than concrete (Cantu & Herron, 1978; Cracolice, 2012; Lawson & Renner, 1975; Lawson & Wollman, 1976; Marek & Cavallo, 1997). Lawson and Renner (1975) found that high school students working at the concrete level could not perform above chance on formal problems in biology, chemistry, or physics. Table 1 summarizes studies that investigated the percentages of students who can reason formally. These studies find that typically, less than 40% of students entering college are formal thinkers. A study done by Cracolice (2012) at the University of Montana shows that of students entering the second semester of general chemistry, only 68% are formal.

#### Table 1

**Percentage of Students at the Formal Reasoning Level**

<table>
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<th>Group</th>
<th>Year of Study</th>
<th>Age Level</th>
<th>% Formal</th>
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<tbody>
<tr>
<td>McKinnon &amp; Renner</td>
<td>1971</td>
<td>College freshmen</td>
<td>25%</td>
</tr>
<tr>
<td>Lawson &amp; Renner</td>
<td>1975</td>
<td>High school</td>
<td>5%</td>
</tr>
<tr>
<td>Bird</td>
<td>2010</td>
<td>College general chemistry</td>
<td>41%</td>
</tr>
<tr>
<td>Cracolice</td>
<td>2012</td>
<td>College general chemistry: 1st semester</td>
<td>38%</td>
</tr>
<tr>
<td>Cracolice</td>
<td>2012</td>
<td>College: 2nd semester</td>
<td>68%</td>
</tr>
<tr>
<td>Moore &amp; Rubbo</td>
<td>2012</td>
<td>College non-STEM sophomores/juniors</td>
<td>25%</td>
</tr>
<tr>
<td>Shayer, Kuchemann, &amp; Wylam</td>
<td>1976</td>
<td>16 years old</td>
<td>30%</td>
</tr>
</tbody>
</table>

*Note.* Summary of the percentage of students at the formal reasoning level, as reported by the listed authors and organized based on the year of the study.

Formal reasoning is quantified by measuring scientific reasoning skills such as combinatorial logic, conservation, exclusion and control of variables, probabilistic reasoning, and proportional reasoning. These skills are often under- or un-developed in general chemistry students as demonstrated by the studies summarized in Table 1. Such skills help students construct conceptual knowledge and understanding. The skills are defined in Table 2 below and will be referenced throughout this proposal.
Table 2

Definitions of Scientific Reasoning Skills

<table>
<thead>
<tr>
<th>Reasoning Skill</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classification</td>
<td>Process in which ideas and objects are recognized, differentiated, and understood based on some commonality. Understanding that different criteria may be used for different purposes of classification without one commonality necessarily being predictive of others.</td>
</tr>
<tr>
<td>Combinatorial logic</td>
<td>Ability to identify all possible combinations for a set of objects or events.</td>
</tr>
<tr>
<td>Conservation</td>
<td>Ability to hold a concept or original image of an object in one's mind and imagine that distorting the object does not change the amount of material it contains.</td>
</tr>
<tr>
<td>Correlation</td>
<td>The degree to which two or more attributes or measurements show a tendency to vary together.</td>
</tr>
<tr>
<td>Equilibrium</td>
<td>Condition of a system in which all competing influences are balanced.</td>
</tr>
<tr>
<td>Exclusion and control of variables</td>
<td>The ability to keep constant or hold in one's mind all but one attribute that will affect the outcome of an experiment and examine how each will affect the outcome.</td>
</tr>
<tr>
<td>Hypothetico-deductive reasoning</td>
<td>Ability to formulate and test alternative hypotheses against given data.</td>
</tr>
<tr>
<td>Probabilistic reasoning</td>
<td>Measure of the likeliness of an event to occur with the understanding that high or low probability does not mean the event will or will not happen.</td>
</tr>
<tr>
<td>Proportions</td>
<td>An equality of ratios; a:b = c:d, etc.</td>
</tr>
<tr>
<td>Ratios</td>
<td>A numerical comparison between two things; a:b.</td>
</tr>
</tbody>
</table>

Students must advance in the way they work with and visualize a problem, but the development of scientific reasoning skills is typically not a focus of instruction. However, these skills are crucial to the ability to conceptualize material between macroscopic, symbolic, and particulate representations, further discussed in Section 2.2 Constructivism. To develop such skills, students must start with physical manipulation of concrete objects that they can hold and see. From those experiences, they construct their own understanding of how properties of science work and progress by applying those already constructed knowledge templates to objects that they cannot hold or see. Refer to Section 2.2.1.3 Context and concepts.

Students must be able to use ratios, do proportional reasoning, work with probability, recognize conservation, control variables, and use correlational reasoning and combinatorial reasoning to succeed in a general chemistry course.

1.1.4 Mathematical reasoning.

Mathematics is also foundational to success in chemistry. In addition to students needing to reason at the macroscopic, particulate, and symbolic levels in chemistry, mathematical expressions are used to express relationships between the macroscopic and particulate levels (Gabel, 1999). Leopold and Edgar (2008) describe mathematics as a language that could be a potential barrier to success in chemistry. They state that "to fluently translate the many quantitative examples and problems used throughout the semester in lectures, labs, and discussions and extract their conceptual meanings," (p. 729) students require experience with mathematics to the extent that they can correctly respond to basic questions regarding scientific notation, logarithms, graphs, and algebra. Mathematics assessment quizzes (Leopold & Edgar, 2008) and SAT scores correlate to grades in second semester general chemistry (Andrews & Andrews, 1979).
The inability of students to apply mathematical skills to a general chemistry context has been shown to be one of the main factors holding students back from performing adequately (Andrews & Andrews, 1979; Armstrong, Fielding, Kirk, & Ramage, 2014; Follette, McCarthy, Dokter, Buxner, & Prather, 2015; Leopold & Edgar, 2008; Nicoll & Francisco, 2001). While perhaps not generalizable to students in small high schools, the Las Vegas Review Journal reported that about 70% of sophomores in high school failed their national math assessment (Milliard, 2013). The United States Department of Education (2008) stated that 93% of 17-year-olds couldn't solve multistep algebra problems. From personal communication with professors of different general chemistry courses, as well as personal experience with students in these courses, the researcher conservatively estimates that about half of students enrolled in first-semester college general chemistry cannot do basic algebra in a chemistry context.

Both arithmetic and algebra are utilized frequently in general chemistry. Arithmetic is a subdivision of math that is concerned with four operations of numbers: addition, subtraction, multiplication, and division. Algebra is a subdivision of math where letters or symbols are used to represent numbers and express relationships.

To determine the mathematical capabilities of chemistry students outside of a chemistry context, an instrument developed by Follette, McCarthy, Dokter, Buxner, and Prather (2015) named Quantitative Reasoning for College Science (QuaRCS), was administered to students in several science courses at the University of Montana in Spring 2016. This instrument assesses students' basic quantitative reasoning science skills, including arithmetic. The data showed that there is no specific area of mathematical weakness in arithmetic when presented without applied context (Busby, unpublished data, 2016).

At the University of Montana students are required to pass an Intermediate Algebra course with a C– or better or place at Level 4 or higher on the Assessment and Learning in Knowledge Spaces (ALEKS) placement test. ALEKS is an online assessment that uses adaptive questioning to determine what students do or do not know. It will ask questions across basic math, pre-algebra, introductory algebra, through to college algebra and even more advanced levels of math. Students must demonstrate competency in intermediate algebra to place into general chemistry at the University of Montana, the setting for this study.

1.2 Graphing: The Conceptual Link between Math and Chemistry

If students are to gain comprehension of chemical concepts they must develop their qualitative (conceptual) thinking skills in addition to quantitative (algorithmic) thinking (Pushkin, 1998). Graphs provide an excellent medium for students to develop both skills (Follette et al., 2015; McKenzie & Padilla, 1986). Graphing represents one of the initial opportunities "for powerful learning" in early mathematics (Leinhardt, Zaslavsky, & Stein, 1990, p. 2). Powerful learning means that, while graphs often go "unmarked" in STEM courses they "are fundamental to other more sophisticated parts of mathematics" (Leinhardt et al., 1990, p. 2).

Algebra and graphical representations are two different symbol systems that cooperatively "construct and define the mathematical concept of function" (Leinhardt et al., 1990, p. 3). A mathematical function is a relationship that involves one or more variables. A graph provides a mathematical representation of a function by showing the construction of the relationship between the independent and dependent variables. The fact that these two symbolic systems "are used to illuminate each other" places increased demand on the learner "in terms of new ideas, notational uniqueness, and symbolic correspondences," but does not exclude intuition of meaning.
Graphing is multifaceted. It requires two areas of construction: construction of the graph from data and construction of the algebraic equation, or function. The student must then be able to translate between the two and interpret the relationships.

While constructing a graph from data, a person must appropriately choose which variables to use—dependent and independent—and which axis each variable should go on. From there, scales must be appropriately determined and drawn, and if units are a relevant part of the context, they must be applied to axes. The units could potentially determine alterations in scale as well; for example, a log scale may be more appropriate if numbers for a variable are increasing quickly. Typically, scales must be determined by the student in chemistry contexts, but are often provided in mathematical contexts to reduce the number of steps in graph construction (Leinhardt et al., 1990).

Interpretation refers to making sense or gaining meaning from a graph, equation, or situation (Leinhardt et al., 1990). Interpretation can be general or specific. A general example is determining patterns or extrapolating from an equation, whereas a specific example is when specific conditions are met (Leinhardt et al., 1990). All of this depends on where the student's focus is, but that is something the student must also determine.

Graphical representations are used extensively in science courses to provide conceptual information in a visual manner (Leinhardt & Steele, 2005; Mitnik, Recabarren, Nussbaum, & Soto, 2009; Roth & Bowen, 1999, 2001; Roth, Bowen, & Masciotra, 2002). Interpretation in these cases often requires students to make sense of a situation or abstract relationship that is expressed by an equation or ordered pairs (Leinhardt et al., 1990).

Unfortunately, there are several common graphical misconceptions: Students can misinterpret the x-axis for the y-axis, lack understanding for interpretations between variables, show an inability to manipulate variables, lack understanding of independent and dependent variables, mistake graphs as pictures—concrete entities, rather than as conceptual representations of unseen entities, be unable to determine slopes, and confuse slopes and areas (Leinhardt et al., 1990; Shah & Hoeffner, 2002).

To determine if general graphing construction and interpretation was underdeveloped for students at the University of Montana, the Test of Graphing Skills (TOGS), an instrument validated for high school, was administered to students taking several science courses in Spring 2016, to survey general graphing skills (McKenzie & Padilla, 1986). The results showed that the existing basic graphing skills of our students are at a desired level; they performed with a majority of correct answers in both graphical construction and interpretation. See Appendix G.

Several other surveys were administered to investigate how students utilize textbooks to study and learn, i.e., what features do they focus on, do they utilize graphs, etc.? Do students understand the two necessary criteria for a relationship to be directly proportional? Can students extract the intended learning objectives from a textbook by using a graph? These pilot studies demonstrated a deficiency using graphs when studying and learning, a lack of understanding about direct proportions, and an inability to extract intended learning objectives from a textbook among students. See Appendix I. These problems indicate that students are not completely processing the information they need to learn.
Throughout the first semester of general chemistry directly proportional relationships are highlighted. If students do not utilize the graphs of the relationships being expressed, there is necessarily less reasoning about the independent and dependent variables and how they interact. This is further demonstrated by a distinct lack of understanding for the need of a zero-y–zero-x point in a relationship that is directly proportional. The fact, too, that students do not comprehend what they should be learning while they study reveals a lack of thought while reading. Thinking about the concepts and relationships exhibited in chemistry is necessary for students to learn and succeed in the course.

1.3 Transfer

This leads to the question: Do students lack an ability to transfer math skills to a chemistry context? Transfer has been described as students' ability to apply knowledge and skills in a context different from the one in which the knowledge and skills were learned (Chi & VanLehn, 2012; Dori & Sasson, 2013; Roberts, Sharma, Britton, & New, 2007; Sasson & Dori, 2015). It appears that while students can utilize math in a mathematical or everyday context, they have trouble applying it once those skills are needed in chemistry, or even a general science context; this demonstrates an issue with transfer. Mathematics is considered essentially context-free; it is domain-independent and abstract. Chemistry, on the other hand, is abstract but bound in context. That is, physical objects are unobservable, as previously discussed, and variables describing those objects have both physical meaning and units.

If students learn math skills but are unable to transfer them to other contexts, such as chemistry, the skills are not useful. Without the ability to transfer, students must learn a seemingly new set of skills for each context. It is preferable for students to transfer their existing mathematical knowledge to applied problems and contexts. Transfer takes place when a person can induce a schema, or mental representation, from an example learned in one context into novel problems (Holyoak & Koh, 1987).

Conceptual understanding is crucial in chemistry, but without the application of math skills, students will not be able to get to the point of interpreting chemical relationships. Since graphs represent a physical relationship that is displayed as a math-based representation they are a logical tool to explore the lack of transfer because they sit at the interface of math and chemistry.

1.4 Purpose of the Study

The purpose of this two-phase, sequential mixed methods study was to determine if students demonstrate the ability to transfer math-graphing skills to science context. Information from the first, quantitative phase was explored further in a second, qualitative phase. The qualitative research in the second phase was needed to ensure an accurate understanding and explanation of the quantitative results.

1.5 Research Questions

In the first phase of the study, quantitative research questions and hypotheses were investigated in regards to the following four areas of interest:

1. Compare graphing ability in three domains.
2. Relate ability to transfer graphing ability across those three domains to scientific accuracy of graphs constructed in the chemistry laboratory and on chemistry exams.

3. Relate scientific reasoning ability, prior content knowledge, intelligence, experience with story problems, and experience with inquiry labs, to ability to transfer math-graphing skills into science context.

4. Compare scientific accuracy of graphs constructed in lab or on exams across instructional treatments, controlling for prior graphing ability of participants.

In the second phase, qualitative interviews were used to probe students’ understanding of graphs and their ability to transfer graphing skills into science context with purposefully selected participants. This allowed the phenomenon of transfer to be further investigated from the students’ point of view and provide substantive reasoning to explain the quantitative results observed. Open ended questions were asked to explore the specific research question:

How do college chemistry students reason through the construction and interpretation of a graphical representation, including the algebraic expression, of a physical relationship in a chemistry context; do they recognize that their mathematical skills are the underlying structure for the chemistry graphs?
Chapter 2: Literature Review

The problem of the high failure rate in college general chemistry examined in Chapter 1 is addressed here. Throughout Chapter 2, theories governing chemistry learning will be discussed in detail based on the literature: constructivism, math knowledge theory, graphing in science, and transfer. Constructivism provides the overarching theory in which the other topics reside and are developed. Math knowledge theory provides the foundation for factors that may influence student ability to work with graphs and transfer those skills outside of a math context. Graphing in science provides an interface to represent quantitative data in a conceptually accessible form. Transfer of mathematical skills and graphing to a chemistry context is necessary for students to demonstrate understanding of conceptual chemistry concepts and succeed in chemistry. Figure 2 illustrates the connections between these theories and how they relate to chemistry learning.

![Concept map of factors related to learning chemistry.](image)

Figure 2. Concept map of factors related to learning chemistry. To learn chemistry at a conceptual level requires both math and graphing skills, which are gained through the paradigm of constructivism. However, students must be able to transfer these skills to a chemistry context. It appears, based on the literature, that the transfer link is the breakdown bottleneck to learning chemistry.

For this dissertation, research factors within each of these theories that support chemistry learning were tested with paper-and-pencil instruments to determine correlations to students' ability to transfer from a math graphing context to science graphing contexts. To understand why those factors are relevant, this chapter will describe previous research in the literature review.

2.1 Definition of Terms

*Formal reasoning abilities* are defined as the ability to comprehend abstract ideas (Trifone, 1897, p. 411). Constructs of formal reasoning are scientific reasoning skills such as: controlling variables, proportional reasoning, combinatorial reasoning, probabilistic reasoning, and correlational reasoning. These, and other, scientific reasoning skills are defined in Table 2.

*Concrete reasoning abilities* are defined as the inability to conceptualize unseen objects without a model.
Constructivism is a theory that states the individual must construct knowledge through interaction with the world around him or her.

Graphing construction consists of two parts: First, construction of the frame of the graph through proper use of axes, scales, and units, etc.; second, construction of the algebraic equation that describes the pattern of data mathematically (Leinhardt et al., 1990).

Graphing interpretation refers to the global qualitative understanding of the concept, or physical relationship, described by the algebraic equation in the graph (Leinhardt et al., 1990).

Transfer is the ability to apply knowledge or learned skills into a context other than the one originally learned in (Chi & VanLehn, 2012; Dori & Sasson, 2013; Georgiades, 2000; Roberts et al., 2007).

2.2 Constructivism

Conceptual understanding at macroscopic, particulate, symbolic, and mathematical levels requires formal scientific reasoning abilities. Even students not majoring in chemistry or biochemistry require these skills—they must be able to think scientifically, if not necessarily chemically.

The theory of constructivism provides a lens for understanding the nature of students' cognitive growth (Adey & Shayer, 1990; Bird, 2010; Bodner, 1986; Cracolice, 2005; Cracolice et al., 2008; Deming, O'Donnell, & Malone, 2012; Farrell, Moog, & Spencer, 1999; Gabel, 1999; Hake, 1998; Igaz & Proksa, 2012; Pavelich & Abraham, 1979; Piaget, 1970, 1997; Renner & Lawson, 1973; Spencer, 1999; Talanquer, 2015). Constructivism emphasizes the active construction of knowledge by an individual through the integration of new evidence to modify existing thought patterns. The late Swiss developmental psychologist, Jean Piaget, actively worked in this field from 1922 to 1980 and devised much of the theory.

The irreducible belief underlying Piaget's theory of development is that people must act on the world around them to gain knowledge of it. People are active thinkers, constantly constructing more advanced views of their world and more advanced strategies for problem solving. These views of reality are what we consider to be knowledge. Even when current strategies are effective, people continue to construct new views and strategies that better conform to that person’s observations (Siegler & Ellis, 1996). Our knowledge of the world originates from acting on objects, and the physical or mental transformations the objects go through. We all have general structures of these actions, or schemes, by which we construct knowledge through interactions with the world (Piaget, 1970).

Piaget is perhaps best known for proposing that cognitive development occurs in four stages. These stages maintain a constant order of succession. Each subsequent stage requires the previous stage to build upon. The stages proposed by Piaget are:

1. Sensorimotor
2. Pre-operational
3. Concrete operational
4. Formal operational

These stages will be discussed in detail in 2.2.2 Stages of development (Piaget, 1970, 1997).
Biological applications for inclusion, order, and correspondence, as well as the relations between them, occur in every stage of development and are the fundamental scaffolding of behavior and intelligence. Inclusion is the action of including something within a group. Order is the arrangement of things in relation to each other based on a pattern. Correspondence is a similarity or connection. These structures form the foundations of logic and mathematics; from them we may mentally construct abstract processes, operate upon them, and judge the veracity of our knowledge (Piaget, 1970).

Abstract processes must be developed. New information is never added to a blank slate, it is always incorporated into some previously existing scheme. Integration of such external elements into the mind’s scaffold is termed “assimilation.” Subsequent modification of a scheme by assimilated elements is therefore called “accommodation.” This active process of assimilation and accommodation, resulting in variations of action schemes, or operations, is the process by which knowledge is constructed (Piaget, 1970).

What foundational scheme assimilation acts on is debated. Nativists argue that knowledge, such as language, is present at birth and not constructed from external sources (Chomsky, 1975, 1980). While there are innate processes in the brain, people are not born with a complete or even consistent set of information, so knowledge cannot all be based on nativist theory. At the other end of the spectrum, the empiricist view is that knowledge can be transferred from one person to another or from some other external source to an individual (Matthews, 1993; Nola, 1997). In education, traditional lectures are arranged based on this theory. However, this fails to consider the common experience that no matter how eloquently you tell someone something, the knowledge is not assimilated uniformly, and sometimes not at all. The structure of the chemistry course that is the setting for this study is specifically designed to promote formal thought and advance students by utilizing the principles of Piagetian constructivism, rather than a traditional lecture format. See Section 3.3 Brief Description of the General Chemistry Course for more information on course design.

David Ausubel, an American psychologist, believed in meaningful learning achieved through deductive reasoning. He proposed that the most important factor influencing someone's learning is what the person already knows (Ausubel, Novak, & Hanesian, 1978; Driscoll, 2005). This theory was further nuanced by Lawson (2001) who stipulated that "knowing" includes both declarative (facts, etc.) and procedural (how to do something) knowledge. Assimilating these ideas into Piaget's theory can result in a powerful developmental and teaching tool. For this research, students' prior chemistry content knowledge and alternate conceptions were measured to observe any correlation to transfer of math skills to a chemistry context. For further descriptions see Section 3.5.3 Research instruments.

Lev Vygotsky, a Russian developmental psychologist whose prominent works were conducted from the early 1920s until his death in 1934, contributed to constructivism with his Social Developmental Theory of Learning. Vygotsky's approach to development posits that learning is interrelated with development. However, unlike Piaget who proposes that development leads learning, Vygotsky claims that learning "awakens a variety of internal developmental processes that are able to operate only when the child is interacting with people in his environment and in cooperation with his peers," so learning leads development in Vygotsky’s epistemology (1978, p. 90). While Piaget did emphasize social transmission, he looked at communication more as a means to confirm thoughts, rather than as a tool to develop them (Vygotsky, 1978). Both views are likely true in some combination. Within each developmental stage that Piaget proposes, only
certain learning can take place. However, once a student has biologically matured to each developmental stage, social learning can lead to further development of thought patterns.

Piaget (1997) claimed the link between development and learning is active assimilation, or the integration of information into current structures. People must experience, invent, and discover things for themselves, and these cognitive actions depend on the maturation of the pathways on which they are carried out. Thus, learning depends on an individual's level of cognitive development because learning depends on the structures available for improvement and the ability of each individual to utilize those structures. Once the foundational structures are in place learning can lead to further development as Vygotsky claims.

Many aspects of Piaget's theory have provided a remarkably sound foundation on which to build a unified and inclusive epistemology for education. Constructivism, as described by Piaget and expanded by others, remains the most appropriate model for meaningful improvements to learning in the science classroom (Cracolice, 2005). Within constructivism Piaget has two specific theories: the theory of equilibration and the theory of cognitive development.

2.2.1 Theory of equilibration.

Piaget's underlying mechanism for advances in knowledge is the theory of equilibration, which proposes that people must go through disequilibrium and re-equilibrate to learn (Flavell, 1996). Equilibrium is essential to explain development because people acquire knowledge actively.

2.2.1.1 Disequilibrium.

While some researchers have referred to disequilibrium as cognitive conflict, the term disequilibrium will be used here (Driscoll, 2005). Disequilibrium occurs when information being assimilated is not easily linked to information already present in the mind (Marek & Cavallo, 1997). A person becomes confused as they try to fit the new data with what was previously regarded as true. When someone goes into disequilibrium, they must develop questions that will help themselves sift through the information in a way that will either replace or modify old conclusions, or lead to the person ignoring the new information partially or even entirely. If the information is not ignored, the questions can lead to further exploration, which will in turn shape more questions, continuing the process of working to resolve disequilibrium. Social interactions may greatly influence the type and degree of exploration that is pursued. These interactions can also help a person come up with relevant questions or explore existing questions. Exploration in itself can produce disequilibrium.

Disequilibrium drives accommodation, that is, the modification of how information has previously been organized in one's mind. When information cannot be assimilated, a person will go into disequilibrium and that process will bring about accommodation, given reinforcement of the other elements of learning, such as self-regulation and experience.

2.2.1.2 Self-regulation.

Correction of thought, working through assimilation and accommodation, leads to equilibration. Self-regulation describes the willingness of the individual to equilibrate new knowledge. If they
do not choose to regulate they will not learn (Piaget, 1997). Stated another way, equilibration is a function of the will. Regardless of whether they consciously recognize the choice, a person must choose to learn to advance. In self-regulation, a person works to change his or her own mind or perception about a concept. If a person self-regulates, accommodation, the modification of information in one’s mind, becomes possible and more efficient.

2.2.1.3 Context and concepts.

Context greatly impacts disequilibrium and accommodation. A person does not become confused in a vacuum. Allowing oneself to go through disequilibrium brings about the construction of the links between macroscopic, particulate, and symbolic representations necessary to gain understanding of chemical concepts in whatever contexts they are learned.

Generalizing concepts constitutes advancement in expertise. Cantu and Herron (1978) propose that a “concept” is a set of things that have the same defining characteristics. When these defining characteristics become generalized, more direct links can be made between concepts. According to Lawson and Renner (1975), concrete concepts can be developed through direct experience with the objects or events.

Formal – abstract – concepts are developed not through physical senses, but through imagination or through following logical relationships in a system. As Cantu and Herron (1978) state: “correct classification of such concepts cannot be based on identification of relevant and variable attributes through direct observation because either these concepts lack perceptible examples or the defining attributes are not perceptible in the example” (p. 136). The ideal gas law \((PV = nRT)\) is one such example. No model can illustrate that particles of an ideal gas do not occupy space or exert attractive forces on other particles, especially because there is no such thing as an ideal gas (Cantu & Herron, 1978, p. 136). The ideal gas is in and of itself a model used to simplify understanding of gases and their relationships with temperature, pressure, and volume. Hypothetico-deductive reasoning is necessary to comprehend such abstract concepts, which is a characteristic of formal thought, not concrete thought.

2.2.2 Stages of development.

Piaget proposed that cognitive development occurs in four stages (Piaget, 1970, 1997).

1. Sensorimotor
2. Pre-operational
3. Concrete operational
4. Formal operational

The first stage, sensorimotor, is characterized by the development of object permanence, chronological succession, and basic realization of causality of actions. These provide practical knowledge required for later stages to build upon.

In the second stage, pre-operational individuals start to develop symbolic functions, thought, and representations (Piaget, 1997). Some symbolic functions include deferred imitation, symbolic play, drawing, and mental imagery (Marek & Cavallo, 1997). These are still not operations, however, because they cannot be reversed; children in this state cannot cognitively represent what
they can do in action. Pre-operational individuals are characteristically at this stage from the onset of language acquisition, about one and one-half to two years of age, until six or seven years of age (Marek & Cavallo, 1997).

In the third stage, concrete operations build on pre-operational structures, and are named for the learner’s new ability to operate upon concrete objects. Concrete operational children must have objects present to interact with; they cannot yet operate on verbal hypotheses. They cannot conceptualize unseen objects without a model but must be able to physically manipulate the object. Some examples include: classification of types of objects, ordering by size or volume, and spatial and temporal operations such as recognizing a constant volume regardless of container shape (Piaget, 1997). Someone who is concrete operational can conserve, or hold an object in their mind, while a second object is distorted and compared to the first. They can do mental operations as well where they create a mental replica of reality and mentally transform what reality is. This leads to thought reversal, the ability to see transformation states. From these skills, the child can develop deductive and inductive reasoning (Marek & Cavallo, 1997).

Formal operation is the fourth and most advanced stage, where people can reason on both hypotheses and objects and subsequently construct new operations and develop propositional logic (Piaget, 1970, 1997). Learners can conceptualize and mentally transform objects in their minds; they do not need a model created for them (Piaget, 1970). The transition to the formal operational stage has the potential to happen around the onset of adolescence. Formal operational people are no longer bound by reality and can work in the abstract (Marek & Cavallo, 1997).

These stages are sequential (Piaget, 1970, 1997). One must start at sensorimotor and develop into formal capabilities. Students coming into college are at the concrete or formal stages as discussed in detail in Section 2.2.3 College chemistry students. If an individual is still concrete in any area he or she must have opportunities to construct his or her own knowledge of the processes of the natural world (Piaget, 1970). We know that there is a correlation between formal thought and success in general chemistry (Cracolice & Busby, 2015). In this research, we investigated if there was also a correlation between formal thought and ability to transfer math skills to a chemistry context. See Section 3.5.5 Research questions.

There have been criticisms of Piaget's stage theory, indicating that the ages where stages develop are too rigid and not generalizable since much of Piaget's work was done with affluent students. Research has also been attempted to disprove Piaget's idea of logical operations used in formal thinking (Adey & Shayer, 1997). These logical operations are the scientific reasoning skills described in Table 2. Unfortunately, critics have not considered that contexts within the real world are crucial in Piaget's stages. Intellectual capability and context are both important.

Another criticism questions the validity of the tasks Piaget designed because some studies have shown that children younger than Piaget specified could complete developmental tasks such as the point of view task. The point of view task involves a scene, i.e. a barnyard or series of mountains, etc. and the learner is asked to describe what someone would see depending on that person's position within the scene. A pre-operational child believes that a doll placed within the scene would see what the child sees because they believe everything centers around them. Once a child is no longer egocentric they can perform this task. (Adey & Shayer, 1997). Bruner proposed that younger children could complete this task because the environment, not biological development, was the specific influence on stage acquisition (Driscoll, 2005). This contrasts with Piaget’s proposal that four factors are necessary for development through the stages: maturation, physical experience, social experience, and equilibration (discussed above, p. 13) (Piaget, 1970).
While it is important to recognize the criticisms of the constructivist theory to understand what is still an area of research, the areas of criticism do not directly impact this work.

### 2.2.2.1 Maturation.

Maturation is defined by embryogenesis, which involves the development of the body and nervous system and thus the development of cognitive functions tied to biological systems. Development in a person’s nervous system are vital to what they are capable of learning. While maturation explains the order of succession from one stage to the next, it does not explain the rate of maturation because the age at which children enter each stage varies greatly in different societies (Piaget, 1997). The conceptualizations, theories, and strategies available to a child’s mind are different at different ages due to their biological development (Siegler & Ellis, 1996).

Maturational transitions have been noted in several studies. Research conducted in public schools by Shayer and Adey demonstrated that application of teaching shown to promote formal thought did not affect boys and girls at the same age (1990). They have also shown children developing the physical capability for formal thinking at about age 15 (Shayer & Adey, 1990). More recently, magnetic resonance imaging (MRI) data has contributed maturational stage data by showing girls reaching a maximum volume of gray matter at the age of 11 and boys at the age of 12, coinciding with the age of puberty for healthy boys and girls (Lenroot & Giedd, 2006). Not surprisingly, this correlates to the ages that Piaget identified children developing the capability to think formally, that is, with hypothetical scenarios rather than only with physical reality.

Environment is linked to maturation. If a person is not physically or emotionally healthy, their nervous system will not be able to mature properly or at the normal rate. Maturation may be stunted or delayed by malnutrition, physical or emotional abuse, etc. Learning environments also affect maturation. If a person is in an environment, such as school or home, that does not promote the use of thinking skills applicable to the stage the child is in, the brain will develop slower than if it is being actively stimulated. Piaget’s work was done with privileged children so it is no surprise that they could maturate to formal operational around the ages of 11 and 12 (Piaget, 1997).

After maturation is reached for each stage, a person's experiences and teaching instruction can influence how quickly they progress within the stage, but they cannot be taught beyond their current stage. The duration of each stage depends on the individual and the environment, but the stages must be progressed through sequentially. External stimuli cannot be used to hasten maturation, so advancement to the next stage cannot be controlled (Piaget, 1970, 1997).

Maturation provides the opportunity for each developmental stage to be achieved, but the realization of the advancement depends on many more factors than just maturation. Each individual must actively equilibrate between assimilation and accommodation, restructuring schemes and accumulating knowledge to acquire the mental skills needed to advance to the next stage of development. Experience and social experience are primary areas in which these processes are practiced to develop the needed operations that allow for the possibility of development to become reality (Piaget, 1970).

### 2.2.2.2 Physical Experience.

Experience encompasses the effects of the physical environment on entire intelligence that directs learners' interactions with their surroundings (Marek & Cavallo, 1997). Because knowledge is
constructed from observations of reality, experience is necessary for development to take place (Piaget, 1997). It has been shown that personal construction of knowledge has a large impact on the degree to which meaningful learning can be achieved (Marek & Cavallo, 1997). This implies that every person needs some contact with the physical environment to learn. Without experience, no one would have anything to learn about.

Piaget describes three types of experience: exercise, physical experience, and logico-mathematical experience. Exercise, as in a sport, involves action exerted on objects but does not imply knowledge will be gained from those objects. An example could be throwing a ball just for the pleasure of throwing it. It helps automate reflexes and improves with repetition. Exercise includes functional assimilation (autoregulation) and accommodation to an object. Accommodation is based on object property acquisition, which can be gained through physical experience or logico-mathematical experience (Piaget, 1970).

In physical experience, a person acts on the object, and information is gained from the object by abstraction, where one property is focused on and others disregarded. Physical experience is a child playing in the dirt, feeling the pressure in a tire, causing a balloon to pop, or any other experience where they are physically touching, feeling, or manipulating an object. This experience can potentially lead to an observation about that object, providing input for the person’s sensory memory, such as the smell or taste of dirt, or the feel of pressure when he or she pushes on a tire. These sensory inputs allow assimilation of the new information into the structures already existing within the person’s mind.

Logico-mathematical experience is when knowledge is gained from observing modifications to an object rather than from observation of the object itself; a person gains information from actions on objects (Piaget, 1997). This could take the form of making a paper plane out of a sheet that was initially flat, or rearranging Legos® from a barn to a tower. From this type of experience, a person discovers conceptual properties.

2.2.2.3 Social experiences.

Social experiences, such as language and education, are also necessary for development. According to Piaget, advancement to further stages can be "accelerated or retarded in their average chronological ages according to the child's cultural and educational environment" (1970, p. 119). However, these factors only affect the person if he or she has the maturation and possess adequate structures to assimilate them.

Social interactions can often bring about applications of experience. If instructors and parents are available and actively helping a child to learn, the environment will be far more conducive to the development and maturation of the child’s brain.

Additionally, Vygotsky’s work illustrated that students require social interactions with peers to learn. Vygotsky found that social interactions help people push through discomfort caused by the attempt to modify old thought patterns during disequilibrium. This aspect of constructivism is most effective within the knowledge gap between the level of problems an individual can independently solve and the level he or she can solve with guidance from an instructor or capable peer (Vygotsky, 1978). Vygotsky defined this range as the person’s Zone of Proximal Development (ZPD).
It is noted that experience is only a part of development. It cannot explain on its own how some concepts spontaneously appear at the beginning of concrete operational thought, for example. For a pre-operational child, the idea of the conservation of matter will not be developed until the appropriate developmental stage, regardless of how often the concept is experienced (Piaget, 1997).

2.2.2.4 Motivation.

One area that is critical to education that is missing within Piaget's theory construct is the role of motivation. Piaget proposed that people are inherently motivated because they have biologically developed to each stage that precedes learning (Piaget, 1970). However, as mentioned above, Vygotsky has made a compelling demonstration that learning can also lead development (Vygotsky, 1978), an idea that Piaget did not explore.

While there will be those biologically-driven cases where a person seems to suddenly know or understand a concept previously unobtainable for them, if someone is not motivated to learn, they will not explore or engage in disequilibrium. Without motivation, a person will not self-regulate (Siegler & Ellis, 1996; Vedder-Weiss & Fortus, 2012; Zeldin, Britner, & Pajares, 2008). Motivation implies some emotional investment, whether that is love of a subject, curiosity, creativity, money, guilt, or fear. Culture can also affect one's emotional investment either positively or negatively: socio-economic, family, friends, classroom, etc. (Vedder-Weiss & Fortus, 2012; Zeidler, Herman, Ruzek, Linder, & Lin, 2013).

Piaget may not have seen the impact of motivation as he was clearly motivated himself and was working with well-to-do children who were most likely already very motivated or encouraged by parents who were themselves highly motivated.

2.2.3 College chemistry students.

As we have seen, Piaget’s theory of cognitive development includes four developmental levels that each person has the potential to advance through, culminating in formal operations. Formal-operational people are no longer bound by concrete manipulation and can work in the abstract (Marek & Cavallo, 1997). To conceptualize chemistry and form links from symbolic and particulate models to macroscopic experiences, students must be able to operate at the formal level. Such formal conceptualization is especially required in chemistry where most of the topics studied are unseeable and thus abstract (Gabel, 1999).

Students in college are usually either at the concrete or formal stages as described by Piaget's theory (Piaget, 1997; Shayer, Kuchemann, & Wylam, 1976). Although they may begin to mature into formal thought in their early teens, around the age of 15 or 16, a large percentage of students in high school and college have still not reached formal capabilities (Cantu & Herron, 1978; Cracolice, 2012; Lawson & Renner, 1975; Lawson & Wollman, 1976). Pilot studies at the University of Montana indicate that only 38% of students were formal thinkers in their first semester of general chemistry, whereas 68% of the remaining students (after some students dropped the class or did not meet the prerequisite grade to continue in the sequence) were formal thinkers in the second semester (Cracolice, 2012).

The data support a hypothesis that if students are unable to think formally in general chemistry, they are much less likely to pass the first semester course. The resulting second semester is an
accumulation of formal students from the first semester and some similar percentage from all new enrolling students (Cracolice, 2012). Bird (2010) found that only 41% of students enrolled in college level general chemistry have reached the formal-operational level, suggesting that the findings are generally representative of a general lack of formal reasoning ability among incoming freshmen.

If students are not capable of formal thinking, they will be unable to fully comprehend abstract scientific concepts such as atoms, kinetics, and electromagnetism. Chemical concepts such as stoichiometry, conservation of mass, and thermodynamics are based on these concepts and therefore inaccessible to concrete thinkers. Concrete students require interaction with concrete objects and empirical reality to develop concepts, and much of chemistry cannot be readily observed; it is primarily the study of electrons and electrons cannot be observed. (Lawson & Renner, 1975).

The necessity for formal thought in science is further illustrated in research conducted by Lawson and Renner (1975) with high school science students, where they found that any students at the concrete-operational or transitional-concrete levels could not perform above chance on formal conceptual problems in biology, chemistry, or physics. They showed evidence that concrete-operational students are "unable to develop understanding of formal concepts" but formal-operational students can understand both concrete and formal concepts (p. 352). Even in this study, about 65% of high school biology students were at the concrete level. Overall, about 85% of students were considered above concrete-operational but below formal-operational, with only about 5% fully formal-operational thinkers even though the "majority of the concepts taught in three science disciplines were categorized as formal" (Lawson & Renner, 1975, p. 355).

While formal-operational thought is both required for success in chemistry and generally absent in incoming freshmen, many studies provide evidence that students can develop formal reasoning abilities.

A study conducted by Lawson and Wollman (1976) found that when they trained students in a Piagetian controlling variables task involving bending rods and controlling variables, fifth- and seventh-graders performance indicated an increase from concrete to formal thinking in that task. The training was also generalizable for other controlling variable tasks using novel objects. However, when they tested the students on nonspecific transfer tasks for concepts other than variable control that still involved concrete and formal reasoning they found formal reasoning was nontransferable. This is indicative that general understanding of formal concepts cannot be developed until students have developed to that level. Concrete students did demonstrate an inherent understanding of the controlling variables concept, but did not actually comprehend the concept; "they had a feeling for evenness, fairness, and symmetry, but not a general rule to act as a guide for behavior—i.e., they lacked the ability to use language to structure their thinking" (Lawson & Wollman, 1976, p. 427).

Cantu and Herron (1978) found similar evidence to Lawson and Renner (1975), indicating that most concepts in science are abstract and require formal-operational thought, and many students in science classes are unable to use formal thought. Cantu and Herron believe that by utilizing proper instruction techniques, many concepts in science can be understood by concrete thinkers. Nevertheless, they "do not believe that concrete-operational students will learn these ideas as well as formal-operational students, and [they] do not believe that their level of understanding will even be adequate unless the instructional procedures used to teach the concepts are carefully designed so that formal reasoning is not involved in the lesson" (p. 141). Concrete models can be
used to help students imagine formal concepts. However, unless students are fully formal, they will not obtain complete understanding.

2.2.4 Curricular tools from Piagetian constructivism.

Despite the deficit of formal thinking in college students, several curricular interventions have been reported that have bridged this gap by promoting the development of formal thought. A British study done in secondary schools demonstrated a marked improvement in formal thinking using an instructional intervention that promoted scientific reasoning skills through hands-on active learning. Students were given opportunities to collect data, construct their own understanding, and make links to previously developed knowledge (Adey & Shayer, 1990, 1993, 2011; Shayer & Adey, 1992, 1993; Shayer et al., 1976). The purpose of the intervention was to help students develop cognitive abilities that could be generalized and transferred to other subjects and provide the foundation for improved science achievement in years to come. The intervention showed that it could change students and student outcomes not only in science, although the intervention was done in science classes, the effects transferred to English and math as well (Adey & Shayer, 1993, 2011). Lawson et al. (2000) demonstrated that through an intervention focused on scientific reasoning, college general biology students could make significant gains in their scientific reasoning skills in one semester.

In addition to the external results shown here, the general chemistry course at the University of Montana reflects these same principles inferred from Piagetian constructivism to close this gap in formal thought. See Section 3.3 Brief Description of the General Chemistry Course. A one-group pretest-posttest design has been used for correlational research at the University of Montana. The Classroom Test of Scientific Reasoning (CTSR) (Lawson, 1978, 2000) was used to test students' scientific reasoning abilities as they began and completed the two-semester General Chemistry course sequence. The results demonstrated that the guided-inquiry curriculum does significantly increase students' reasoning skills over the course of two semesters (p = 0.04, Cohen's d = 0.43) (Busby & Cracolice, 2014, unpublished). Scientific reasoning ability was also one of the main predictors of success on both the American Chemical Society Examinations Institute (ACS-EI) final exam (p < 0.001) and students' final grade in the course (p = 0.002) (Busby & Cracolice, 2014, unpublished; Cracolice & Busby, 2015).

2.2.5 Summary.

Piaget's theories about cognitive development provide the foundation for understanding where students are at in their cognitive development and subsequently what concepts they can learn. To understand chemistry concepts, students must function at the formal operational level. However, most students coming into college, while maturationally capable of formal thought, are still concrete operational. Curricula have been shown to improve scientific reasoning skills and transition students into formal thought.

However, students still struggle to apply many of their developed reasoning skills and pre-existing mathematical skills. This gap in skill transfer is most evident for math skills that all first-semester general chemistry students have demonstrated some competency in, yet often struggle with even the simplest chemistry problems that can be solved by the application of those math skills.
2.3 Math

In addition to scientific reasoning skills and formal thinking ability described by Piagetian constructivism, students need strong mathematical skills for success in science (Cooper & Pearson, 2012). This conclusion is supported by Follette et al. (2015), who not only demonstrated that science courses utilize math skills, but they can also complement the development of numerical skills (Follette et al., 2015).

The concept map in Figure 3 illustrates the theory links encompassed in the research (Byrnes & Wasik, 1991; Demetriou, Spanoudis, & Shayer, 2013; Fuchs et al., 2012; Kroeger, Brown, & O'Brien, 2012; McGrew & Wendling, 2010; Nezhnov, Kardanova, Vasilyeva, & Ludlow, 2015; Pillay, Wilss, Boulton-Lewis, 1998; Primi, Ferrão, & Almeida, 2010). This map does not include all factors, but rather aims to simplify the theory of math knowledge acquisition, and it emphasizes several of the main links to math achievement.

Researchers may attribute students’ difficulty in science to poor understanding of the science rather than a lack of mathematical competency; students must be tested for "an adequate fluency in mathematics" (Leopold & Edgar, 2008, p. 724). In the case of general chemistry, mathematical fluency is defined as a student having no barrier to understanding mathematical material specific to general chemistry (Leopold & Edgar, 2008). This means that the student’s mathematical skills and literacy match or exceed those required by the content of the course.
In chemistry, both the qualitative and quantitative aspects of topics such as chemical equilibrium, energy etc., "are expressed in language liberally seasoned with conversational mathematics" (Leopold & Edgar, 2008, p. 724). Leopold and Edgar (2008) created a mathematics assessment for their second semester general chemistry students to determine level of mathematics fluency, specifically with logarithms, scientific notation, graphs, and algebra. They found that:

1. Many students were familiar with log rules, but not the meaning of the log.
2. There is a lack of comfort with scientific notation. Students would write out the full number before converting to scientific notation, denoting a lack of comfort with directly interpreting numbers in scientific notation as well as the arithmetic rules necessary for manipulation of numbers.
3. Students have a hard time extracting quantitative information from exponential or logarithmic graphs.

Quantitative examples and problems are used frequently in general chemistry. To determine the conceptual meanings behind such problems, students need a mathematical background that allows them to produce correct answers to at least the most basic math questions involving scientific notation, graphs, and algebra (Leopold & Edgar, 2008). Part of such a background depends on the level of mathematics studied in high school (Schmidt & Kaslow, 1952). Armstrong, Fielding, Kirk, and Ramage (2014) state "the single variable with the strongest positive correlation to passing [Introductory Physical and General Chemistry] is the high-school mathematics result" (p. 92). Andrews and Andrews (1979) found that math SAT scores also correlated to grades in second semester general chemistry.

At the college level, Nicoll and Francisco (2001) illustrated that performance on a math diagnostic was significantly correlated to performance on midterm exams and the overall course grade for physical chemistry. They found that the ability to solve word problems was predictive of success over that of ability to do algebra or calculus (Nicoll & Francisco, 2001). In a study of 9th and 10th grade students, Schwartz, Martin, and Pfaffman (2005) showed that use of mathematics could help develop physical knowledge. Their students interacted with balance beams and were then asked to explain the physical rule determining whether the beam was balanced. Those who were asked to explain their understanding with no direction to use mathematics had a shallower understanding of the physical rule utilizing the product of weight and distance to determine if a balance beam was balanced, than students who were directed to use mathematics in their explanation (Schwarz, Martin, & Pfaffman, 2005).

An article from the Journal of Chemical Education Editorial (Moore, 2008) states: "Mathematics is fundamental to science because a great many aspects of science are best described and elucidated using mathematical tools. Lack of preparation in mathematics hampers many students' efforts to learn science and prevents many other students from pursuing science at all" (p. 1019). Proficiency is described in this article as "conceptual understanding, ability to do tasks like addition or subtraction without thinking, accurate execution of standard algorithms, ability to solve problems, and belief that mathematics is useful, worthwhile, and something that can be learned through diligent study" (p. 1019). This means that not only are algorithmic and procedural aspects of mathematics important, but conceptual understanding is important as well (Nesher, 1986). Algorithmic solutions however, tend to be favored by students and are catered to by more conventional types of problems presented in textbooks. Problems that require unusual use of a familiar algorithm or use of logic are less conventional, and resited more by students (Gallagher, De Lisi, Holst, McGillicuddy-De Lisi, Morely, & Cahalan, 2000).
2.3.1 Math knowledge theory.

If mathematical knowledge is so important to student success in science, how is it developed? There are numerous factors that are shown to be related to learning and math. The concept map in Figure 3 was developed by the researcher to illustrate the theory links described in several articles (Byrnes & Wasik, 1991; Demetriou et al., 2013; Fuchs et al., 2012; Kroeber et al., 2012; McGrew & Wendling, 2010; Nezhnov, et al., 2015; Pillay et al., 1998; Primi et al., 2010). This map does not include all factors, but rather aims to simplify the theory of math knowledge acquisition and emphasizes several of the main links to math achievement. In the discussion below “math” refers to arithmetic, computational skills, word problems, concepts, algebra, and application of operations and concepts (McGrew & Wendling, 2010).

Overarching all other factors relating to mathematical knowledge is constructivism, which was discussed in detail above in Section 2.2 Constructivism. It provides the context in which we may understand how a student can grow in intelligence, develop scientific reasoning skills, and obtain content knowledge.

General intelligence (g-factor) is the first factor identified by math knowledge theory. This is the efficiency of the cognitive executive function and includes abilities of perception, attention (memory span), and working memory (McGrew & Wendling, 2010; Primi et al., 2010). It is measured by IQ assessments of various sorts and was measured in this research using the Raven Standard Matrices-Plus Version (SPM+), described in Section 3.5.3 Research instruments. General intelligence is related to reading and math achievement (McGrew & Wendling, 2010). Perception is related to development of fluency with math facts, memory span is related to counting numbers and mental arithmetic, and working memory is related to arithmetic and computational skills (McGrew & Wendling, 2010).

Fluid intelligence (Gf) is related to general intelligence. It is also known as fluid reasoning or scientific reasoning. Fluid intelligence is defined as "the use of deliberate mental operations to solve novel problems (i.e., tasks that cannot be performed as a function of simple memorization or routine). Such mental operations include drawing inferences, concept formation, classification, generating and testing hypothesis, identifying relations, comprehending implications, problem solving, extrapolating, and transforming information" (Primi et al., 2010, p. 446). Several of these operations relate to graphing and transfer. For this study, fluid intelligence, i.e., scientific reasoning, was measured using the Classroom Test of Scientific Reasoning (CTSR) (Lawson, 1978, 2000). See Section 3.5.3 Research instruments.

Cattell's investment theory states fluid intelligence is the foundation for crystallized intelligence, discussed below, as it supports the attainment of skills and knowledge (Primi et al., 2010). As such, fluid intelligence is perceived as "the ability to learn new information and, consequently, to adapt to novel situations;" it is seen as causal to learning (Primi et al., 2010, p. 446). Primi, Ferrão, and Almeida (2010) found that individuals with higher fluid intelligence showed a faster increase, over two years, in math scores as compared to those with lower fluid intelligence.

In early phases of learning, new information can be perceived as disorganized or disconnected. Fluid intelligence is necessary to work through such information systematically and to find patterns, allowing for the formation of new knowledge (Primi et al., 2010). High cognitive abilities are required to select, maintain, update, and reroute—assimilate and accommodate—novel or complex information (Primi et al., 2010).
Fluid intelligence is related to reading and math, with a strong predictive nature for math achievement (McGrew & Wendling, 2010; Primi et al., 2010). Comprehension of mathematical, and scientific, concepts requires formation of abstract representations of relationships between variables (Primi et al., 2010), which is also required for interpretation of graphing and problem-solving skills, such as those used in word problems. This has been shown to be impaired in people with math difficulties (McGrew & Wendling, 2010). Dementriou et al. (2013) found that there are relationships between a person's age, processing speed, working memory, and fluid intelligence, but they are dependent on developmental stage as well. They found that age-related changes in fluid intelligence are mediated by working memory at least until age 16 (Dementriou et al., 2013).

Crystallized intelligence (Gc) is supported by fluid intelligence. It can also be viewed as content knowledge as it "refers to the wealth (breadth and depth) of acquired knowledge" (Primi et al., 2010, p. 446). It includes intelligence as process (procedural knowledge) and intelligence as knowledge (declarative knowledge). Crystallized intelligence is related to reading and math, with a strong predictive nature for math achievement (McGrew & Wendling, 2010). In this study, crystallized intelligence, i.e., chemistry content knowledge, was measured using the Chemistry Content Inventory (CCI) (Mulford & Robinson, 2002). See Section 3.5.3 Research instruments.

Procedural knowledge is knowing how—steps necessary to reach a goal—whereas declarative knowledge, or conceptual knowledge, is knowing that: facts, core concepts, and concept interactions (Byrnes & Wasik, 1991). These are not one in the same; students can have high procedural knowledge and lack declarative knowledge or vice versa. However, they are related. Byrnes and Wasik (1991) conducted several experiments that supported the idea of a dynamic interaction between procedural and declarative knowledge. This means that both can enhance and enrich the other (Byrnes & Wasik, 1991).

Math achievement has already been described briefly regarding the areas of intelligence necessary for its fruition. Additionally, Kroeger, Brown, and O'Brien (2012) employed neuroscience to determine level of mathematic ability by mapping specific nonverbal, verbal, and visual mental operations. Nonverbal operations are meaning-based representations of size and distance, more vs. less, approximation tasks, and estimation engage certain regions of the brain. Verbal operations represent numbers in a verbal format, lexically, phonologically, and syntactically. It is used when rote arithmetic facts are retrieved, such as multiplication tables, and engages one area of the brain, while visual operations engage another area of the brain as it represents and spatially manipulates numbers (Kroeger et al., 2012).

These patterns are also noted to change with age. Children with math difficulties have different activations of brain regions associated with general intelligence and working memory but training on arithmetic fact retrieval can lead to changes in brain activation (Kroeger et al., 2012). Basic math achievement in this research is implied by math prerequisite courses or placement tests necessary for enrollment in the course.

The development of algebraic knowledge has been analyzed by Pillay, Wilss, and Boulton-Lewis (1998). This development starts with arithmetic—use of operations, focus on the computation of answers, and operating on numbers—and advances in abstractness to algebra. Algebra is the use of operations and the manipulation of symbolic language, or variables. Algebra focuses on relationships rather than a computed answer. Algebra procedural concepts, such as solving an equation for y, evolve into structural concepts, such as the simplification of a multi-variable equation. Thus, symbols, operations, and laws of arithmetic become generalized to concepts of the variable, equation, expression, and equality (Pillay et al., 1998). As a person continues to learn, levels of structural organization of knowledge recur in cyclical fashion for increasingly
more formal modes of learning, moving from arithmetic operations to solving logic if-then statements; “knowledge is cumulative and each stage is prerequisite to subsequent stages” (Biggs & Collis, as cited in Pillay et al., 1998, p. 90).

*Word-problem skills* incorporate use of symbolic representations in the form of numbers and language as well as calculations. Understanding the relationships between the known and unknown variables is necessary to solve such problems. Often there is difficulty using algebraic expressions when they are represented in word problems. Transforming the narratives of word problems to algebraic equations is a main source of these errors (Fuchs et al., 2012). This is an intrinsic feature of chemistry problems as they are presented as macroscopic phenomena, described in words, but solved mathematically. This requires students to translate problems from a word form to a mathematical form much of the time they are presented with a chemistry problem. The need for such problem-solving skills becomes compounded further when graphical representations are also required for conceptual understanding.

Nezhnov, Kardanova, Vasilyeva, and Ludlow (2015) have discussed Vygotsky's sociocultural theory of development, where learning leads to development, in relation to levels of academic mastery of mathematics. They identify three stages:

1. *Procedural knowledge* is the early stage. Students have a narrow extent of understanding here, primarily of specific algorithms and standard procedures. They rely on external, descriptive, features of a problem allowing for identification of a category of problem. This invokes the appropriate algorithm to be applied. Student ability to solve problems at this stage depends on the similarity of problems.

2. *Conceptual understanding* is the middle stage. Students begin to understand how to solve problems with known algorithms, as well as a range of conceptually related problems, even if format is dissimilar to the algorithmic problems. This requires understanding of mathematical principles, or fundamental relationships underlying a concept. Types of problems at this level are formulated in a way that makes it difficult to map a specific algorithm to the problem. Students need to be able to analyze the meaning of the problem, which may require transformation of the description to understand how to approach a solution.

3. *Functional competence* is the highest stage. Students acquire a depth of understanding and conceptual flexibility to mentally see the full range of possible means to solve the problem; they can identify the sequence of steps leading to a solution. They master concepts in a generalizable way to solve novel problems. This requires a comparison of multiple ways to approach a problem where the student carries out a series of mental experiments and compares the results.

The goal of this study was to investigate student ability to transfer math skills to a chemistry context. In this section, the major components necessary for students to obtain math knowledge were outlined. Specific components of math knowledge theory were measured in this research using the tools as noted here and later discussed in Chapter 3. Analogous to Section 2.2 Constructivism, that showed formal reasoning can be developed in college students, the following section on math instruction will demonstrate the same principle of instruction promoting development of math skills.
2.3.2 Math instruction.

Vass, Schiller, and Nappi (2000) worked with education majors planning to teach math and science who lacked formal reasoning and showed difficulty with proportional, probabilistic, and correlational reasoning skills. They used an intervention based on Piaget's model of cognitive development that focused on development of probabilistic and proportional reasoning. The instruction increased performance in all three areas and problem-solving skills (Vass et al., 2000). They also found that students with backgrounds in science and math performed better on all three pre- and posttests; such background correlated to better reasoning skills. They did discover that students in chemistry did not focus on underlying math skills and suggest that in future instruction of the two be tied together and connected to the real world (Vass et al., 2000). They also emphasize that scientific reasoning skill development needs to start earlier.

Influenced by Vygotsky's work, Falcade, Laborde, and Mariotti (2007) used a semiotics—study of meaningful communication through signs—computer Trace tool to explore function understanding through a teaching sequence that included lab activities, independent writing, and collective discussion. The computer Trace tool gives basic representation of variation and is meant to help construct the meaning of function. It displays a trace on the computer screen and allows different objects on the screen to be moved or displays a moving point that represents the motion of independent and dependent variable points. The tool mediated action, through use of the trace, to concept formation. They concluded that students need a construction procedure and real-world experience to develop concepts (Falcade, Laborde, & Mariotti, 2007).

Dubinsky and Wilson (2013) conducted a math intervention called the Algebra Project that utilized interactive learning for an underprivileged and underrepresented population. The project was social, hands-on, and meant to increase understanding of the concept of a function. The intervention was shown to increase understanding and decrease misconceptions (Dubinsky & Wilson, 2013). Fatokun and Fatokun (2013) used problem-based learning (PBL)—use of brainstorming and hands-on learning—as an effective way of learning in their calculus and chemistry courses. They integrated math and chemistry knowledge using life scenarios by using graph construction & interpretation to link math and chemistry knowledge and understanding.

These systems of instruction are designed to improve reasoning skills, mathematical abilities, and conceptual understanding. They each incorporate some mechanism for students to construct their own knowledge. They utilize hands-on experiences, metacognition, and social communication. They also identify a need to link different domains, such as math and chemistry, to enhance understanding.

2.4 Graphing in Science

Graphs are common tools used to communicate quantitative information. They are crucial for conveying hypotheses, data results, and other research processes (Sarto-Jackson, 2015). They are used in textbooks, scientific journals, and in the media. Students are expected to learn from such materials and "integrate information from these external representations into coherent knowledge structures." (Schnoz & Baadte, 2015, p. 605). Graphs are used to depict mathematical functions and specify scientific theories (Shah & Hoeffner, 2002). They are important because they facilitate reasoning, can be processed quickly, and the abstractions of such representations prompt conceptual advances; our brains are set up to detect patterns so extracting information from a diagram is faster and easier than just using equations (Sarto-Jackson, 2015).
Recordings of brain activity have shown that graphs, as more abstract diagrams than pictures, equations, or text, require more mental resources to process (van Leeuwen, Manalo, & van der Meij, 2015). In science, abstract diagrams are used frequently, and it is important for students to be able to use them competently (van Leeuwen et al., 2015). Students who used more abstract diagrammatic representations demonstrated greater success in mathematical problem solving compared to students who used concrete, pictorial diagrams. Students who used concrete, pictorial, diagrams demonstrated a negative correlation with success in mathematical problem solving (Hegarty & Kozhevnikov, 1999). This means that using abstract representations requires students to develop higher cognitive ability—formal reasoning—to counteract the increased cognitive cost of using the abstract representations.

Graphs are meant to make quantitative data or scientific concepts easier to understand. However, this is not always the case. Larkin and Simon (1987) found that two-dimensional representations could increase efficiency of information recognition, but only if the person possessed computational processes to recognize the relevant information. Misinterpretations are a risk when transferring between disciplines as well (Sarto-Jackson, 2015).

### 2.4.1 Construction and interpretation.

Bar graphs are introduced in elementary school. Linear graphs are usually introduced in algebra and revisited in calculus (Leinhardt et al., 1990). This means that in general chemistry, most students will have received explicit instruction on graphing during algebra two years before they arrive in general chemistry, possibly less if they took junior-level chemistry or senior-level physics, and been exposed to general graphing most of their school careers.

#### 2.4.1.1 Focus.

A student’s area of focus when creating or interacting with a graph can be described by three criteria (Leinhardt et al., 1990):

1. Construction or Interpretation
2. Global or Local
3. Qualitative or Quantitative

A student interacts with a graph in the context of either constructing it or interpreting it. While engaged in this interaction, the student will be focusing on either global phenomena or on local features. For example, a student engaged in interpreting a graph may focus on a global feature like the linearity of the graph to recognize a reaction order, or they may need to focus on a local feature to determine the amount of reactant consumed after five hours. The third criterion is qualitative or quantitative. The student observing reaction order is engaged in a qualitative observation because identification of reaction order conveys the conceptual meaning represented in the graphical representation, while the student focused on the quantity of reactant consumed is making a quantitative observation.

As we have now defined it, graphing tasks consist of what the student must do with a graph: either construction or interpretation. Both construction of graphs or interpretation of graphs can be a global or local process. Global and local processes may also be either qualitative or quantitative (Leinhardt et al., 1990).
In this work, we are interested in determining how successful students are at applying the correct combination of these criteria, or stated a different way, by using these criteria we aim to determine at which point(s) students fail to arrive at a successful interaction with a graph.

2.4.1.2 Interpretation.

Most often students are asked to interpret graphs. The interpretation task is often global so relationships and concepts can be detected. This requires a student to shift their focus from the overall graph to the algebraic equation, and then from the algebraic equation to the situation it represents—the concept (Leinhardt et al., 1990). However, students tend to overemphasize reading data points (local focus) rather than reading the whole graph (global focus) (Leinhardt et al., 1990). Bell and Janvier (1981) recommend showing qualitative graphs in instruction first, rather than having students construct quantitative graphs, so students can attend to the global concept the graph is conveying. This is often how graphs are depicted in textbooks.

For graph interpretation, students must identify important visual features and relate them to the conceptual relationship represented by those features; this is part of the mental graph schema (Sarto-Jackson, 2015; Shah & Hoeffner, 2002). Schnotz and Baadte (2015) refer to this process as structure mapping, using external features to develop a mental model, or schema. A schema in general refers to an attempt to represent reality without transforming it (Piaget, 1997).

The process of constructing schema can be biased by students' prior knowledge of graphing and prior experiences with similar data and concepts, as well as by the type of graph (Shah & Hoeffner, 2002). Shah and Freedman (2009) found that students were more likely to construct inferences about the graphs they viewed if they had prior graphing knowledge, the data were familiar, and the graph format supported the inferences. For example, students may perceive that line graphs are only used for x-y trends, bar graphs for discrete comparisons, and pie charts for relative proportions. Visual characteristics of the graph, such as animation, color, legends used, and whether it is two-dimensional or three-dimensional can also affect interpretation ability (Shah & Hoeffner, 2002). The research will be focused on construction and interpretation of two-dimensional line graphs because they are the most commonly used type of graphs in general chemistry.

The setting in which the graph is presented, i.e., mathematical or chemical, may also affect students' perspective of the graph (Leinhardt et al., 1990). In a mathematical approach, understanding local subtleties of graphs is emphasized (Leinhardt et al., 1990). In a scientific approach, graphs are representations of real observations and are used as analytical tools to detect underlying global patterns. This informs the student about the phenomena observed (Leinhardt et al., 1990). The fundamental difference in the context in which graphs are presented may be a contributing factor to students’ difficulty transferring graphing skill between contexts.

2.4.1.3 Construction.

Construction refers to the generation of something new. This includes both the construction of a graph from raw data as well as construction of the algebraic equation that describes the pattern in the data. Construction may be local or global. Local quantitative work includes matching data points and determining the slope and intercept of the equation. Global qualitative work is sketching the entire graph representing a situation (Leinhardt et al., 1990).
Construction of the algebraic equation may be the more difficult part of graph construction because it can be unclear where the student should focus and what given data would be useful to determine the equation (Leinhardt et al., 1990). This is because both global and local foci are needed. This is a valuable parameter to test because Vitale, Lai, and Linn (2015) found that graph construction provides a way to evaluate the complexity of students’ ideas about scientific data representation.

Determining choice of axes, scales, and units is part of construction. It is also part of interpretation. Both these processes must occur in parallel. For example, depending on the scale, the shape of the graph will change (Leinhardt et al., 1990). In science, certain units are more sensible to use than others, such as a log scale or amount in moles instead of mass in grams. The graph may need to be constructed, interpreted, and reconstructed to present the data clearly. Determination of axes, scales, and units requires iteration between construction and interpretation to develop an optimized graph.

### 2.4.2 Misconceptions.

Concepts are constructed in our minds and tested by our experiences. Sometimes the concepts we construct are inaccurate, or misconceptions, and can be very resistant to change. Misconceptions are repeatable and explicit incorrect features of student knowledge (Leinhardt et al., 1990). Any changes to our misconceptions must be reconstructed; they will not simply go away by being told of the error.

Several tests have been constructed to investigate specific graphing concepts. Beichner (1994) investigated students’ interpretation of kinematics graphs. He found that while calculus-based physics students performed better than those in algebra/trigonometry-based physics, high school and college students did not perform differently. The misconceptions he found were that students interpreted graphs as pictures based on the students’ assumption that if variables were changed, the graph would still look the same. He also found that students have trouble determining slopes and distinguishing slopes from areas.

Hale (2000) looked at students’ understanding of kinematics through graphs in college calculus. She found that while students understood the math involved, they did not understand the concepts the math was representing. She found that “common problems include discriminating between the slope and height of a graph and relating one type of graph to another” (Hale, 2000, p. 414). Misconceptions seemed to be based on the students’ prior experiences and could not be replaced by the teacher’s explanations; they needed to be reconstructed (Hale, 2000). Robust misconceptions were demonstrated in other contexts as well. Use of the x-axis for the y-intercept was prevalent in middle school grade levels both with the construction and interpretation of graphs (Chiu, Kessel, Moschkovich, & Munoz-Nunez, 2001; Hadjidementriou & Williams, 2008; Moschkovich, 1998).

Construction of algebraic equations is necessary for a complete interpretation of a graphed relationship. The algebraic equation for linear relationships consists of a slope and intercept. The ability to utilize proportions is necessary to calculate slope, which is related to the idea of steepness. Steepness is "a physical characteristic of the line which can be determined visually using an angle or analytically using a proportion" (Stump, as cited by Cheng, Star, and Chapin, 2013, p. 22). Cheng, Star, and Chapin (2013) found that if students did not have a conceptual understanding of ratios and proportions, they did not perform as well on a steepness test because students could not determine relevant data or understand the meaning of the slope formula.
Mevarech and Kramarsky (1997) found that Israeli 8th grade students tend towards linearity, meaning that even if a scatterplot shows a curved pattern, students will apply a straight line to the data, an observation also seen in general chemistry students at the University of Montana (Busby & Cracolice, personal observation, 2012-2016). These 8th graders showed several misconceptions about graphical construction. They drew graphs as a single point and used the same form of graph (a bar graph for example) independent of the function the data depict.

General misconceptions that Leinhardt et al. (1990) identified in their review were that students tend to gravitate toward linearity and default to straight lines even when inappropriate. They commonly see only discrete local data points rather than the continuous function that describes the overall global pattern of the data, and they have a hard time going from graph to equation. These misconceptions present as difficulties related to students’ attempts to construct and interpret graphs that represent situations.

Difficulty in the construction and interpretation of graphs has been demonstrated in several studies, which are outlined in Table 3. Tairab and Khalaf Al-Naqbi (2004) found that 10th grade science students provided poor interpretations when they were asked qualitative questions “such as giving general conclusions about the graphs or describing the trends depicted in the graphs” (p. 129). It was also observed that students were unable to “interpret interactions among variables” (p. 129). Overall, they found that students must rely on multiple strategies to interpret graphs, but often merely rely on their general observations and insights of the graphs, rather than formal reasoning. Students also demonstrated confusion on types of graphs to use, an inability to manipulate variables, and a lack of understanding of independent and dependent variables (Friel & Bright, 1996; Tairab & Khalaf Al-Naqbi, 2004).

Aberg-Bengtsson and Ottosson (2006) studied high school students in Sweden. They collected data from five schools and discovered that the overall performance of the school made a difference in the overall performance of the student, which they propose as evidence of “a more general ability as being involved in solving the diagrammatic tasks” (p. 55). Also, those who had greater mathematical understanding and those who had more knowledge of the context of each graph performed better (Aberg-Bengtsson & Ottosson, 2006). McKenzie and Padilla also noted these patterns in their 1986 test to explore seven areas of difficulty for students in 7th through 12th grade with line graphs. Their “Test of Graphing in Science” (TOGS) will be discussed in much greater detail later in Section 3.5.3 Research instruments.
### Table 3

**Summary of Research on Graphical Understanding**

<table>
<thead>
<tr>
<th>Author(s)</th>
<th># Participants</th>
<th>Design</th>
<th>Grade Level</th>
<th>Overview</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aberg-Bengtsson &amp; Ottosson (2006)</td>
<td>363</td>
<td>5 schools; Sweden</td>
<td>10th</td>
<td>Content of graphical interpretation matters</td>
</tr>
<tr>
<td>Beichner (1994)</td>
<td>895</td>
<td>Development of the test; North Carolina</td>
<td>High school &amp; college</td>
<td>Calculus-based, algebra/trig-based physics students; Test of Understanding Graphs in Kinematics (TUG-K): see graphs as pictures, trouble with slopes and areas</td>
</tr>
<tr>
<td>Cheng, Star, &amp; Chapin (2013)</td>
<td>413</td>
<td>Correlational; 1 public school; USA</td>
<td>Middle school: 6th – 8th</td>
<td>Relationship between proportional reasoning and steepness</td>
</tr>
<tr>
<td>Chui, M. M. et al. (2001)</td>
<td>1</td>
<td>Case study; California</td>
<td>8th</td>
<td>Misconception: x-axis for y-axis</td>
</tr>
<tr>
<td>Friel &amp; Bright (1996)</td>
<td>76</td>
<td>Pre- posttest design; North Carolina</td>
<td>Middle school: 6th</td>
<td>Learning concepts related to use of graphs: axes confusion, difficulty with intervals of data, visual features and wording may affect interpretation</td>
</tr>
<tr>
<td>Hadjidementriou &amp; Williams (2008)</td>
<td>425</td>
<td>Development of instrument; NW of UK</td>
<td>9th – 10th</td>
<td>Development of graphical assessment tool: graphical thinking &amp; interpretation of graphs – slope height confusion, graph as a picture, reversal of x and y coordinates, etc.</td>
</tr>
<tr>
<td>Hale (2000)</td>
<td>–</td>
<td>Review of case studies; California</td>
<td>College</td>
<td>Lack generalizability Must reconstruct concepts</td>
</tr>
<tr>
<td>McKenzie &amp; Padilla (1986)</td>
<td>377</td>
<td>Development of test; Georgia</td>
<td>7th – 12th</td>
<td>Test of Graphing in Science (TOGS): selecting axes, locating points, drawing trend lines, etc.</td>
</tr>
<tr>
<td>Mevarech &amp; Kramarsky (1997)</td>
<td>92</td>
<td>Qualitative analysis + O₁ X O₂ ; Israel</td>
<td>8th</td>
<td>Conceptions and misconceptions in graph construction</td>
</tr>
<tr>
<td>Moschkovich (1998)</td>
<td>18</td>
<td>Case studies; California</td>
<td>9th</td>
<td>Misconception: x-axis for y-axis</td>
</tr>
<tr>
<td>Potgieter, Harding, &amp; Engelbrecht (2008)</td>
<td>82</td>
<td>Test development; South Africa</td>
<td>College chemistry</td>
<td>Mathematics test and chemistry test using the Nernst equation</td>
</tr>
<tr>
<td>Tairab &amp; Khalaf Al-Naqbi (2004)</td>
<td>94; random 14 interviewed</td>
<td>Test development; British education model</td>
<td>10th; science students</td>
<td>Interpretation and construction of graphs; poor qualitative interpretations, unable to manipulate variables, etc.; United Arab Emirates &amp; Brunei schools</td>
</tr>
<tr>
<td>Teuscher &amp; Reys (2012)</td>
<td>193</td>
<td>Pre, post, delayed post; Midwest US</td>
<td>10th – 12th</td>
<td>Non-linear functions shown difficult to calculate, graph, or interpret in real-world context; lack understanding of rate of change</td>
</tr>
<tr>
<td>VanDyke &amp; White (2007)</td>
<td>&gt; 500</td>
<td>Instrument development; US</td>
<td>College</td>
<td>Calculus test to measure visual thinking skills; lack of success in calculus related to inability to work with graphs</td>
</tr>
</tbody>
</table>
2.4.3 Relation to transfer.

Students have difficulty connecting mathematical concepts with graphical representations. In her study of college calculus students and their trouble with motion graphs, Hale (2000) found that the students understood the mathematical concepts but had trouble interpreting kinematics graphs due to misconceptions based in the students' experiences (Hale, 2000). Teuscher & Reys (2012) found that students had difficulty calculating, graphing, and interpreting graphs in real-world context if the relationships were non-linear.

Interpretation of graphical representations is a specific concern for conceptual understanding in chemistry. It has been observed that students in introductory chemistry courses have difficulty with linking surface features of graphs with their physical representations. For example, students do not understand why specified variables belong on specific axes, i.e., students lack understanding of independent and dependent variables, how to determine them, and what they mean (Busby & Cracolice, personal observation, 2010-2014; Friel & Bright, 1996).

Students also have difficulty recognizing that the slope of a linear regression line tells them something about the relationship between the variables. Directly proportional relationships are common in the general chemistry curriculum, where the point (0,0) is valid as the y-intercept on the graph. However, many students are ignorant of the concept of a direct relationship necessitating a (0,0) intercept (Busby, 2016, unpublished data). Consequently, students who are unable to recognize the physical meaning underlying a graphical depiction also demonstrate a lack of understanding of foundational chemical concepts (Busby & Cracolice, personal observation, 2010-2014).

VanDyke and White (2007) developed an instrument to assess calculus ability using graphs. They found that students had no clear connection between the graph and equation of the graph for several reasons. Misconceptions about the nature of graphs and a lack of exposure to graphs as well as a lack of vocabulary, difficulty with the wording of the questions, a lack of understanding about slope (if they could calculate it), a reliance on memorized procedures, misconceptions on the role of axes, and preconceived images of the graphs all interfered with the students' interpretation of the graphs (VanDyke & White, 2007).

Much like Hale’s (2000) finding that students understood mathematical concepts but were unable to transfer that knowledge to the kinematics concepts, Potgieter, Harding, and Engelbrecht (2008) found with their math and chemistry tests of the Nernst and Henderson-Hasselbach equations that the students tested had a solid algebraic foundation. However, these South African undergraduate chemistry students demonstrated difficulties in both the mathematical and chemical application of graphical construction and interpretation. They demonstrated a lack of connectivity, which “impacts negatively on the conceptual understanding of a chemical process” (Potgieter et al., 2008, p. 214). Students had trouble graphing mathematical expressions, but “when moving to an application field such as chemistry the lack of graphical skills and of making connections in mathematics becomes more pronounced” (Potgieter et al., 2008, p. 214). This demonstrates a lack of transfer in addition to the misconceptions already discussed.

Leinhardt et al. (1990) identify several areas requiring more study: focus on tasks based both on contextualized and abstract situations, investigation of the nature or form of variables connected to the context, and investigation of graph reading and interpretation including difficulties related to construction and interpretation of graphs that represent global concepts. This work will address some of these gaps. Specifically, tasks based both on contextualized and abstract situations, and
investigation of graph reading and interpretation including difficulties related to construction and interpretation of graphs that represent global concepts.

Shah and Hoeffner (2002) posed several questions about cognitive research of graph construction, especially outside of mathematics context: What kinds of construction errors are made? Are different graph formats chosen by students for different goals? How do students' abilities to construct graphs relate to their abilities to interpret graphs, especially as it relates to data they have collected? How can critical thinking be nurtured regarding data presented in a graphical form, rather than simply information retrieval? Do students think graphs are useful or beneficial and how? What activities might promote scientific reasoning in relation to graphs? This work helps to answer these questions by specifically contributing to understanding construction errors made by students and the relationship between construction and interpretation abilities in graphing, both with data provided to students and collected by students.

In another vein, Leinhardt et al. (1990) state that there are few studies on teaching graphical topics. They suggest the use of qualitative graphs to introduce graphing to students. Up to the point of Leinhardt's review there has been no empirical data on different sequences of teaching. Shah and Hoeffner (2002) suggest studies to determine how teachers can foster student's critical thinking about data in graphs, what students think about the uses and benefits of graphs, and the role of graphs in scientific reasoning.

2.4.4 Instruction.

Although students are taught mathematical graphing skills, they often remain subject to misconceptions about graphing. The specific paths from which graphing skills can be approached and described have been studied (2.4.1 Construction and interpretation), and the difficulties students exhibit have also been thoroughly investigated (2.4.2 Misconceptions). Much of the inability to successfully create and use graphs stems from an inability to transfer the graphing skills into the context of the graph and from a lack of conceptual understanding of graphs (2.4.3 Relation to transfer). In this section, the question of how to remedy these problems is considered.

2.4.4.1 Start global – interpretation.

Instruction related to graphing can be examined on two scales: either global, with an aim of developing and linking concepts, or local, with an aim of developing and linking skills. Leinhardt et al. (1990) categorize teaching graphs into four operations: sequence of instruction and development of student conceptions, classroom setting, computer use, and teacher's content knowledge. They state that teaching involves guiding and presenting, and argue that students should be trained to see the concept and the link between algebraic formulas and the concept it represents. This would constitute promoting transfer.

Typically, graphical instruction starts either with students being asked to discover the rule, where they are given a global representation of a graph to see the pattern and interpret graphs of situations, or they are asked to generate and plot data before searching for the conceptual meaning or relationship (Leinhardt et al., 1990). The first is a global interpretation approach, the second a local to global quantitative approach, but both aim to produce a conceptual understanding.

Shah & Hoeffner (2002) agree with the first approach focused on global features. They state that to teach graphical literacy in science, graphs need to be taught in science context. Students need
to translate between representations, focus on the links between visual features and meaning, and use metacognition when reading graphs (Shah & Hoeffner, 2002). This also represents an emphasis on generalizing graphing concepts into a broader science context.

### 2.4.4.2 Start local – construction.

Tairab and Al-Naqbi (2004) conducted a study with 10th graders and found that while students performed better in interpretation than construction, interpretations were poor when students had to interpret general conclusions. Students did not use thinking skills, showed an inability to interpret interactions between variables, and could not manipulate variables or understand the difference between independent and dependent variables (Tairab & Al-Naqbi, 2004).

Roth and colleagues have conducted numerous studies over the past several decades investigating graphical instruction. Bowen and Roth’s 1998 study with college ecology students asserted that students must construct graphs to make sense of the data with the goal of constructing an argument from it. They argue that practice with graphing skills is more important to gain graphical literacy than students' level of cognitive ability (Bowen & Roth, 1998; Bowen, Roth & McGinn, 1999). Reading graphs involves recognition of all the graphical features, as well as their meanings, before students can interpret (Roth & McGinn, 1997). Roth and McGinn (1997) stipulate that a claim against student cognitive ability should not be made until other explanations do not fit.

Roth (2002) classifies conceptualization of graphing as an activity of studying local features of a graph and relating those features with meaning. He claims it is not about mental activity, but rather reading clearly. This requires familiarity with:

1. Local features.
2. Phenomena.
3. Transformations that link features with phenomena.

In 1998, Bowen and Roth videotaped lectures for undergraduate ecology courses to see how professors lecture about graphs and determine what helps or hinders student learning. They found that students must interact with others when working with graphs, and not just look at the graphs (Bowen & Roth, 1998; Bowen, et al., 1999). Students become competent graph users by constructing them, making sense of data, and constructing arguments from them (Bowen & Roth, 1998; Roth, 1996). Roth, Bowen, and Masciotra (2002) videotaped lectures for a study comparing undergraduates with experts. They concluded that graphs could be considered like texts; they can be structurally analyzed through specific features of the graph and relationships of those features. Reading graphs can become transparent when the features are known and context is familiar (Roth, Bowen, & Masciotra, 2002).

This is consistent with their earlier finding that when interpreting graphs, people can most easily understand when they draw on a "real" experience or apply a context they are familiar with. Students need experience with both specific graphs and the contexts involved with their use (Roth & Bowen, 2000). The findings are in line with findings of Piagetian constructivism that concrete experiences are necessary for the initial construction of new knowledge.

It is taken as a given that scientists need to be able to produce, read, and critique graphs. Bowen, Roth, and McGinn (1999) compared the graphical interpretation abilities of students and experts.
in biology and ecology. They found that the expert scientists drew on a large portfolio of specific resources to make judgments about graph meaning. Different concerns led scientists to draw on different resources and engage in different practices. This practice was reflexive and the experts would adjust features and content until the graphs were clear and comparable. When experts were familiar with the content of a graph, they exhibited transparent reading—the interpretation was obvious to them (Roth, 2002; Roth & Bowen, 1999, 2001, 2003; Roth et al., 2002). Students, however, used a small number of recourses compared to experts, and most students analyzed similar graphs by focusing on local points rather than the global picture (Bowen et al., 1999).

Shah, Mayer, and Hegarty (1999) discovered that while students in social science were often unable to extract the intended message when asked to describe graphs, if the graphs were revised by altering scales to something more familiar, such as percentages rather than absolute values, interpretation became easier.

2.5 Transfer

Up to this point we have discussed the theories of constructivism, math knowledge acquisition, and graphing. This section addresses transfer: What it is, what researchers have done in the past in studying it, and how that informs this study’s work to ultimately determine the ability of students to transfer math graphing skills to a chemistry context and the ability of instructional tools to promote transfer.

2.5.1 Definitions of transfer.

Transfer is a major educational goal; we want students to be provided with an education that will last a lifetime, not just for one course (Georghiades, 2000; Sasson & Dori, 2012). Transfer has been defined as the use of skills and knowledge in a different context from which it was learned originally (Bassok & Holyoak, 1989; Britton, New, Sharma, & Yardley, 2005; Roberts et al., 2007; Sasson & Dori, 2012). Chi and VanLehn (2012) describe transfer as seeing similar deep structures in source and target problems despite surface features being different, allowing an individual to consider a new concept or problem as similar to concepts or problems previously experienced. The terms source and target are used frequently in describing transfer. Target refers to a novel situation or problem that the student wants to, or needs to, solve. Source refers to the domain or context in which the student originally learned the problem-solving skills. Even negative transfer has been investigated and defined as the overgeneralization of prior learning (Schwartz, Chase, & Bransford, 2012). While there are many definitions of transfer, they each describe a common underlying process that is central to learning, and applying that learning more broadly throughout the life of the student.

Nuances of transfer definitions may change depending on the area of research. Theory descriptions of transfer may also differ from empirical research descriptions. Dori and Sasson (2013) conducted a literature review on transfer of learning up to the year 2013. They reviewed 664 peer-reviewed journal articles, where transfer was the primary issue, summarized definitions of specific forms of transfer, and categorized those definitions. Dori and Sasson (2013) found that definitions of transfer tended to be combined in pairs, so they combined definitions into seven category pairs. The following table is taken from the Dori and Sasson (2013) review and provides the definition of each category of transfer, along with attributes of that category and citations.
Table 4

Transfer Definitions and Attributes as Reproduced from Dori and Sasson (2013).

<table>
<thead>
<tr>
<th>Definition</th>
<th>Attribute</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near transfer occurs when the new learning situation is similar to a</td>
<td>Refers to similarities and differences between learning situations (TD)</td>
<td>Clark and Mayer (2008), Marton (2006), Barnett and Ceci (2002), Perkins</td>
</tr>
<tr>
<td>previous situation, and only slightly differs from it.</td>
<td></td>
<td>and Salomon (1996), Dettmerman (1993)</td>
</tr>
<tr>
<td>Far transfer occurs when the new learning situation is of different</td>
<td>Refers to the knowledge being transferred; context or contents, and skills (I + S)</td>
<td>Dettmerman (1993), Perkins and Salomon (1996)</td>
</tr>
<tr>
<td>patterns from those of previous ones.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific transfer refers to transferring contents of learning to a new</td>
<td></td>
<td></td>
</tr>
<tr>
<td>situation.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-specific or general transfer occurs when general skills or principles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>are transferred to new situations.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Negative transfer occurs when learning in one context undermines a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>performance in another context.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positive transfer occurs when learning in one context enhances a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>performance in another context.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Within-task transfer is defined as use of dimensional integration by</td>
<td>Refers to the role of instruction, comparison, and integration of skills (S)</td>
<td>Butterfield and Nelson (1991)</td>
</tr>
<tr>
<td>addition of a novel part to a task that was taught before.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Across-task transfer is used for addition of a task that had not yet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>been taught at all.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low road transfer occurs in situations similar to previous practice,</td>
<td>Refers to similarities and differences between learning situations, skills,</td>
<td>Perkins and Salomon (1987; 1996)</td>
</tr>
<tr>
<td>and is often characterized by a reflexive response in the transfer situation and little ability to verbally or otherwise symbolize the strategy or principle being applied.</td>
<td>a variety of contexts, domains, or disciplines (TD + I + S)</td>
<td></td>
</tr>
<tr>
<td>High road transfer is the application of ideas and principles in different domains, and involves deliberate abstractions from one context and application to another, leading to deliberate response and ability to describe the strategy or principle being applied.</td>
<td>Salomon and Perkins (1989)</td>
<td></td>
</tr>
<tr>
<td>Specific and short-term learning – retention: cognitive-structure that</td>
<td>Refers to the performance level in the same subject matter (I)</td>
<td>Ausubel et al. (1978)</td>
</tr>
<tr>
<td>refers to the organizational properties of the immediate and relevant concepts that affect learning and retention of relatively small units of related and new subject matter.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>General and long-term learning: cognitive-structure that refers to</td>
<td></td>
<td></td>
</tr>
<tr>
<td>significant properties of the learner's total knowledge.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical transfer requires mastering a certain level of skills in order to</td>
<td>Refers to the learning hierarchy and thinking skills (I + S)</td>
<td>Gagne (1975)</td>
</tr>
<tr>
<td>learn higher-level skills.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lateral transfer requires generalization of learning themes without</td>
<td></td>
<td></td>
</tr>
<tr>
<td>necessarily learning new skills.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Dori and Sasson (2013) further condense the seven pairs of transfer categories into three primary attributes of transfer: task distance, interdisciplinarity, and skill set. They have utilized these three main attributes to craft a theoretically founded framework for transfer. The research will focus on the aspect of task distance identified in this framework and will be looking at the ability of students to transfer math-graphing skills into a chemistry context; this constitutes a form of near transfer (Dori and Sasson, 2013).

2.5.2 The problem.

While transfer is an expected outcome and goal of education, it has been shown to be difficult for students. Society's expectation of the educational system is to provide students with the skills to both critically think and apply the knowledge they have acquired to unique situations, i.e., to transfer existing knowledge and skills to address the new problem (Educational Policies Commission, 1961). To do this, students must be able to generalize the concepts they learn in the classroom (Greeno, 2006; Holyoak & Koh, 1987; Ng & Yeung, 2012; Ng, Yeung, & Phan, 2015; Smith & Villarreal, 2015).

Unfortunately, research has shown that students are context bound; they learn a set of skills within a given context but are unable to transfer those skills (Becker & Towns, 2012; Catrambone
& Holyoak, 1989; Hester, Buxner, Elfring, & Nagy, 2014). For example, in college preparatory chemistry, it has been found that the inability to transfer math skills to chemistry solutions is a key point of student failure (Angel & LaLonde, 1998; Bridle & Yezierski, 2011; Hall, Curin-Soydan & Canelas, 2014; Wink, Gislason, McNicholas, Zusman, & Mebane, 2000). However, this point of student failure can be mitigated: When Wink, Gislason, McNicholas, Zusman, and Mebane (2000) addressed this through an integrated math and chemistry preparatory course, even though students started with lower grades than students in the traditional courses, they performed better in subsequent chemistry courses.

Students' difficulty in transferring math skills to science is not a new dilemma. Menis (1987) discusses several studies done prior to his work that provide evidence of students struggling with basic mathematical procedures in high school and university levels. Several studies also link the ability of students to master science with their ability to solve math problems (Menis, 1987).

Difficulty with transfer is seen in analogical transfer work, Table 5, where stories are used as the source and target, and we expect students to see the patterns and commonalities between them, but they do not (Catrambone & Holyoak, 1989; Gick & Holyoak, 1983; Holyoak & Koh, 1987). It is observed in the inability to transfer math skills, whether algebra, calculus, or word problems, into science contexts – biology, chemistry, computer science, and physics (Table 6) (Bassok & Holyoak, 1989; Becker & Towns, 2012; Dori, Dangur, Avargil, & Peskin, 2014; Gentner, Loewenstein, & Thompson, 2003; Hester et al., 2014; Lappalainen & Rosqvist, 2015; Marshall, 1995; Menis, 1987; Ngu & Yeung, 2012; Nicoll & Franscisco, 2001; Scott, 2012). It is also observed when transferring math skills from one math context to another, as seen in Table 7 (Cunningham, 2005; De Bock, Deprez, Van Dooren, Roelens, & Verschaffel, 2011; Kapur, 2014; Koban & Sisneros-Thiry, 2015; Richland, Stigler, & Holyoak, 2012). In addition, it is observed when students need to transfer chemical understanding across macroscopic, particulate, and symbolic levels within a science context (Dori, et al., 2014; Dori & Sasson, 2008; Grove, Cooper, & Cox, 2012; Sasson & Dori, 2012, 2015; Smith & Villarreal, 2015), or from one science context to another (Table 7) (Johnson & Rutherford, 2010; Sasson & Dori, 2015; Waight & Abd-El-Khalick, 2011), and it is seen with use of graphing between math and science contexts or within science contexts, reviewed in Table 8 (Beichner, 1994; Cunningham, 2005; Dori & Sasson, 2008; Kaminski & Sloutsky, 2013; Nemirovsky, 2011; Planinic, Milin-Sipus, Katie, Susac, & Ivanjek, 2012; Potgieter et al., 2008; Pyke, Betts, Fincham, & Anderson, 2015; Roberts et al., 2007; Sasson & Dori, 2012; Stern, Aprea, & Ebner, 2004; Terwel, van Oers, van Dijk, & van den Eden, 2009). The tables below list the research conducted in each of these areas of transfer.
### Summary of Research on Analogical Transfer

<table>
<thead>
<tr>
<th>Author(s)</th>
<th># Participants</th>
<th>Grade Level</th>
<th>Overview</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catrambone &amp; Holyoak, 1989</td>
<td>5 experiments: 77; 97; 65; 90; 23</td>
<td>University</td>
<td>Comparison of source analogs and a hint in the target help facilitate transfer</td>
</tr>
<tr>
<td>Chi &amp; Van Lehn, 2012</td>
<td>Review</td>
<td>Experts versus novices; There are two processes, initial learning and applying what was learned. Failure to transfer is due to either a lack of deep initial learning and/or a lack of seeing deep underlying structures between problems. Knowing a problem-solving procedure does not equate to understanding the deep structure of a problem. Experts see the interactions of surface features and thus underlying structure.</td>
<td></td>
</tr>
<tr>
<td>Gentner, Loewenstein, &amp; Thompson, 2003</td>
<td>3 experiments: 48; 128; 158</td>
<td>University</td>
<td>Analogical encoding fosters transfer because it allows for abstraction of relational schemas. Case studies were used for analogical transfer and comparison of more than one case study increased transfer.</td>
</tr>
<tr>
<td>Gick &amp; Holyoak, 1983</td>
<td>Review</td>
<td>Reviews research done in analogical transfer; Use of multiple source analogs helps facilitate transfer</td>
<td></td>
</tr>
<tr>
<td>Holyoak, 1985</td>
<td>Review</td>
<td>Reviews research done in analogical transfer</td>
<td></td>
</tr>
<tr>
<td>Holyoak &amp; Koh, 1987</td>
<td>21; 63</td>
<td>University</td>
<td>Surface and structural features support spontaneous transfer. However, only structural features allowed for use of the source analogue once it was pointed out as useful.</td>
</tr>
</tbody>
</table>
### Table 6

**Summary of Research on Math to Science Transfer**

<table>
<thead>
<tr>
<th>Author(s)</th>
<th># Participants</th>
<th>Grade Level</th>
<th>Overview</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bassok &amp; Holyoak, 1989</td>
<td>3 experiments: 12; 22; 38</td>
<td>9th grade; University; 9th &amp; 10th grade</td>
<td>Algebra &amp; Physics; Transferring from algebra to physics was more likely to be spontaneous due to recognition of structural similarities from a more abstract learning source domain.</td>
</tr>
<tr>
<td>Becker &amp; Towns, 2012</td>
<td>10</td>
<td>University</td>
<td>Calculus to Physical Chemistry; Prior knowledge influences transfer as well as how students frame problem solving. Students need guidance from instructors to help facilitate transfer.</td>
</tr>
<tr>
<td>Britton, New, Sharma, &amp; Yardley, 2006</td>
<td>47</td>
<td>University</td>
<td>Math to Chemistry, Physics, &amp; Computer Science; A transfer instrument was developed and quantification of transfer suggested. They found that transfer rarely occurs.</td>
</tr>
<tr>
<td>Hester, Buxner, Elfrin, &amp; Nagy, 2014</td>
<td>40</td>
<td>University</td>
<td>Math to Biology; Students could not transfer prerequisite math skills to biology so the instructors designed a biology course that integrated math. Students in the integrated course had greater gains in transfer than those in regular biology courses. They also had comparable gains in biology content so inclusion of math did not affect biology learning.</td>
</tr>
<tr>
<td>Lappalainen &amp; Rosqvist, 2015</td>
<td>8</td>
<td>University</td>
<td>Math to Computer Science; Students were grouped into three groups based on their awareness of past experiences and current problems. Those with greater awareness could transfer more consistently.</td>
</tr>
<tr>
<td>Menis, 1987</td>
<td>85</td>
<td>11th grade</td>
<td>Math to Chemistry; Only students at a formal thinking level or high transitional level could transfer math skills. Math achievement requires mastery of math concepts and problem solving experience. Level of math achievement must be higher than what is being asked in chemistry.</td>
</tr>
<tr>
<td>Ng &amp; Yeung, 2012</td>
<td>4 experiments: 23; 33; 40; 43</td>
<td>11th grade</td>
<td>Math to Chemistry; Multiple components that address the four critical tasks necessary for transfer, as determined by Holyoak and colleagues, increase transfer. The main component and two sub-components (categorization and hint) at least, are required for transfer to occur. Worked examples do not facilitate transfer.</td>
</tr>
<tr>
<td>Ng &amp; Yeung, 2015</td>
<td>26</td>
<td>11th grade</td>
<td>Math to Chemistry; Text editing draws attention to underlying problem structure, even with no computation, and helps facilitate transfer. Worked examples do not facilitate transfer.</td>
</tr>
<tr>
<td>Nicoll &amp; Francesisco, 2001</td>
<td>77</td>
<td>University</td>
<td>Math to Chemistry; Performance in physical chemistry is a function of logical thinking skills. This is supported by the math diagnostic that showed word problems were highly correlated to chemistry performance – algebra and calculus were not significantly correlated. Student perceptions of their abilities were not correlated.</td>
</tr>
<tr>
<td>Sasson &amp; Dori, 2012</td>
<td>Review</td>
<td></td>
<td>There is a disagreement about the definition of transfer based on several dimensions incorporated into transfer. Using case studies has been shown to help facilitate transfer. A three-dimensional transfer model is proposed.</td>
</tr>
<tr>
<td>Scott, 2012</td>
<td>52</td>
<td>11th grade</td>
<td>Math to Chemistry; Math skills were the problem rather than transfer. Students made arithmetical mistakes, did not understand division, could not or did not perform unit conversions, were unable to extract and manipulate information from a table, and were unable to use ratios. It appears math skills are not understood so used algorithmically.</td>
</tr>
</tbody>
</table>
## Table 7

### Summary of Research on Within Subject Transfer

<table>
<thead>
<tr>
<th>Author(s)</th>
<th># Participants</th>
<th>Grade Level</th>
<th>Overview</th>
</tr>
</thead>
<tbody>
<tr>
<td>De Bock, Deprez, Van Dooren, Roelens, &amp; Verschaffel, 2011</td>
<td>130</td>
<td>University</td>
<td>Math; Students can transfer from abstract to abstract domains or concrete to concrete domains, i.e. within context. However, some students who worked in a concrete source domain reached a higher level of abstraction by forming context-independent rules.</td>
</tr>
<tr>
<td>Dori, Dangur, Avargil, &amp; Peskin, 2014</td>
<td>122 HS honors students &amp; 65 undergrads</td>
<td>High school &amp; University</td>
<td>Chemistry; Visual &amp; Textual Chemical Understanding, Graphing, &amp; Far Transfer: Scientific reasoning is required for chemical understanding, graphing, and transfer. Use of a visual-conceptual teaching approach with real-life applications improves chemical understanding and graphing. Transfer may require more explicit instruction.</td>
</tr>
<tr>
<td>Dori &amp; Sasson, 2008</td>
<td>857; 3-years</td>
<td>12th grade; honors</td>
<td>Chemistry; Use of a case-based computerized laboratory improved graphing and chemical understanding retention skills, and transfer between visual and textual representations.</td>
</tr>
<tr>
<td>Dori &amp; Sasson, 2013</td>
<td>Review; 664 papers</td>
<td>Chemistry; Development of a theoretical transfer framework</td>
<td></td>
</tr>
<tr>
<td>Grove, Cooper, &amp; Cox, 2012</td>
<td>399</td>
<td>University</td>
<td>Organic Chemistry; Use of mechanisms helps facilitate transfer within synthesis reactions.</td>
</tr>
<tr>
<td>Johnson &amp; Rutherford, 2010</td>
<td>104</td>
<td>Pre-service teachers</td>
<td>Chemistry to Earth Science; Pre-service teachers with earth science knowledge recognized it as being applicable only to earth science questions, not chemistry. Those with more chemistry background realized more often that the underlying structure of earth science questions was chemistry.</td>
</tr>
<tr>
<td>Kapur, 2014</td>
<td>2 experiments: 75; 111</td>
<td>9th grade</td>
<td>Math; Students who engage in problem solving before being taught a concept demonstrated greater conceptual understanding and increased ability to transfer as opposed to being taught concepts prior to problem solving. Practice and construction also help with conceptual understanding and transfer.</td>
</tr>
<tr>
<td>Koban &amp; Sisneros-Thiry, 2015</td>
<td>252</td>
<td>University</td>
<td>Math; Use of FOIL is only understood by about half the students who use it. Students have trouble transferring the FOIL concept from one type of problem to another. Transfer requires both procedural success and good attitude toward math.</td>
</tr>
<tr>
<td>Marshall, 1995</td>
<td>Book</td>
<td>Math; Reviews schemas in problem solving. Key words can be misleading and detract attention from the underlying problem structure.</td>
<td></td>
</tr>
<tr>
<td>Richland, Stigler, &amp; Holyoak, 2012</td>
<td>Review</td>
<td>K-12; University</td>
<td>Math; K-12 instruction should be such that students are able to develop connections through comparisons of relational problems. What is found in university is that students prefer to utilize memorized, often incorrect, procedures. There is a need to develop schemas through analogical reasoning. Even if instructional opportunities are presented students are likely to not take advantage of them. Reasoning skills must be developed.</td>
</tr>
<tr>
<td>Sasson &amp; Dori, 2015</td>
<td>2 experiments: 670; 50</td>
<td>12th grade; 9th grade</td>
<td>Chemistry &amp; Other Sciences; Application of the three-dimensional transfer framework. A computerized chemistry lab program helped improve transfer and low achievers showed higher gain. Learning is a life-long process and transfer is essential for such learning. Algorithmic learning is no longer enough. Complex learning must take place that requires integration of knowledge, skills, and transfer to new contexts and life.</td>
</tr>
<tr>
<td>Smith &amp; Villarreal, 2015</td>
<td>155</td>
<td>University</td>
<td>General Chemistry; Use of animations did not help students lose all misconceptions about particulate movement and did not help facilitate transfer.</td>
</tr>
<tr>
<td>Waight &amp; Abd-El-Khalick, 2011</td>
<td>30</td>
<td>HS &amp; University</td>
<td>Science, Technology, Engineering, and Math; Integration of disciplines and technology can help with precollege science teaching.</td>
</tr>
</tbody>
</table>
## Table 8

### Summary of Research on Graphical Transfer

<table>
<thead>
<tr>
<th>Author(s)</th>
<th># Participants</th>
<th>Grade Level</th>
<th>Overview</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beichner, 1994</td>
<td>895</td>
<td>HS &amp; University</td>
<td>Kinematics graphing test developed. Students are not able to interpret kinematics graphs, although calculus-based students performed higher than algebra-based students. There are many misconceptions about graph interpretation.</td>
</tr>
<tr>
<td>Cunningham, 2005</td>
<td>28</td>
<td>Algebra teachers</td>
<td>Math &amp; Graphing; Teachers focus least on transfer between graphic to numeric problems and students have the most trouble with these. To understand functions transfer between algebraic, numeric, and graphics are necessary.</td>
</tr>
<tr>
<td>Dori &amp; Sasson, 2008</td>
<td>857; 3-years</td>
<td>12th grade; honors</td>
<td>Chemistry; Use of a case-based computerized laboratory improved graphing and chemical understanding retention skills, and transfer between visual and textual representations.</td>
</tr>
<tr>
<td>Kaminski &amp; Sloutsky, 2013</td>
<td>4 experiments:</td>
<td>Kindergarten</td>
<td>Math; Perceptual information is often included in problems to help them be engaging; however, it can deter from noticing the deeper structure. Interference effects were reduced with age.</td>
</tr>
<tr>
<td>Planinic, Milin-Sipus, Katic, Susac, &amp; Ivanjek, 2012</td>
<td>114</td>
<td>HS</td>
<td>Line graphs in Physics &amp; Math; Students performed higher on the math graphing than the physics graphing. Transfer was an issue rather than a lack of mathematical skills. There were also misconceptions about graph interpretations.</td>
</tr>
<tr>
<td>Potgieter, Harding, &amp; Engelbrecht, 2008</td>
<td>82</td>
<td>University</td>
<td>Math to Chemistry; An instrument was designed based on the Nernst equation. Algebraic problems were not an issue; however, graphical construction and interpretation skills were poor. The problem seems to be at the mathematical side rather than transfer of math.</td>
</tr>
<tr>
<td>Pyke, Betts, Fincham, &amp; Anderson, 2015</td>
<td>49</td>
<td>University</td>
<td>Math Graphing; Groups could solve trained problems learned via formulas or graphs. Those who learned by graphs mentally associated problems with visuo-spatial referents and performed higher on relational problems.</td>
</tr>
<tr>
<td>Roberts, Sharma, Britton, &amp; New, 2007</td>
<td>49</td>
<td>University</td>
<td>Math to Physics; Developed a transfer index to measure transfer. They found that the correlation between graphing and transfer was one of the strongest in addition to prior math knowledge.</td>
</tr>
<tr>
<td>Stern, Aprea, &amp; Ebner, 2004</td>
<td>281</td>
<td>University &amp; Vocational</td>
<td>Economics &amp; Linear Graphs; Active construction of graphs was a powerful tool for transfer as compared to passive interpretation or use of no graph.</td>
</tr>
<tr>
<td>Terwel, Oers, Van Dijk, &amp; van den Eden, 2009</td>
<td>239</td>
<td>5th grade</td>
<td>Math Graphing; Students who constructed their own graphs showed higher ability to transfer than those who were provided with graphs.</td>
</tr>
</tbody>
</table>

The narrative across these studies is that students must first learn skills from the source domain—and then transfer those skills to another context. Ability to transfer involves construction of a mental schema that links the underlying problem structure of both the source and target problems. There are several instructional methods that have been explored to help improve transfer and schema construction. In general, quality of transfer relies on the quality of students’ source knowledge, their level of scientific reasoning, schema construction, and instructional tools. Each of these topics will be discussed in sections below and the relationships illustrated in Figure 4.
2.5.3 Source knowledge: Prior knowledge and practice.

To succeed in chemistry, prerequisite knowledge is crucial (Bassok & Holyoak, 1989; Menis, 1987; Potgieter et al., 2008; Scott, 2012). Terwel, van Oers, Van Dijk, and van den Eden (2009) found that 50% of the variance in their measured transfer was based on what students came in knowing as measured by the pretest. Initial learning is facilitated by level of scientific reasoning, which is also correlated to chemistry performance (Cracolice & Busby, 2015; Menis, 1987; Nicoll & Franscisco, 2001) and the ability to transfer (Dori & Sasson, 2008; Kapur, 2014; Lappalainen & Rosqvist, 2015; Menis, 1987; Nicoll & Franscisco, 2001; Roberts et al., 2007; Sasson & Dori, 2012). Scientific reasoning can be measured to quantify students' level of formal reasoning, or ability to comprehend abstract ideas. Menis (1987) found that over 80% of students who were at a formal level of thought could transfer math skills into a chemistry context as opposed to 20-50% of students at a transitional level and 4-14% of students who were concrete.

Ability to transfer math skills also determines success in chemistry (Menis, 1987; Nicoll & Franscisco, 2001). Menis (1987) found that only one third of students could transfer their math skills into a chemistry context. This number correlates to the percentage of students found to be concrete (that is, unable to comprehend abstract ideas) in first semester general chemistry (Bird, 2010; Cracolice, 2012; McKinnon & Renner, 1971).

To succeed in chemistry, students need to have mastered fundamental math skills. These are abstract ideas, which are being applied to chemistry—also an abstract topic. Fundamental math skills are described by Denny (1971) as listed in Table 9 below:

<table>
<thead>
<tr>
<th>Math Skills</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computation</td>
</tr>
<tr>
<td>Use of parentheses</td>
</tr>
<tr>
<td>Signed number usage</td>
</tr>
<tr>
<td>Use &amp; manipulation of fractions</td>
</tr>
<tr>
<td>Use &amp; manipulation of decimals</td>
</tr>
<tr>
<td>Use &amp; manipulation of numbers with exponents or logarithms</td>
</tr>
<tr>
<td>Use of percentage</td>
</tr>
<tr>
<td>Manipulation of one-variable equations</td>
</tr>
<tr>
<td>Use of ratio &amp; proportion</td>
</tr>
<tr>
<td>Producing &amp; interpreting x, y graphs</td>
</tr>
</tbody>
</table>
Graphs provide a conceptual link between math and chemistry. The study will explore math-graphing skills specifically, which include processing data, constructing graphs, describing and interpreting graphical representations, comparing between graphs, and drawing conclusions. These graph skills require formal thinking as well as chemical understanding over four levels: macroscopic, particulate, symbolic, and process. (Dori & Sasson, 2008; Sasson & Dori, 2012). Potgieter, Harding, and Engelbrecht (2008) found that students in undergraduate chemistry, when working with the Nernst equation, had poor math skills, poor graphing skills in both math and chemistry, and poor connection of those skills between their algebra and graphs.

Not only do students need to "know" these skills, they need to understand them. Source skills cannot just be memorized for a particular course; they must be constructed and retained by the learner (Grove et al., 2012; Richland et al., 2012). Such conceptual understanding is a form of higher-level competence. Students tend to focus on algorithms rather than understanding, so when math skills are not generalized, breakdown in problem solving is often the result of arithmetic and other basic math mistakes (Koban & Sisneros-Thiry, 2015; Scott, 2012). Competence in math, whether in conceptual understanding or actual level of math, needs to be at a higher level than that in the context the student is transferring the skills to (Bassok & Holyoak, 1989; Menis, 1987; Scott, 2012; Stern et al., 2004). This leads to generalization of source skills and thus transfer (Bassok & Holyoak, 1989; Ng & Yeung, 2012).

Unfortunately, people have difficulty with transfer because they are context bound (Beauford, 2009; Catrambone & Holyoak, 1989; Johnson & Rutherford, 2010; Planinic et al., 2012; Roberts et al., 2007). Bassok and Holyoak (1989) found that 72% of students could transfer their math skills into a physics context but only 10% of students were able to transfer their physics skills into math context. They determined that students trained initially in physics were encoding content cues as required conditions rather than generalizing the underlying structure, which reduces ability to transfer (Bassok & Holyoak, 1989). There have been several studies done to investigate ability to transfer after a time delay as well (Bassok & Holyoak, 1989; Catrambone & Holyoak, 1989; Holyoak & Koh, 1987). It was found that the shift in context, not the time delay, was the biggest obstacle for transfer (Catrambone & Holyoak, 1989). To help students generalize they need to practice and train in algebraic equations and word problems; this helps students learn to ignore irrelevant details in problems and focus on the underlying structure (Bassok & Holyoak, 1989; Kaminski & Sloutsky, 2013; Kapur, 2014).

In addition to the necessity for practice in the mathematical source domain, specific guidance and practice in the science target domain may also be helpful. Students were unable to spontaneously transfer their math skills to the target domains (Becker & Towns, 2012; Catrambone & Holyoak, 1989; Hester et al., 2014). Interdisciplinary work with professors in math, physics, and chemistry can help students transfer math to chemistry (Beauford, 2009; Becker and Towns, 2012; Waight & Abd-El-Khalick, 2010). Hester, Buxner, Elfring, and Nagy (2014) found that integrating math into the target subject was helpful for students' ability to transfer by the end of the course.

These aspects of developing source knowledge and recommendations for facilitating that learning are important. Students cannot transfer knowledge if they do not own it to begin with. However, they must also be able to recognize the knowledge they already have and connect it to the subject they need to transfer to. This requires them to construct schemas.

### 2.5.4 Schema construction.

A schema is a generalized mental model, or a mapped structure that has common characteristics
within both the source and target problems that represents that subset of problems (Gick & Holyoak, 1983; Holyoak, 1985). Schema construction can be broken into accessibility to prior knowledge and construction of links between the prior knowledge and the target problem.

### 2.5.4.1 Access to prior knowledge.

For transfer to occur, prior knowledge must be accessed and students need to link the prior knowledge to the target problem. Bassok and Holyoak (1989) declared that three classes of information are needed to foster access to relevant prior knowledge:

1. **Surface content**: Prominent features of the specific domain (also Chi & VanLehn, 2012).
2. **Underlying structure**: Less salient features, often relational and associated to the factors necessary to solve the problem.
3. **Context**: Comes from the situation where the initial information, or source domain information, was encoded.

Four relational levels between the source and target problems have been identified regarding algebra word problems, but they also provide a good overview for transfer problems in general (Reed, 1987; Ngu & Yeung, 2012):

1. **Equivalent Problems** have similar surface and structural features.
2. **Isomorphic Problems** have the same structural features and dissimilar surface features.
3. **Similar Problems** have the same surface features and dissimilar structural features.
4. **Unrelated Problems** have both dissimilar surface and structural features.

When working with Equivalent Problems, Holyoak and Koh (1987) found that 69% of students spontaneously generated solutions to the target problem from the source analog. If surface or structural features were reduced between the two problems, transfer was impaired, and if both were dissimilar—Unrelated Problems—only 15% spontaneously generated a solution (Holyoak & Koh, 1987). They found that both surface similarities and structure similarities aid in retrieval and use of source analogs, but that, while structural dissimilarity impaired transfer even after a hint to notice the source analog, surface dissimilarity did not affect transfer after the hint was provided (Holyoak & Koh, 1987). That said, surface similarity only impacts retrieval, whereas structural similarity impacts both retrieval and mapping. If a person has trouble distinguishing between surface and structural differences, then surface differences will impair transfer (Holyoak & Koh, 1987).

Differences in the source and target analogs that do not alter the causal aspects of the analog are structure preserving and are typically differences in surface features. Differences that do not maintain the causal aspects are structure-violating and make a student incapable of relating their schema to the analog (Gick & Holyoak, 1983; Holyoak & Koh, 1987). Holyoak and Koh (1987) state, "the more the problem solver is able to identify and focus on the causally relevant aspects of the target problem, the greater the probability that a useful but remote analogue will be retrieved" (p. 334).

These aspects of transfer occur within a subject context. Relevant prior knowledge must come from the context where the original information was encoded. For example, most students first encode graphing knowledge in a math context. If the context of the transfer task differs significantly from the source (e.g., chemistry context), transfer can be impaired (Becker &
Towns, 2012; Bassok & Holyoak, 1989; Catrambone & Holyoak, 1989; Hester et al., 2014; Johnson & Rutherford, 2010; Ngu & Yeung, 2012; Reed, 1987). Context is not limited to physical components, but also refers to the expectations and perceptions people have of the problem-solving task, which will influence access to prior knowledge (Bassok & Holyoak, 1989; Beauford, 2009; Hester et al., 2014; Holyoak, 1985; Nemirovsky, 2011). For example, Bassok and Holyoak (1989) discuss that while physics is learned in context of school, and students can apply that knowledge to other textbook examples, that does not mean they will be able to apply the knowledge to everyday situations. Here the real world is a different context in which students face different expectations for problem solutions. Hester, Buxner, Elfring, and Nagy (2014) found that their students' perception of math being irrelevant in biology influenced their ability to transfer.

2.5.4.2 Constructing links to prior knowledge.

Previously, it was mentioned that students have trouble transferring analogies as a specific area of transfer to be studied. However, analogical transfer can also describe the general concepts and means of transfer. In its truest sense, analogical transfer utilizes analogies, or comparable stories, where the underlying structure of the stories is similar. Analogical transfer is an umbrella term for transfer between math and science, math and math, science and science, etc. While it was originally used to describe transfer between analogous stories, the theory does apply to transfer in general.

The function of an analogy is to determine a new solution, hypothesis, or prediction. To achieve that, the person working to solve the new problem must take notice of similarities between a known problem and the new, unsolved problem to construct the ‘map’ (Gick & Holyoak, 1983). Holyoak (1985) identifies four iterative steps to problem solving.

1. Construct a mental representation for the source and target problems.
2. Select an appropriate source problem.
3. Map components of the source and target problems.
4. Extend mapping to generate a solution to the target.

In their seminal 1983 paper, Gick and Holyoak state "The essence of analogical thinking is the transfer of knowledge from one situation to another by a process of mapping – finding a set of one-to-one correspondences (often incomplete) between aspects of one body of information and aspects of another" (Gick & Holyoak, 1983, p. 2). Mapping the underlying structure consists of identifying components that are causal of the outcome and is necessary for generalization and transfer to take place (De Bock et al., 2011; Gick & Holyoak, 1983; Holyoak & Koh, 1987; Ngu & Yeung, 2012; Ngu et al., 2015; Terwel et al., 2009). Similar surface features can be helpful with selection of an appropriate source problem (Task 2 above), but are not helpful in mapping for transfer to occur (Bassok & Holyoak, 1989; Catrambone & Holyoak, 1989; Gick & Holyoak, 1983; Holyoak & Koh, 1987). To understand mapping at an operational level, we must first discuss how our minds process new information within the lens of transfer.

Much like Piaget, Holyoak recognizes that human intelligence is adaptive. Current knowledge of a system can be modified based on environmental feedback (Holyoak, 1985; Piaget, 1977). However, if our systems of knowledge get stuck in extreme domain specificity, even small changes to the system will require large efforts to incorporate new knowledge (Holyoak, 1985).
Holyoak terms this transformation of existing knowledge as induction, the "inferential processes that expand knowledge in the face of uncertainty" (Holyoak, 1985, p. 60). Piaget uses the terms assimilate and accommodate, but the principle is the same. Without induction, such brittleness of mind will result in students being unable to transfer knowledge to new situations and problems (Holyoak, 1985).

For induction to take place, the new information must be relevant to the overall goal of the current system of knowledge. Ultimately, a system of knowledge must provide accurate predictions of an outcome for it to be of use either in the classroom or the real world. Mental models are representations of parts of the environment that "generates predications about its expected behavior" (Holyoak, 1985, p. 62). For this process of induction and mental model update to take place, information moves through a feedback loop in our minds. First, predications are made about a situation based on the student's current system of prior knowledge. Second, a comparison is made between those predications and the new information received from the environment (Holyoak, 1985). Finally, if the comparison lines up and the predication is accurate, induction will not take place. However, if the comparison between prior knowledge and environmental feedback does not match, induction will be triggered and update the current mental model—if the student allows it. The researcher developed a model of this theory of induction based on Holyoak's work as displayed in Figure 5.

![Development of a schema. Map of processes contributing to induction to transform a mental model into a schema.](image)

Schema induction is essentially discarding differences noted between the source and target while preserving the similarities (Gick & Holyoak, 1983; Holyoak & Koh, 1987; Ngu & Yeung, 2012). Unsurprisingly, schema production and quality is a predictor of immediate transfer (Catrambone & Holyoak, 1989; Gick & Holyoak, 1983; Ngu & Yeung, 2012). Students showed a significant difference for transferring more difficult problems as compared to simpler problems (Grove et al., 2012; Ngu & Yeung, 2012; Terwel et al., 2009). Simpler problems would not require such a generalized schema; the more generalized the schema, the better the transfer (Ngu & Yeung, 2012; Ngu et al., 2015; Terwel et al., 2009).

Transformation of a schema can be considered the final step of transfer (Gick & Holyoak, 1983; Holyoak, 1985). This results in a generalized mental model that facilitates novel problem solving. This process is illustrated below in Figure 6. The pattern is like Vygotsky's three stages of social development discussed in Section 2.3.1 Math knowledge theory, where the third stage reaches a generalization of concepts that allows novel problems to be solved.
Figure 6. Development of a generalized schema. This allows a person to solve novel problems within a category. This occurs via induction of separate source and target mental models to create a schema linking commonalities between the source and target. Induction occurs again to further generalize the schema.

No induction can take place if the student is not aware of his or her mental schemas, which is necessary for transfer to occur (Lappalainen & Rosqvist, 2015; Ngu et al., 2015; Terwel et al., 2009). While investigating transfer, Lappalainen and Rosqvist (2015) categorized students into three groups based on their awareness of linkages between past and current situations. They found that a nonconscious student does not "explicitly indicate associations between past experience and current situation," an unactionable student "indicates connections to past experiences, but fails to apply them successfully in the current context," and an actionable student "indicates connections to past experiences and successfully draws on it while solving the current problem" (Lappalainen & Rosqvist, 2015, p. 411). None of the students in the nonconscious associations group could complete a solution and seemed to have primary connections to surface learning and memorization. Students who were more aware of their current mental schema were more likely to transfer their current knowledge; most of the actionable students could solve the target problem (Lappalainen & Rosqvist, 2015).

The schema provides the mechanism for analogical transfer because through it the person accesses potential retrieval cues. However, if the schema is not at least partially abstracted, retrieval becomes more difficult; it is easier to map an analog to a schema, which involves only similarities, versus mapping an analog to another analog, which would involve both similarities and differences (Gick & Holyoak, 1983).

Students require source knowledge to be able to transfer certain possessed skills, and they must be able to construct useful, generalized schemas to build connections between their source and target to transfer. Transfer is still a huge issue for students despite it being an educational goal, consequently instructors must incorporate instructional tools to help facilitate transfer. The following section will review findings that have already been shown to help students improve their ability to transfer.

2.5.5 Instructional tools.

Instruction should emphasize four critical tasks, as determined by Holyoak and colleagues, and discussed in the previous section, which are necessary for analogical transfer (Holyoak, 1985):

1. Construct a mental representation for the source and target problems.
2. Select an appropriate source problem.
3. Map components of the source and target problems.
4. Extend mapping to generate a solution to the target.

Anything that helps draw attention to the underlying structure of the source and target problems will help with the mapping (Gick & Holyoak, 1983; Holyoak & Koh, 1987; Ngu & Yeung, 2012;
Ngu et al., 2015; Terwel et al., 2009). Several instructional tools have been identified to help improve students' ability to transfer. They are listed in Table 10 below.

Table 10

List of Instructional Tools

<table>
<thead>
<tr>
<th>Instructional Tools</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source example</td>
<td>Holyoak &amp; Koh, 1987</td>
</tr>
<tr>
<td>Multiple source examples</td>
<td>Catrambone &amp; Holyoak, 1989; Gentner, Leowenstein, &amp; Thompson, 2003; Gick &amp; Holyoak, 1983</td>
</tr>
<tr>
<td>Comparison of source examples</td>
<td>Catrambone &amp; Holyoak, 1989; Richland, Stigler, &amp; Holyoak, 2012</td>
</tr>
<tr>
<td>Reading ideal solutions for the target after solving</td>
<td>Catrambone &amp; Holyoak, 1989</td>
</tr>
<tr>
<td>Multiple components:</td>
<td>Bassok &amp; Holyoak, 1989; Catrambone &amp; Holyoak, 1989; Dori et al, 2014; Gentner, Loewenstein, &amp; Thompson, 2003; Gick &amp; Holyoak, 1983; Holyoak &amp; Koh, 1987; Richland, Stigler, &amp; Holyoak, 2012</td>
</tr>
<tr>
<td>Text editing</td>
<td>Ngu, Yeung, &amp; Phan, 2015</td>
</tr>
<tr>
<td>Use of similar problem wording</td>
<td>Catrambone &amp; Holyoak, 1989</td>
</tr>
<tr>
<td>Integrated courses</td>
<td>Hester, Buxner, Elfring, &amp; Nagy, 2014</td>
</tr>
<tr>
<td>Case studies</td>
<td>Dori, Dangur, Avargil, &amp; Peskin, 2014; Dori &amp; Sasson, 2008; Sasson &amp; Dori, 2012</td>
</tr>
</tbody>
</table>

It may seem obvious, but to transfer, a source example or analogy is necessary (Holyoak & Koh, 1987). Holyoak & Koh (1987) found that only 10% of students produced a solution to a target problem if they did not have an analogical source example versus 80% of students who were able to transfer when they did. Multiple source examples are also helpful (Catrambone & Holyoak, 1989; Gentner et al., 2003; Gick & Holyoak, 1983), and comparison of examples draws attention to the underlying structure to help facilitate schema construction (Catrambone & Holyoak, 1989; Richland, Stigler, & Holyoak, 2012). While multiple examples are helpful, multiple contexts for those examples are not necessary (Bassok and Holyoak, 1989).

Also, reading a solution for the problems after comparison and solving target problems has been shown to help with subsequent transfer, even before a hint is given (Catrambone & Holyoak, 1989). Examples and summaries of the components with the source and target must be crafted to draw attention to the underlying structure (Ngu & Yeung, 2012), and multiple components are necessary to advance a student through the four stages of transfer given above (Gentner et al., 2003; Marshall, 1995; Ngu & Yeung, 2012).

Four components that have been identified as contributing to analogical transfer are: the use of symbolic equations (Ngu & Yeung, 2012); categorizing statements in the source and target (Gick & Holyoak, 1983; Marshall, 1995; Ngu & Yeung, 2012); a hint in the target domain linking to a feature in the source (Catrambone & Holyoak, 1989; Gick & Holyoak, 1983; Holyoak & Koh, 1987; Ngu & Yeung, 2012); and practicing the construction of the symbolic equations in the first component (Bassok & Holyoak, 1989; Dori et al, 2014; Ngu & Yeung, 2012).

Ngu and Yeung (2012) found that accurate construction of symbolic equations during the acquisition phase – learning from the source examples – correlated to accurate transfer, and that categorization links the problem to a category, helping with retrieval of the source – Task 2 – as well as helping with construction of a mental representation – Task 1. This means that designing source instruction (math skills for example) to emphasize the underlying features of the skills
should promote future skill transfer and improve student outcomes in other courses by way of the improved transfer.

The role of hints in the instructional promotion of transfer has been identified as a key requirement. It primarily acts as a retrieval cue for the source (Catrambone & Holyoak, 1989; Ngu & Yeung, 2012), pointing out the linkage of underlying structure between the source and target schema. This provides an intermediate stage for students to experience transfer without having yet fully developed the ability to construct good enough schema to achieve autonomous transfer.

Gick and Holyoak illustrate this in their 1983 paper by looking at students' schema production after asking them to summarize a source analog. They found that only 21% of students produced a good schema, 20% were intermediate, and 59% were poor. Of those with a good schema though, 91% produced a solution without a hint and 100% did after a hint was provided. Only 30% of poor schema students produced a solution prior to a hint. However, the hint allowed 70% of these students to produce a solution after the hint was provided.

Holyoak and Koh (1987) later found that both surface and structure similarities aid in retrieval and use of source analogs, but that, while structural dissimilarity impaired total transfer – transfer included after a hint to notice the source analog – surface dissimilarity did not affect total transfer after the hint was provided (Holyoak & Koh, 1987). This further suggests that hints are a viable tool to enable students to work their way into a fuller capacity to transfer. Catrambone and Holyoak (1989) found that since there was a much greater percent transfer following the hint it indicates that structural features relevant to the solution were still available in the memory even after a week delay, meaning that students still had source features present in their memory, ready to be retrieved.

Consistent with the use of symbolic equations, categorizing statements in the source and target, and the concept of practice, text editing has also been shown to increase transfer as it helps students focus on relevant information and thus the problem structure (Ngu et al., 2015). This focus on underlying problem structure is also seen in graphing, where construction of graphs or other external representations, rather than having them provided, increases transfer and the ability to solve new problems, as it forces students to think about the basic structure (Stern et al., 2004; Terwel et al., 2009). There are also specific ways problems can be worded and set up to help draw students' attention to underlying problem structure and thus facilitate retrieval of prior source knowledge and development of good schema construction. If problems can be worded in such a way as to resemble each other it can also draw attention to structural similarities and help with schema development (Catrambone & Holyoak, 1989).

Specific learning environments utilizing constructivism and social interactions based on work by Piaget and Vygotsky have also been shown to help facilitate transfer, just as they have been shown to facilitate source learning and development of scientific reasoning (Dori & Sasson, 2008; Dori, et al., 2014; Hester et al., 2014; Sasson & Dori, 2012; Smith & Villarreal, 2015).

The potential for pedagogical methods to improve transfer has been seen in several environments. Hester et al. (2014) report a learner-centered, integrated math and biology course that utilized think-pair-share breakout sessions during lecture, which saw a significant increase in transfer from math to biology.

Case studies and computerized labs have also been used within a constructivist course framework resulting in an increase in graphing skills and transfer across the levels of chemistry.
understanding (Dori & Sasson, 2008; Sasson & Dori, 2012). This has also been specifically
demonstrated in a physical chemistry course where a visual-conceptual approach to teaching
quantum mechanics resulted in an increased performance in visual and textual chemistry
understanding, graphing skills, and transfer, in comparison to a traditional mathematical
instruction approach (Dori, et al., 2014).

During their 2013 literature review, Dori and Sasson also investigated the types of learning
environments that have been used in attempts to improve transfer. Table 11 describes the learning
environments utilized in studies on transfer, as well as whether any theoretical background was
discussed in the article, the objectives of the study, and the transfer attributes, or dimensions as
listed in the table, that were studied based on the three main attributes Dori and Sasson (2013)
created.
# Table 11

**Empirical Research Literature on Transfer Skills as Reproduced from Dori and Sasson, 2013**

<table>
<thead>
<tr>
<th>Learning Environment</th>
<th>Theoretical Background</th>
<th>Objectives</th>
<th>Transfer Dimensions of the Research Design</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Problem solving</td>
<td>None</td>
<td>Assessing the usefulness of skills taught in a medical course based on problem solving in the workplace. Investigating the effect of orienting and self-judgment instructions during a series of 10 sessions based on problem-solving activities related to transfer occurring between courses. Investigating the effect of a problem-based educational package on breast disease and early detection of breast cancer on the improvement of knowledge and comfort in patient management. The researchers compared students' transfer ability while studying with a home-study module vs. a workshop format.</td>
<td>Skill set</td>
<td>Adams et al. (2003), Masui and De Corte (1999), Young et al. (1998)</td>
</tr>
<tr>
<td></td>
<td>Discussed</td>
<td>Investigating the effect of problem-based learning (PBL) on transfer of principles and concepts.</td>
<td>Skill set</td>
<td>Norman and Schmidt (1992)</td>
</tr>
<tr>
<td>Inquiry-based</td>
<td>Discussed</td>
<td>Investigating students' performance and meta-level scientific competency by strengthening their mental models of multi-variable causality. Comparison between three experimental conditions was made: performance-level exercise, performance-level exercise + prediction practice, and performance-level exercise + prediction practice + direct instruction. Investigating the effects of different scientific inquiry activities on museum exhibition visitors' science understanding. The visitors were given near transfer assignments. Testing the hypothesis that discovery-based instruction affects students' performance in near and far transfer problems and develops students' ability to think and communicate mathematically. The research compared between direct strategy instruction, guided discovery, direct teaching plus discovery and control condition.</td>
<td>Skill set</td>
<td>Keselman (2003), Lawson et al. (2000), Sue (1997), Muthukrishna and Borkowski (1995)</td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>Investigating what type of review is effective for transfer of computational skills.</td>
<td>Skill set</td>
<td>Lee (1980)</td>
</tr>
<tr>
<td>Instructional-based</td>
<td>None</td>
<td>Investigating the effect of instructing the Genetic Revolution on the development of knowledge in biology, argumentation skills and transfer of these skills to new contexts. Investigating the effect of instructional-based learning in LOGO on the development of near and far transfer skills.</td>
<td>Interdisciplinarity, skill set, task distance</td>
<td>Zohar and Nemet (2002), Lee and Thompson (1997)</td>
</tr>
<tr>
<td></td>
<td>Discussed</td>
<td>Investigating whether and how students transfer genetics understanding to argumentation contexts of biotechnology and society.</td>
<td>Skill set</td>
<td>Sadler and Fowler (2006)</td>
</tr>
<tr>
<td>Reasoning instruction</td>
<td>Partial. Theoretical reference is limited: only to the threshold model of content knowledge transfer.</td>
<td>Investigating the effect of the instruction type (reasoning, justification, rule based, emotion focused, or none) on near and far transfer skills in computerized simulation-based biology studies.</td>
<td>Interdisciplinarity, skill set, task distance</td>
<td>Lin and Lehman (1999)</td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>Investigating the generalizability of metacognitive skills across domains during development of those skills. Investigating the effect of metacognitive instructions on children's transfer skills. Three types of transfer skills were examined: within-task, across-tasks and inventive transfer. Two kinds of metacognitive instructions were used: strategy similarity and hypothesis generation.</td>
<td>Interdisciplinarity, skill set, task distance</td>
<td>Veenman et al. (2004), Butterfield and Nelson (1991)</td>
</tr>
<tr>
<td>Meta-cognitive</td>
<td>Discussed</td>
<td>Investigating transfer of thinking skills across domains, and comparison between learning of a strategy individually and in a &quot;class-like&quot; setting.</td>
<td>Interdisciplinarity, skill set, task distance</td>
<td>Zohar (1994)</td>
</tr>
<tr>
<td></td>
<td>Discussed</td>
<td>Investigating children's ability to transfer what they have learned to analogous problems.</td>
<td>Skill set, task distance</td>
<td>Brown et al. (1989)</td>
</tr>
<tr>
<td>Cooperate learning</td>
<td>Discussed</td>
<td>Investigating transfer of thinking skills across domains, and comparison between learning of a strategy individually and in a &quot;class-like&quot; setting.</td>
<td>Interdisciplinarity, skill set, task distance</td>
<td>Zohar (1994)</td>
</tr>
<tr>
<td>Analogies</td>
<td>Discussed</td>
<td>Investigating children's ability to transfer what they have learned to analogous problems.</td>
<td>Skill set, task distance</td>
<td>Brown et al. (1989)</td>
</tr>
</tbody>
</table>

*Note.* The empirical research literature on transfer skills - theoretical background, objectives, and transfer dimensions. Reproduced from Dori and Sasson (2013).
Within any of these learning environments, as previously mentioned, practice is very important. Several studies were done that recommended provision of specific practice within the target context (Becker & Towns, 2012; Dori et al., 2014; Hester et al., 2014; Smith & Villarreal, 2015). Sasson and Dori (2015, p. 164) state "complex learning involves the integration of knowledge, skills, and the transfer of what students have learned in one domain or situation to the new one and to daily life. Routine tasks that require an algorithm solution are no longer enough." Students also need to practice transferring and to receive explicit instruction pointing out connections (Chi & VanLehn, 2012; Cunningham, 2005; Dori et al., 2014; Smith & Villarreal, 2015).

2.5.6 Method to measure transfer.

There are many variations to the methods utilized to measure transfer. However, they all include common factors such as: (a) instruction, either given previously or currently, (b) a pretest in the source domain consisting of either a parallel set of questions or a questionnaire, (c) instructional treatment, preferably with a control and experimental group, (d) confirmation that learning of source domain occurred via a source posttest, review of material, homework, etc., and (e) a transfer test, again either a parallel set of questions or a questionnaire. Steps (a) and (b) can be interchanged and there may or may not be a delay before step (e). In addition, step (d) is not always included although it seems wise to do so (Chi & VanLehn, 2012). Figure 7 is a depiction of this overall method setup as summarized by the researcher.

All the concepts discussed in this section on transfer, as well as several specifics on instructional tools found in the literature, were utilized to inform the research.

2.6 Transfer Project Overview

Within all the research on transfer, even looking at transfer of math skills to chemistry, there had not yet been research done specifically on transfer of math graphing skills to the general chemistry context. Because chemistry requires a great deal of conceptual understanding, graphs are a logical tool to explore transfer. They represent a physical relationship that is displayed as a math-based representation and thus sit at the interface of math and chemistry. Conceptual understanding is crucial in chemistry, but without the application of math skills, students will not be able to get to the point of interpreting chemical relationships. Therefore, our specific interest in transfer is in students' ability to apply mathematical graphing skills in a chemistry context and how to best facilitate such transfer based on the totality of the relevant transfer literature.

Based on the generalized method in Figure 7 and the rest of the transfer literature review, students must learn the source material, either previously or deliberately during the course. For this study, the students entering general chemistry placed at a certain level of math competency (see Section 1.1.4 Mathematical reasoning) so we could assume they had adequate previous instruction in both algebra and graphing. Pilot studies had also shown that students come into general chemistry with
adequate quantitative computational skills (see Section 1.1.4 Mathematical reasoning). A demographics questionnaire was used to establish students' highest level of math in high school.

A pretest in the source domain of math graphing was conducted using a test of graphs, validated for high school level (McKenzie & Padilla, 1986). This established a baseline of received instruction in graphing prior to entering the general chemistry course. Additionally, a pretest in transfer of math graphing skills was given through administration of an instrument that incorporated three sets of eight parallel questions in the contexts of math, physics, and economics (Planinic, Ivanjek, Susac, & Milin-Sipus, 2013).

The instructional treatment plan was based on literature findings on ways to facilitate transfer. The idea behind the research was to combine the multiple components found to facilitate transfer (Bassok & Holyoak, 1989; Dori et al, 2014; Ngu & Yeung, 2012) with construction and interpretation of graphs, which has been shown to focus students' attention on underlying structure and relational concepts (Gick & Holyoak, 1983; Holyoak & Koh, 1987; Ngu & Yeung, 2012; Ngu et al., 2015; Terwel et al., 2009).

The hypothesis was that this combination provided in an instructional treatment would allow students to notice the underlying similarities between the problems involving their math graphing skills and newer problems with the same underlying structure but presented in chemistry or other science contexts. This was tested with a worksheet given during class described in more detail in Chapter 3.

A transfer post-test was given as well–that incorporates a posttest for the source domain of math graphing and transfer domains of science graphing. It is the same test that was given for the math graphing transfer pretest but after 10 weeks of class so there was minimal risk of students remembering the questions. For further details on the method used in this research see Section 3.5 Quantitative Research.
Chapter 3: Methods

3.1 Ethics Statement

Permission for use of human participants was obtained by the Institutional Review Board (IRB) at the University of Montana. Participant consent was acquired before any assessments or treatments were given. The researcher presented the research study to the students but left the room while students signed the consent form to reduce any perception of coercion.

All assessments were incorporated into the course curriculum and course points awarded based on participation in the assessments. To help ensure student effort on the assessments, students were told that assessments would be graded and points assigned based on number of correct responses. However, to establish the final course grade, full possible points were awarded to students. Portions of student laboratory reports were also used as an assessment. For purposes of the course those questions were graded by the teaching assistants (TAs) in such a way as to provide an equal evaluation of grades despite the instructional treatments given to different groups. See Section 3.4 The Research below.

3.2 Brief Description of the University of Montana

The University of Montana is a medium-sized research institution. Including undergraduates, graduates, and professional students, there were about 12,000 full or part-time students enrolled in 2016. About 22% of students graduate within four years, 36% in five, and about 48% of remaining students in six (“Common Data Set,” 2012-2013; “Adding Value,” 2009; “University of Montana,” 2014).

Approximately 75% of students continue enrollment after their first year. The admissions rate is 90%, with 40% of those admitted enrolling. About 80% of the undergraduate students live in campus housing and 20% commute. The average student to faculty ratio is 18 to 1 (“Common Data Set,” 2012-2013). UM is effectively an open-enrollment university; a low percentage of students entering general chemistry perform at a high scientific reasoning ability (Cracolice, 2012). Refer to Section 1.1.3.1 Scientific Reasoning. However, those students still desire to work in medical fields, biology, and physical sciences. Competency in general chemistry is required to enter those fields.

3.3 Brief Description of the General Chemistry Course

The course is designed to cover the standard U.S. first-semester content, based on the contents of the American Chemical Society First-Term General Chemistry exams and the best-selling general chemistry textbooks over the past two decades. However, it is taught using a combination of pedagogies including adaptations of guided inquiry (Abraham & Pavelich, 1999; Cracolice & Busby, 2015; Lewis & Lewis, 2005) and peer-led team learning (Cracolice & Busby, 2015; Gosser, Cracolice, Kampmeier, Strozak, & Varma-Nelson, 2001; Lewis, 2011). The course is comprised of three main parts: Lecture, Workshop, and Laboratory (Lab).

3.3.1 Lecture.

Lecture is given three days each week for 50 minutes. There is one section. The first 10 minutes of each lecture is used for a quiz to assess understanding of homework from the previous lesson
and motivate daily engagement with the material. After the quiz, the lecture itself is broken up into blocks of traditional presentation separated by “breakout” sessions where students work on example problems with their classmates based on what was just presented. There are several tools that complement this lecture style.

The textbook, General Chemistry: An Inquiry Approach, (Cracolice & Peters, 2016) is divided into lessons rather than chapters. Each lesson is completed in a 50-minute class period. Additionally, it does not follow an “atoms first” approach, but rather explores macroscopic examples of the phenomena to help establish observable concepts prior to delving into the abstract. This pedagogy is consistent with Piaget’s findings that people initially require concrete experiences before they can conceptually understand unobservable phenomena. Each lesson is introduced with questions for students to answer as they work through the lesson. Much like the lecture, the text in the lessons is broken up with example problems for students to work through. Following each lesson, the homework is divided into four categories: A, B, C, and D. Sets A and B are parallel questions so if students do not comprehend the concept in one set they can work through a similar question in the other set. These two categories require basic understanding of the lesson. Problem sets C and D integrate concepts from other lessons. Set D includes challenging questions designed to help students employ their full understanding of chemistry. All quizzes and exams are based on homework, workshop, and laboratory.

A workbook is also provided for students to use during lecture as a supplement to the textbook. Students can take the workbook to class and use it for notes. They are encouraged to add to it as they work. It is called Think Out Loud! and includes a basic outline of each textbook lesson, room to take notes, and example questions related to the lesson (Cracolice, 2016). Students use the questions in this workbook to answer questions during lecture breakout sessions.

Breakout sessions are timed periods after concepts are presented in lecture. There are typically two or three breakouts per lecture. It is during these times that the adaptation of peer-led team learning is implemented. Students are arranged into groups of 12, depending on the team and temporally as it changes over time, during lecture. Each group of 12 students has one peer-leader sitting with them. Peer leaders are students who have already completed the general chemistry course with an A or B grade and are trained prior to the semester starting as well as each week throughout the semester. During breakouts, the peer leader is available to help their group with any questions that may arise from the workbook questions or concepts from the lecture.

### 3.3.2 Workshop.

The peer leaders also run workshops for their group of students. Workshops are held once each week for two hours. The two-hour block was selected because students could not finish the workshop problems in less time, but more time led to inattentiveness and decreased engagement. The group size of 12 was also determined to be big enough for students to provide ideas, but not so big that participation decreased. Ideally, a group contains eight students, but the course starts with 12 to account for attrition in the groups (Gosser et al., 2001). In addition, there are usually not enough peer leaders to start with fewer students per group. Each workshop session works on material related to the three lessons covered in the lectures from the week.

Each lesson incorporates three questions, designed to invoke Vygotsky’s Zone of Proximal Development (ZPD), where students need to help each other and utilize their peer leader to determine how to solve the problems (Gosser et al., 2001). Each individual’s ZPD needs to be assessed so problems can be provided “just beyond the student’s present capabilities, and then
give assistance in solving those problems" (Cracolice, 2005). If questions are beyond students' ZPD they will simply memorize and regurgitate content but not learn in a meaningful, comprehensive way (Seymour & Longden, 1991; Marek & Cavallo, 1997).

The Workshop problems build on concepts from the homework but are more challenging than the Set D homework questions. Ideally these problems are solved in a three-step process: First, students think individually to focus on individual problem solving. This is meant to generate disequilibrium and make conscious the current conceptual understanding of the individual student. Second, the students are paired with another student at a homogeneous level for those topics and the pair continues working on the problem. Homogeneity prevents domination and promotes discussion. Partners are selected by the peer leader based on quiz scores from the week immediately previous. Finally, students share their thought processes and solutions with the group to engage in discussion, debate, and collectively solve the problems. This process description is idealized. It is acknowledged that in actual practice the ability of leaders to implement their training of this process varies.

3.3.3 Laboratory.

Laboratories are designed to provide students the opportunity to measure data as a basis for developing conceptual understanding of the phenomenon before the concept is discussed in lecture. This is a guided inquiry format; data precedes concept introduction. Students collect data and from those data they synthesize their own concepts, which get verified later in lecture. Most of the labs are designed in a similar fashion where students make qualitative observations of the materials, and interactions of materials, prior to collecting quantitative data. This encourages students to explore what might be happening at the particulate level before they collect quantitative data.

During data analysis, students are asked to describe the pattern they observed. To do so, the text recommends they graph the data and come up with an algebraic expression to describe the pattern. Students are also asked to draw mental models. These are visual representations of students' understanding of the physical phenomenon at the particulate level.

Laboratories are set up so two sections of workshop at 12 students each make up each section. One teaching assistant (TA) leads each section. The TA's are typically chemistry graduate students, although at times undergraduate chemistry students or environmental studies graduate students have served as TA's. Lab sections meet at one of six three-hour lab times. Three lab times are on Wednesdays, two on Thursdays, and two on Fridays. Students do not randomly choose lab times, as they must fit in with other course times, typically math and science. However, over the past three years, 2013 – 2015, there has been no difference in scientific reasoning ability based on the time students take laboratory. As previously discussed, scientific reasoning ability is one of the necessary components of student success. See Figure 8.

3.3.4 Course summary.

The course synthesizes the theories of Piaget and Vygotsky using guided inquiry and peer-led-team-learning pedagogies. It provides a social environment for interaction and collaboration. Students are given opportunities to work within their ZPDs to help develop scientific reasoning skills.
3.4 The Research Goals

The purpose of this two-phase, sequential mixed methods study was to determine if students demonstrate the ability to transfer math-graphing skills to science context. In the first phase of the study, quantitative research questions were posed in four categories:

1. Compare ability to transfer math-graphing skills to two other domains.
2. Relate ability to transfer graphing skills to scientific accuracy of graphs constructed on chemistry exams.
3. Relate scientific reasoning ability, prior content knowledge, intelligence, experience with story problems, and experience with inquiry labs, to ability to transfer math-graphing skills into science context.

Information from this first phase was explored further in a second qualitative phase. In the second phase, qualitative interviews were used to probe students’ understanding of graphs and their ability to transfer graphing skills into science context with purposefully selected participants. The qualitative research in the second phase ensured an accurate understanding and explanation of the quantitative results.

3.5 Quantitative Research

3.5.1 Participants.

The population in this study consisted of students enrolled in the first semester general chemistry course at the University of Montana, during the Fall of 2016. This consisted of a little less than 200 traditional and non-traditional students. The sampling design was a single-stage procedure; the researcher had access to names of individuals participating and collected information from them directly.

Individuals were not randomly sampled. Rather, most students from the general chemistry course participated in the research study. However, instructional treatments were assigned randomly across laboratory sections. Participants in each instructional treatment group were believed to be representative of the population of chemistry students, increasing the validity of the results.

This general chemistry course is unique from traditionally taught lecture courses, as discussed. However, the issues students exhibit with math, and potential transfer of math, appear to be universal as described in Section 2.5 Transfer.

3.5.2 Research design.

The purpose of the quantitative portion of this mixed method, quasi-experimental, group research study was to test the theory of transfer to compare and relate aspects of transfer as listed in Section 3.4 The Research.
Pretests and demographics were administered at the beginning of the first semester of general chemistry to establish baseline levels of student skills. Five pretests were administered: Classroom Test of Scientific Reasoning (CTSR), Chemical Concepts Inventory (CCI), Raven’s Standard Progressive Matrices Plus (SPM+), Textbook Reading Pilot (TRP), and Test of Graphing Skills (TOGS). These are described in detail in Section 3.5.3 Research instruments. The students completed these in their laboratory sections during the first two weeks of the 15-week semester. The tests take about three hours in total, so an hour and a half of tests were administered each week.

See Appendix D through Appendix J for the tests used. While the Textbook Reading Pilot was administered, it was later decided to leave it out of analyses as the data acquired from it was very complex. This could perhaps be studied later with a series of simpler research questions and analyses.

**Week 1**

Prior to conducting any research, a description of general chemistry and how it is taught at the University of Montana was reviewed in lecture. Some topics covered included: where students can receive help during the day or night, major topics covered in general chemistry including algebra, where to find detailed descriptions of the course (syllabus) and how to succeed in the course (textbook Prologue), course structure and the reasoning behind the structure, and the necessity to practice problem solving and the increase in required homework and study time compared to high school. The time spent outside of the classroom is further broken down with a pie chart showing that 66% of the course time should be spent doing homework. Finally, the first lesson, "How do Scientists Use Algebra to Reason and Calculate?" was discussed. This includes reviewing definitions of algebra, variable, direct proportionality, and inverse proportionality. Direct and inverse proportionality is also explained symbolically and graphically, including the requirement for a direct proportionality to pass through (0,0) on a graph. The use of algebra to calculate in the sciences is described as quantity algebra, where a quantity includes a value and a unit, and calculations done must involve the cancellation of units. Several examples and the steps involved to do algebraic calculations are worked through.

In lab, the TOGS, CTSR, and TRP were given the first week along with opportunity for students to provide consent for their grades to be utilized in this research. Following assessments, a measurement lab was conducted. The first component of the measurement lab asked students to develop a personal unit of measure, based on each student's wrist size, and investigate its relationship to length in centimeters. They were asked to describe the direct proportion relationship observed. The second component investigated the inverse relationship of pressure and volume of a fixed amount of air at constant temperature. The lab worksheets on which students recorded their data, interpreted their observations, and reported their deduced relationships are included in Appendix K.

To explore a baseline level of what students constructed for a graph after collecting data, two questions were developed. One investigated what students do spontaneously when asked to describe a pattern shown in their data. The other question provided complete instructions about what to graph to see how accurately students could construct a graph with guidance and acted as a control. As shown below, Question 1 was open-ended and Question 2 was explicit. Both the unit measurement and pressure vs. volume labs had open-ended and explicit versions.
1. What are the patterns shown? 
   (Graphing grids will be provided. The laboratory coordinator will announce that graph paper will be available on both sides of the lab if desired.)

2. On the grid(s) below, construct a plot of your data. Determine the equation of the line. Use words to describe the meaning of your algebraic equation.

This was a quasi-experiment, so students were not randomly assigned to one of the questions. Rather, laboratory sections as shown in Table 12 completed each question version. The times were balanced so each time slot with two sections had both question versions. Teaching assistants were kept consistent to ensure consistency for the students with their TA.

Table 12

*Breakdown of Measurement Lab by Version of Question Assessment – Open-Ended or Explicit*

<table>
<thead>
<tr>
<th>Laboratory Section</th>
<th>Laboratory Time</th>
<th>Open-ended versions</th>
<th>Explicit versions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wednesday 8 am – 11 am</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Wednesday 8 am – 11 am</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>3</td>
<td>Wednesday 11 am – 2 pm</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>4</td>
<td>Wednesday 3 pm – 6 pm</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Thursday 8 am – 11 am</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Thursday 8 am – 11 am</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>7</td>
<td>Thursday 1 pm – 4 pm</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Thursday 1 pm – 4 pm</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>9</td>
<td>Friday 8 am – 11 am</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The responses of students to the explicit questions were analyzed to determine baseline graphing construction and interpretation ability. The open-ended questions were utilized to determine how students spontaneously respond to direction to describe relationships and their ability to recognize graphing as a tool to investigate such a relationship. These two measurements provided the overall baseline for the subsequent instructional treatments given during the second week of lab, which were used to help facilitate transfer.

**Week 2**

Prior to administration of the instructional treatments, the SPM+, CCI, and demographic questionnaire were administered in the second week as shown in Table 14.

Demographic information included:

1. Previous high school experience with percent of time homework in math, physics, and chemistry incorporated story problems as opposed to "solve for x" problems.
2. If students had labs in physics and chemistry.
3. If students had labs in physics and chemistry, the percent of time data collection occurred before lecture.
4. If students have had any previous college experience.
5. Gender, age, highest course in math, and parent’s highest educational level.
Also, during the second week of class students received an instructional treatment to potentially promote transfer. The treatments provided students with basic graphing definitions, an opportunity to work through a math-graphing scenario, and subsequent application in a chemistry context. To determine the most effective form of instruction for the promotion of transfer, three treatments were given. These treatments were chosen based on literature methods shown to promote transfer (Ngu & Yeung, 2012; Ngu et al., 2015; Stern et al., 2004). All three versions contained some basic instruction and definitions of common graphical terms. This was followed by a graphing example in a mathematical context and then a transfer question in a chemistry context. All versions presented the same scenario of a relationship between the number of rotations of a small and large cog. In version one, students were presented with a table of data and asked to construct a graph representing the relationship – *active graphing example*. In version two, the students were presented with a graph already depicting the relationship and asked several questions about why the graph was constructed the way it was – *passive graphing example*. In version three, students were presented with a worked example of how a graph was constructed but no reflective questions were asked – *worked graphing example*. This was the control group, as worked examples have been shown, with regards to transfer, to be ineffective (Ngu & Yeung, 2012; Ngu et al., 2015). A worked example is meant to move the learner "through each step towards the solution but it does not emphasize the construction of a coherent problem model" (Ngu et al., 2015, p. 391).

A transfer question in a chemistry context followed each math-graphing example, specifically asking students to construct a graph describing the relationship between pressure and temperature of a fixed amount of gas at a constant volume. The transfer question had a similar structural foundation to the math-graphing example but was framed in a chemistry context— isomorphic problems (Reed, 1987; Ngu & Yeung, 2012). This provided the students with an opportunity to immediately apply what they learned from the instruction and math-graphing example in a transfer scenario. These instructional treatments were developed based on transfer results from several researchers, all of whom utilize a similar structure of providing basic instruction in the source domain, an instructional treatment in the source domain, and an opportunity to apply what they learned from the examples in an analogous problem in the transfer domain (Ngu & Yeung, 2012; Ngu et al., 2015; Stern et al., 2004). This is in line with the overall method to measure transfer that was developed based on literature review in Section 2.5.6 Method to measure transfer. Students were provided with instruction explicit to graphing in both math and chemistry contexts, pretested in math graphing (TOGS), and given an instructional treatment including control and experimental groups. All three instructional treatments can be found in Appendix L. These treatments were given to lab sections as described in Table 13 below.

**Table 13**

*Breakdown of Instructional Treatments Across Laboratory Time*

<table>
<thead>
<tr>
<th>Laboratory Section</th>
<th>Laboratory Time</th>
<th>Version 1 Active</th>
<th>Version 2 Passive</th>
<th>Version 3 Worked</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wednesday 8 am – 11 am</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Wednesday 8 am – 11 am</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Wednesday 11 am – 2 pm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Wednesday 3 pm – 6 pm</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Thursday 8 am – 11 am</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Thursday 8 am – 11 am</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Thursday 1 pm – 4 pm</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Thursday 1 pm – 4 pm</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Friday 8 am – 11 am</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Over the past three years, 2013 – 2015, there has been no difference in scientific reasoning ability based on the time the laboratory section meets, so instructional treatments should not be affected by meeting time. In this case, to reduce participant reactivity, the same instructional treatment was given across both sections that occurred at the same time. See Figure 8 for scientific reasoning ability based on meeting time.

![Figure 8](image)

Figure 8. Three years of scientific reasoning. There is no significant difference in the average scientific reasoning ability of students entering first semester general chemistry based on laboratory time across the three years of data – 2013-2015.

**Week 3**

In the third week, all laboratory sections were given a graphing transfer instrument. This *Test on Graphs (ToG)* was developed by Planinic et al. (2013) and includes eight sets of parallel questions in mathematics, physics, and economics contexts. Again, this follows the overall transfer method described in Section 2.5.6 Method to measure transfer, with the use of parallel questions to test for source domain learning, as there are questions on math graphing and a pre-transfer measure with the other context questions. The ToG was also utilized as a post measure for transfer at the end of the semester—and is further discussed in Section 3.5.3 Research instruments.
Weeks 4 – 15

Throughout the remainder of the semester, ten post measures were collected to investigate students' transfer of math-graphing skills and conceptual understanding of physical relationships described in chemistry. These post measures included:

1. Data analysis questions from labs that advise the use of a graph to explain the pattern found.
2. One graphing question on three of the four midterm exams given throughout the semester.
3. A post measure of the Test on Graphs.

These measures are described in detail in Section 3.5.3 Research instruments. Table 14 provides an overview of the 15-week laboratory course, brief descriptions of each lab period, and lists assessments that were administered or collected each week. After the two-part measurement lab in the first week, and the second week of instructional treatment discussed in detail above, students returned to what was formerly done in laboratories across prior semesters of first semester general chemistry.

Two alterations to the historically followed laboratory procedure, in form of feedback to students, were applied to the laboratory sequence to help ensure accurate measurement of individual conceptual understanding and provide fair grading regardless of the different instructional treatments:

1. Students worked individually on all labs that had instructions to graph data so the resulting lab report was a measure of the individual’s thought processes rather than that of a group. These labs included Hydrates (Week 3), Zinc and Hydrochloric Acid (Week 5), Dissolution Reactions (Week 6), and Open Inquiry: Mass Relationships (Weeks 7-8). Students were also encouraged by their teaching assistants (TAs) to answer questions individually. The TAs, as well as the lab coordinator, stated this expectation to the students. Rather than convening to the shared section of the laboratory where students could work together in groups, they were told to remain at their lab stations, where they collected data individually, to maintain a more focused environment.

2. Teaching assistants did not provide specific help if students had questions on the data analysis portion of lab. Rather, students were encouraged to do their best. Teaching assistants asked vague questions such as, "What do you think?" as well, but were instructed not to lead students to graph their data specifically or give any explicit graphing directions to students while in lab. See Appendix M on TA training.
Table 14

Layout of the Semester’s Laboratories and Schedule of Assessments

<table>
<thead>
<tr>
<th>Week</th>
<th>Experiment</th>
<th>Description</th>
<th>Assessments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Measurement Lab</td>
<td>Two-parts: 1) Direct relationship between two units of measure 2) Inverse relationship between pressure and volume of a fixed amount of air at constant temperature</td>
<td>CTSR, TOGS, TRP</td>
</tr>
<tr>
<td>2</td>
<td>Instructional Treatments</td>
<td>Worksheets that provide instruction either for math graphing, graphing with a chemistry example, or a chemistry example with no graphing</td>
<td>SPM+, CCI, Demographics questionnaire</td>
</tr>
<tr>
<td>3</td>
<td>Hydrates lab</td>
<td>Heat hydrated copper(II) sulfate to obtain the anhydrous compound and explore the mass relationships found</td>
<td>Test on Graphs, Data analysis questions</td>
</tr>
<tr>
<td>4</td>
<td>Precipitates lab</td>
<td>Explore double displacement reactions, determine identity of the precipitate, and gain conceptual understanding of particulate-level interactions</td>
<td>Exam 1 question</td>
</tr>
<tr>
<td>5</td>
<td>Zinc &amp; Hydrochloric Acid lab</td>
<td>Investigate the reaction between zinc and hydrochloric acid, what products are created, learn how to do a titration, and from the data, determine the relationships that exist between zinc and hydrochloric acid</td>
<td>Data analysis questions</td>
</tr>
<tr>
<td>6</td>
<td>Dissolution Reactions</td>
<td>Study the relationship of amount of heat transferred given different chemical reactions and quantify with magnesium sulfate reaction</td>
<td>Data analysis questions</td>
</tr>
<tr>
<td>7 – 8</td>
<td>Open Inquiry: Mass Relationships</td>
<td>Investigate a system of choice. Students develop the entire experiment, collect the data, and analyze their results</td>
<td>Data analysis results, Exam 2 question</td>
</tr>
<tr>
<td>9</td>
<td>Chemical Properties</td>
<td>Explore chemical properties of various metals with acids and bases</td>
<td>None</td>
</tr>
<tr>
<td>10</td>
<td>Poster Presentation</td>
<td>Students present their Open Inquiry: Mass Relationships results via a poster presentation to the class</td>
<td>Exam 3 question</td>
</tr>
<tr>
<td>11</td>
<td>Molecular Structure</td>
<td>Study the configurations of chemical compounds using molecular modeling kits</td>
<td>None</td>
</tr>
<tr>
<td>12</td>
<td>Open Inquiry: Heat Laws</td>
<td>Investigate a system of choice. Students develop the entire experiment, collect the data, and analyze their results</td>
<td>Data analysis results</td>
</tr>
<tr>
<td>13</td>
<td>Thanksgiving</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Open Inquiry: Heat Laws</td>
<td>Continuation of system exploration</td>
<td>Exam 4 question</td>
</tr>
<tr>
<td>15</td>
<td>Poster Presentation</td>
<td>Students present their Open Inquiry: Heat Laws results via a poster presentation to the class</td>
<td>Post: Test on Graphs</td>
</tr>
</tbody>
</table>

3.5.3 Research instruments.

The instruments utilized in this work are discussed in detail in this section. Table 16 lists the instruments selected from the literature, variables measured, and scales used during analysis. Following the table are detailed descriptions of each instrument, including validity and reliability statistics.

Several pre-measures were used as independent variables to investigate their effect on the ability of students to transfer math-graphing skills to a science context, i.e., Transfer Index—which is discussed in more detail later in this section.

The independent variables were defined as:

1. Scientific reasoning ability.
2. Prior chemistry context knowledge and alternate conceptions.
3. Intelligence.
4. High school graphing ability.
5. Student-stated learning objectives from a textbook passage.
6. Student-reported percent of story problems utilized in high school courses.
7. Student-reported percent of inquiry labs utilized in high school courses.

The dependent variables were defined as:

1. Scientific accuracy of graphs constructed in lab or on exams based on chemistry expert rubrics.
2. Transfer Index, the comparative scores on math-graphing abilities to the two science domains on the Test on Graphs. Specifically, the Test on Graphs was coded and correct answers, whether they were accompanied by an explanation or not, were given a score of 1 in each of the three domains – math, physics, and economics. The Transfer Index (Roberts, Sharma, Britton, & New, 2007) was then determined for both the math to physics scores and math to economics scores. A scoring example, with math to physics being represented, is shown in Table 15 below.

Table 15
Transfer Score Example Based on Application of Math-Graphing Skills to Physics Context

<table>
<thead>
<tr>
<th>Math Score</th>
<th>Physics Score</th>
<th>Transfer Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Roberts, Sharma, Britton, and New (2007) devised the Transfer Index system to account for students who scored very low or extremely well on their mathematics component and would otherwise distort results measured as a raw score (Britton et al., 2005). The Transfer Index looks at the base domain of math and the corresponding question in a new (transfer) domain that utilizes the same underlying mathematical concept. Specifically, “if a student gave the right answer in both sections, they were awarded 2 for that set of questions. If they did not get it right on both sections, they were awarded 0” (Roberts et al., 2007, p. 433). However, if a student displayed knowledge in math but not the other context, “they clearly have not transferred that knowledge” (Roberts et al., 2007, p. 434). The odd scenario is if they did not answer the math question correctly but answered correctly in the other context. “This reflects the view that transfer has occurred, but to a lesser degree than when answering correctly” in both contexts (Roberts et al., 2007, p. 434). This scenario receives a transfer score of one.

The overall Transfer Index is “the normalized sum of the individual transfer scores” on the eight pairs of mapped questions (Roberts et al., 2007, p. 434). The formula used is shown below.

\[
Transfer\ Index = \frac{\sum_{n=1}^{8} Transfer\ Score}{16} \times 100
\]
### Instruments and Their Scales to be Used in This Research

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Abbreviation</th>
<th>Characteristic Measured</th>
<th>Continuous Scale</th>
<th>Grouped Scales</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical Concepts Inventory</td>
<td>CCI</td>
<td>Alternate conceptions about topics typically covered in first-semester general chemistry</td>
<td>0 – 16</td>
<td></td>
</tr>
<tr>
<td>Classroom Test of Scientific Reasoning</td>
<td>CTSR</td>
<td>Scientific reasoning ability</td>
<td>0 – 12</td>
<td>Concrete: 0 – 4 Transitional: 5 – 8 Formal: 9 – 12</td>
</tr>
<tr>
<td>Raven’s Standard Progressive Matrices Plus</td>
<td>SPM+</td>
<td>Intelligence</td>
<td>0 – 60</td>
<td></td>
</tr>
<tr>
<td>Test of Graphing Skills</td>
<td>TOGS</td>
<td>Graphing construction and interpretation skills through high school</td>
<td>0 – 26</td>
<td>Construction: 0 – 14 Interpretation: 0 – 12</td>
</tr>
<tr>
<td>Test on Graphs</td>
<td>ToG</td>
<td>Transfer of graphing skills associated with slope and area for mathematics, physics, and general science context</td>
<td>0 – 100</td>
<td></td>
</tr>
<tr>
<td>Data Analysis Part A</td>
<td>DAA</td>
<td>Spontaneity of physical relationships graphed from data collected in lab</td>
<td></td>
<td>Graph: 0 – 1 (No – Yes)</td>
</tr>
<tr>
<td>Questions on Exams</td>
<td>EQ</td>
<td>Scientific understanding and accuracy of physical relationships presented in table or graphical form on each exam</td>
<td>0 – 11</td>
<td></td>
</tr>
</tbody>
</table>

**Knowledge of topics associated with alternate conceptions: Chemistry Concepts Inventory (CCI)**

The Chemistry Concepts Inventory (CCI) is a multiple-choice instrument designed to measure the extent of alternate conceptions about topics typically covered in a first-semester general chemistry course (Mulford & Robinson, 2002). It consists of 22 multiple-choice questions, with 10 stand-alone questions and 6 paired question sets, resulting in 16 items. Both questions in a paired question must be correct for credit. Participants were given 25 minutes to complete the instrument. A psychometric analysis was conducted (Barbera, 2013), and the instrument was determined to be suitable for large-scale assessment of student understanding. The CCI is reliable (Cronbach’s α ranged between 0.704 and 0.76 in various trials) and reproducible (test-retest correlation = 0.79). A panel of experienced chemical education researchers initially established validity of the instrument, and it has been used in many published, peer-reviewed research studies (Bramaje & Espinosa, 2013; Kruse & Roehrig, 2005).

**Scientific reasoning ability: Classroom Test of Scientific Reasoning (CTSR)**

The Classroom Test of Scientific Reasoning, Multiple Choice Version (CTSR), consists of 24-paired question sets designed to measure scientific reasoning ability (Lawson, 1978, 2000). Questions are paired so a student must answer both items in a pair correctly for credit, resulting in a 12-item multiple-choice instrument. Participants were allowed 35 minutes to complete the instrument. A panel of experts in Piagetian research initially established validity, and the
The instrument has been used in many published, peer-reviewed research studies (Bao et al., 2009; Jensen, McDaniel, Woodard, & Kummer, 2014). Lawson, Alkhoury, Benford, Clark, and Falconer (2000) found the instrument to be reliable (Cronbach’s $\alpha = 0.70$) in a subsequent study.


The Raven Standard Progressive Matrices–Plus Version (SPM+) was used to measure intelligence; a ceiling effect appeared in the original version so the Plus Version was developed to restore discriminative ability at the upper limit (Raven, Raven, & Court, 1998). There are five sets of 12 matrices of increasing difficulty in the instrument, for a maximum score of 60. Participants were given 60 minutes to complete the instrument. Validity of the instrument is established from years of use and is widely accepted as one of the best large-group measures of nonverbal intelligence. Internal consistency reliability for the SPM+ was measured as 0.88 with a test-retest reliability of 0.97. Criterion-related validity has been established through several studies that indicate a relationship between the SPM score and job performance (“Raven’s Standard Progressive Matrices,” 2007).

Table 17 provides internal reliability measures for the CCI, CTSR, and SPM+ instruments from three years of administration.

**Table 17**

**Internal Reliability Statistics**

<table>
<thead>
<tr>
<th>Instrument</th>
<th>CCI</th>
<th>CTSR</th>
<th>SPM+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilot (Au’13) or Expt (Au’14 &amp; ’15)</td>
<td>Pilot</td>
<td>Expt</td>
<td>Expt</td>
</tr>
<tr>
<td>Count</td>
<td>224</td>
<td>233</td>
<td>194</td>
</tr>
<tr>
<td>Mean</td>
<td>7.0</td>
<td>6.7</td>
<td>7.6</td>
</tr>
<tr>
<td>SD</td>
<td>3.0</td>
<td>2.8</td>
<td>2.9</td>
</tr>
<tr>
<td>Median</td>
<td>7</td>
<td>6</td>
<td>7</td>
</tr>
</tbody>
</table>

**Mathematical graphing skills: Test of Graphing Skills (TOGS)**

The Test of Graphing in Science (TOGS) was validated for students in 7th–12th grades. As we were interested in establishing a baseline of graphing ability with our students in 13th grade, it is also valid for those students. Traditional students will have only been in college for one week, so no additional graphing skills will have been learned beyond their high school capability, unless they are non-traditional students. The TOGS investigates students’ ability to select appropriate axes, locate points on a graph, draw lines of best fit, interpolate, extrapolate, describe relationships between variables, and interrelate data from two graphs. The test consists of 26 items and is a paper-and-pencil multiple-choice instrument. Participants were given 35 minutes to complete the instrument. The TOGS has a total test reliability of ($\alpha = 0.83$) for students in 7th–12th grade (McKenzie & Padilla, 1986).

**Transfer of graphing skills: Test on Graphs (ToG)**

The Test on Graphs (ToG) was given to measure any gain in transfer ability from the instructional treatments. There were 10 weeks between administrations of the instrument, so it is unlikely that there was a testing affect. However, as students constructed and interpreted graphs throughout the semester, a maturation affect may be seen. This is measurable through use of a control group, those students who completed version three of the instructional treatment – worked
Graphing example. In addition, confidence ratings were added to the instrument, both pre- and post-, to determine if students' confidence in their ability to transfer changed based on instructional treatment.

The ToG consists of three sets of parallel graphing questions in mathematics, physics, and economics domains. There are 24 questions overall, with eight questions in each domain. Of the eight domain questions, five focus on the understanding of slopes and three on the understanding of areas under a curve. The ToG investigates ability to transfer mathematical graphing skills to other contexts. This was measured using the Transfer Index for both Math to Physics, and Math to Economics, contexts as described above. It was developed by Planinic et al. (2013) and it has an item reliability of 0.99, a person reliability of 0.85, and Cronbach alpha of 0.88. Of the 385 first year university students tested, only 16 were shown to have abilities outside the range of difficulty on the ToG. Students were given 60 minutes to complete the instrument. Permission to use and modify the instrument was obtained from Planinic via email on July 13, 2016. Confidence ratings were added to the assessment but otherwise it was unchanged.

Administration time for each instrument was based on recommended times from the literature as well as experience with administration of these instruments in prior years for pilot studies. There was sufficient time for every student to finish the tests completely and without time pressure. The researcher supervised all test administration. Students were told that the next test would not be started until the provided time was complete, to encourage effort.

Laboratory report graphs: Data Analysis Part A (DAA)

The data analysis section of student laboratory reports, from Inquires Into Chemistry, (3rd Ed.) (Abraham & Pavelich, 1999), asks

"What patterns are shown in these data? It might be helpful to graph the data. Try to come up with an algebraic equation that expresses the pattern you found. Explain why you chose the particular algebraic equation" (p. 21).

A binary scale was used to measure whether students draw a graph.

Exam questions

One question on each of the four midterm exams addressed topics learned during lab and were relevant to other materials covered on the test. These questions examined students' ability to transfer mathematical graphing skills to chemistry context when presented with data like what they collected in lab.

To demonstrate an expert level of understanding students had to:

1. Plot a graph with appropriate scales and designated variables on proper axes – demonstrating an understanding of which variable is independent and dependent.
2. Draw a line of best fit to indicate a 0,0 y-intercept for direct proportions and accurately calculate the slope.
3. Write an explanation describing the physical relationship of the chemistry pattern expressed by the algebraic equation of the line.
These parameters were assessed with a rubric generated from the responses of general chemistry instructors from several institutions. The experts were provided with an example lab report, of which a data set had been filled in. From this they developed an answer key utilizing the data. Their answer keys were aggregated to form the final dimensions of the rubric, ensuring that expectations are comprehensive and not unreasonable. The rubric is shown below. The quality of the student's graphical construction and interpretation was assessed using the rubric. Similar rubrics have also been used in previous research on transfer (Dori et al., 2014).

Table 18

Rubric for Assessment of Graphical Scientific Accuracy

<table>
<thead>
<tr>
<th>Yes or No Questions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Part a</strong></td>
<td></td>
</tr>
<tr>
<td>Did they draw a line? (even if very faint count it)</td>
<td></td>
</tr>
<tr>
<td>If they drew a line, is it linear?</td>
<td></td>
</tr>
<tr>
<td>Do they indicate a need for 0,0 as a point? (If the line goes through 0,0 or if it can be extended to go through 0,0)</td>
<td></td>
</tr>
<tr>
<td>Did they use the line of best fit for the right reason, i.e. calculate slope from the line?</td>
<td></td>
</tr>
<tr>
<td>Did they set up a calculation for a slope? (From the line or points)</td>
<td></td>
</tr>
<tr>
<td>Did they correctly discern that the y-axis is the dependent variable, i.e. calculate the slope as Δy/Δx? (If inverse, or their axes are reversed, then no)</td>
<td></td>
</tr>
<tr>
<td>Do they write an equation? Is it consistent with the slope and intercept previously used or changed?</td>
<td></td>
</tr>
<tr>
<td><strong>Part b</strong></td>
<td></td>
</tr>
<tr>
<td>Do they state the two variables are proportional or directly proportional?</td>
<td></td>
</tr>
<tr>
<td>Is their statement of proportionality consistent with part a)? In part a) it needs to 1) go through the origin and 2) the student needs to indicate the data is linear, either by drawing a straight line or calculating the slope.</td>
<td></td>
</tr>
</tbody>
</table>

The general exam question keys were:

**Exam 1 Question:**

E1 Q. (8 points) When heated, mercury(II) oxide decomposes to elemental mercury and oxygen gas. Students in a general chemistry course similar to ours wanted to determine the mass relationship between the mass of mercury(II) oxide before heating and the mass of elemental mercury produced. Their data is in the table below:

<table>
<thead>
<tr>
<th>Mass of Mercury(II) Oxide (g)</th>
<th>Mass of Mercury (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>0.7</td>
</tr>
<tr>
<td>1.3</td>
<td>1.0</td>
</tr>
<tr>
<td>1.6</td>
<td>1.4</td>
</tr>
<tr>
<td>2.5</td>
<td>2.6</td>
</tr>
<tr>
<td>3.1</td>
<td>2.8</td>
</tr>
</tbody>
</table>

a) Use a graph to quantify the patterns in the data in the table.
Slope determination:

\[ \frac{\Delta y}{\Delta x} = \frac{\Delta \text{Mass of } Hg (g)}{\Delta \text{Mass of } HgO (g)} = \frac{3 - 0}{3.25 - 0} = 0.92 \]

This value will change depending on which values from the graph they use to calculate the slope. Students will be plotting the points from the table and doing their best to manually produce a line of best fit. From that line they need to take two points to calculate the slope, not original data points. Make sure they use points from the line of best fit to calculate the slope. Any reasonable points are acceptable.

Mass of Hg (g) = 0.92 × [Mass of HgO (g)]

b) Using words, describe the physical relationship expressed in part a.

This relationship is a direct proportion, as both increase by a constant proportion. The y-intercept equals zero because if there is no HgO being heated no Hg will be left over.

The slope of 0.92 is the constant proportion that means that 92% of the mass of HgO is from the Hg.

Part (a) 4 points
1 point for a reasonable scale – equal intervals between numbers and numbers that are not more than 2 or 3 significant figures – on both axes and properly labeled axes with units
1 = correct; 0 = incorrect
3 points for the equation of the line: 1 point for a y-intercept of zero; 2 points for the slope

Part (b) 4 points
2 point for the concept of directly proportional. They do not have to say direct proportion but they do need to convey the concept.
1 point for explanation about y-intercept = 0
1 points for explanation about the meaning of the slope

Exam 2 Question:

E2 Q. (8 points) A titration is a method used to analyze precise quantities of reactant in the titration flask. A buret is used to deliver a second reactant to the flask, and an indicator shows the endpoint of the reaction. Students in general chemistry course similar to yours collected data from a titration of sodium hydroxide and hydrochloric acid. Sodium hydroxide was delivered to a flask containing hydrochloric acid left over from a reaction with zinc. The amount of sodium
hydroxide required to reach the endpoint of the reaction indicated the number of moles of excess hydrochloric acid. From that the students subtracted moles of hydrochloric acid titrated from initial moles used to determine the moles of hydrochloric acid that had reacted with the zinc prior to titration. The students then wanted to determine the mole relationship between the hydrochloric acid that reacted with the zinc and the zinc. Their data is displayed in the table below:

<table>
<thead>
<tr>
<th>HCl reacted with Zn (mol)</th>
<th>Zn (g)</th>
<th>Zn (mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.002</td>
<td>0.104</td>
<td>0.00159</td>
</tr>
<tr>
<td>0.006</td>
<td>0.183</td>
<td>0.00280</td>
</tr>
<tr>
<td>0.008</td>
<td>0.255</td>
<td>0.00390</td>
</tr>
<tr>
<td>0.009</td>
<td>0.322</td>
<td>0.00493</td>
</tr>
<tr>
<td>0.012</td>
<td>0.391</td>
<td>0.00598</td>
</tr>
</tbody>
</table>

a) Given the data in the table, construct a graph and use the pattern to quantify the mole ratio of reacted hydrochloric acid and zinc.

This would require the students to convert g Zn to mol Zn, shown in the table.

Ex: 0.104 g Zn x \( \frac{1 \text{ mol Zn}}{65.38 \text{ g Zn}} \) = 0.00159 mol Zn

![Graph](image)

\[ y = mx + b \]
\[ \Delta y = \frac{\Delta HCl (mol)}{\Delta Zn (mol)} = \frac{0.008 - 0}{0.004 - 0} = 2 \]

This value will change depending on which values from the best-fit straight line they use to calculate the slope. Make sure they use points from the line of best fit to calculate the slope. Any reasonable points are acceptable.

mol HCl reacted with Zn = 2 x mol of Zn, b = 0

b) Using words, describe the meaning of the physical relationship expressed in part a.

This is a directly proportional relationship, as both moles of HCl and moles of Zn increase by a constant proportion of 2. The equation from part a, mol HCl reacted with Zn = 2 x mol of Zn, shows a y-intercept of zero because if there is no Zn being added to the HCl no HCl will react with it. The slope of 2 is the constant proportion that means there are 2 moles of HCl reacting with every 1 mole of Zn.
Part (a) 6 points
2 points for the conversion of g Zn to mol Zn
1 point for a reasonable scale on both axes
1 point for properly labeled axes with units
2 points for the equation of the line: 1 point for a y-intercept of zero; 1 point for the slope

Part (b) 2 points
1 point for directly proportional
1 point for explanation about the meaning of the slope

Exam 3 Question:

E3 Q. (8 points) Magnesium sulfate was dissolved in water and the heat of the reaction calculated. Students in general chemistry course similar to yours collected data from the reaction to determine how much heat, in kJ, was released for every mole of magnesium sulfate dissolved in water. Their data is displayed in the table below:

<table>
<thead>
<tr>
<th>MgSO4 (g)</th>
<th>Heat, Q (J)</th>
<th>MgSO4 (mol)</th>
<th>Heat, Q (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>1.25 x 10^3</td>
<td>0.017</td>
<td>1.25</td>
</tr>
<tr>
<td>3.5</td>
<td>2.30 x 10^3</td>
<td>0.029</td>
<td>2.30</td>
</tr>
<tr>
<td>5.4</td>
<td>4.20 x 10^3</td>
<td>0.045</td>
<td>4.20</td>
</tr>
<tr>
<td>6.2</td>
<td>4.70 x 10^3</td>
<td>0.052</td>
<td>4.70</td>
</tr>
<tr>
<td>7.5</td>
<td>5.80 x 10^3</td>
<td>0.062</td>
<td>5.80</td>
</tr>
</tbody>
</table>

a) Given the data in the table, construct a graph to quantify the kJ of heat released per mole of MgSO4 in the dissolution reaction of magnesium sulfate.

This would require the students to convert g MgSO4 to mol MgSO4, shown in the table.

Ex: 2.00 g MgSO4 x \( \frac{1 \text{ mol MgSO4}}{120.37 \text{ g MgSO4}} \) = 0.017 mol MgSO4

\[
y = mx + b \text{ so, } \frac{\Delta y}{\Delta x} = \frac{\Delta \text{Heat (kJ)}}{\Delta \text{MgSO4 (mol)}} = \frac{5.00 - 0}{0.055 - 0} = 91
\]
This value will change depending on which values from the best-fit straight line they use to calculate the slope. Make sure they use points from the line of best fit to calculate the slope. Any reasonable points are acceptable.

\[ \text{kJ heat} = 91 \times \text{mol MgSO}_4, \quad b = 0 \]

b) Using words, describe the meaning of the physical relationship expressed in part a.

This is a directly proportional relationship, as both heat of dissolution and moles of MgSO\textsubscript{4} increase by a constant proportion of 91. The equation from part a, \( \text{kJ heat} = 91 \times \text{mol MgSO}_4 \), shows a y-intercept of zero because if there is no MgSO\textsubscript{4} being dissolved in water no heat will be released. The slope of 91 is the constant proportion that means there are 91 kJ of heat released with every 1 mole of MgSO\textsubscript{4} dissolved in water.

Part (a) 6 points
2 points for the conversion of g MgSO\textsubscript{4} to mol MgSO\textsubscript{4}
1 point for conversion of J to kJ
1 point for properly labeled axes with units
2 points for the equation of the line: 1 point for a y-intercept of zero; 1 point for the slope
(-4 setup if there is no conversion)

Part (b) 2 points
1 point for directly proportional
1 point for explanation about the meaning of the slope

Exam 4 Question:

E4 Q. (8 points)

a) Explain what it means for two variables to be directly proportional.
4 points

Two variables are directly proportional if they increase in a constant ratio / as one variable increases the other increases at the same rate.
If the ratio \( y/x \) is constant they are directly proportional

(0,0) is a point on the graph

b) Are these variables directly proportional? Why or why not?

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-5</td>
</tr>
<tr>
<td>1</td>
<td>-4</td>
</tr>
<tr>
<td>2</td>
<td>-3</td>
</tr>
<tr>
<td>3</td>
<td>-2</td>
</tr>
<tr>
<td>4</td>
<td>-1</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
</tr>
</tbody>
</table>

2 points
No, $k$ is not a constant and $(0,0)$ is not a pair in the table.

c) Explain what it means for two variables to be inversely proportional.

2 points

Two variables are inversely proportional if one changes as the reciprocal of the other / one variable decreases at the same rate the other increases.

If the product of $x$ and $y$ is constant they are inversely proportional.

3.5.4 Research surveys.

Table 19 lists the surveys that were used to investigate the research questions, describes each variable, and provides the scales that were used during analysis. Following the table are detailed descriptions of each survey.

Table 19

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Abbreviation Used</th>
<th>Characteristic Measured</th>
<th>Continuous Scale</th>
<th>Grouped Scales</th>
</tr>
</thead>
<tbody>
<tr>
<td>Textbook Reading Pilot</td>
<td>TRP</td>
<td>Extraction of learning objective</td>
<td>N/A</td>
<td>Mathematical: 0 – 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>mathematically and textually</td>
<td></td>
<td>Written: 0 – 2 (No, Partial, Yes)</td>
</tr>
<tr>
<td>Demographic Questionnaire</td>
<td>DQ</td>
<td>Experience with story problems and inquiry</td>
<td>Story Problems:</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>labs in math, physics, and chemistry</td>
<td>0 – 100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Inquiry Labs:</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0 – 100%</td>
<td></td>
</tr>
</tbody>
</table>

Textbook reading skills from a representative textbook passage: Textbook Reading Pilot (TRP)

The Textbook Reading Pilot (TRP) was developed to measure how accurately students could extract the intended learning objective from the material, both mathematically and textually. In addition, the TRP explored what aspects of a textbook passage – graphs, tables, or text – students focus on and why, including features within each of those aspects. The survey consisted of a short example textbook passage with three questions, one of which asks students to highlight what they focus on and explain why. The TRP has been used in a pilot study and was developed by the researcher. It is not a validated instrument and was used out of curiosity since it showed over 14% of second semester general chemistry students could not explain the intended learning objective in a short text. Students were given 10 minutes to complete the survey. Results indicated that in second semester general chemistry:

1. 14% of students, when given a short textbook passage explaining a mathematical relationship presented explicitly within the body of the text or in a graph or table, where unable to write the mathematical expression.

2. 17% of students, when given a short textbook passage explaining a mathematical relationship presented explicitly within the body of the text or in a graph or table, where unable to write the relationship in words.
3. 67% of students, when given a short textbook passage explaining a mathematical relationship presented explicitly within the body of the text or in a graph or table, focused on the body of the text, not the graph or table.

4. 83% of students, who were unable to either write the mathematical expression or write the relationship in words, focused on the body of the text, not the graph or table.

General student information: Demographic Questionnaire (DQ)

The Demographic Questionnaire was developed to acquire general information from students: age, gender, year in school, high school math, transfer students, and parent’s highest level of education. It also asked students about their prior experience with use of story problems and inquiry labs in high school math, physics, and chemistry. Students were given 20 minutes to complete this survey.

3.5.5 Research questions and data analysis plan.

The specific research questions, related hypotheses, and expected outcomes are listed below. Specific terms were used as defined in Chapters 2 and 3, but the key terms employed in the study are reiterated here to provide a more convenient reference.

Skill – a demonstrated ability.

Transfer – ability to apply math-graphing skills to a science context.

Domain – an area of context, i.e. math, chemistry, economics, etc.

Scientific reasoning ability – ability to do proportional reasoning, combinatorial reasoning, probabilistic reasoning, control of variables, etc. These are listed in Section 1.1.3.1 Scientific Reasoning.

Learning objective – a statement of what the student will be able to do after studying a given textbook passage.

Inquiry labs – laboratories that occur before the concepts are introduced in lecture, allowing for students to collect data and construct their own initial conceptual understanding.

The research questions are divided into three categories: Transfer, Correlations to Transfer, and Treatments.

3.5.5.1 Transfer research questions.

It has been found that students enter general chemistry with adequate mathematical skills in arithmetic, algebra, and graphing. However, there still seems to be a disconnect between math and chemistry because there is a high failure rate of 50% or higher (Chambers & Blake, 2008; Gafney, 2001; Gellene & Bentley, 2005) in general chemistry. It appears to stem from students having a demonstrated difficulty with math use in chemistry context (Britton et al., 2005; Menis, 1987; Ngu & Yeung, 2012; Ngu et al., 2015; Nicoll & Franscisco, 2001).
This leads us to ask: Is transfer where the difficulty with chemistry lies? The following are questions, hypotheses, and expected outcomes that will help quantify this issue as it relates to graphing. Each hypothesis will be denoted as “H”, followed by a subscript number correlating to the question number it relates to. The predictions will be denoted similarly with a “P”.

1. Will there be a difference in students’ ability to transfer, as measured by the Transfer Index score using the Roberts et al. (2007) transfer formula for the Test on Graphs, depending on the Transfer Category, math to physics (M to P) or math to economics (M to E), based on a paired samples t-test? The paired samples t-test incorporates within subject grouping. Power of 0.95 or higher assuming a small effect size (e.g., dz = 0.33) for a two-tailed t-test is estimated to require 122 participants. More than 122 participants completed the Test on Graphs.

H1: It has been observed in the literature that students have difficulty applying their math-graphing skills to other contexts (Beichner, 1994; Dori & Sasson, 2008; Planinic et al., 2012; Potgieter et al., 2008; Roberts et al., 2007; Stern et al., 2004). In the study we expect to see no difference in scores for students applying their math-graphing domain skills to an economics context as compared to the application to a physics context because students tend to be context bound (Beauford, 2009; Catrambone & Holyoak, 1989; Johnson & Rutherford, 2010; Planinic et al., 2012; Roberts et al., 2007), making it difficult for them to recognize the same underlying structure on both the math and application domains (Becker & Towns, 2012; Bassok & Holyoak, 1989; Catrambone & Holyoak, 1989; Hester et al., 2014; Johnson & Rutherford, 2010; Ngu & Yeung, 2012). This means that while they may perform at a higher level in the math domain alone, they will have similar difficulty applying those math-graphing skills to other contexts.

The distributions for both math to physics and math to economics are shown below and meet the assumption of a normal distribution so parametric tests are used. To investigate the research question, the continuous dependent variable of Transfer Index (0-100%) is compared based on the Transfer Category of (a) M to P and (b) M to E.

![Figure 9. Distribution of transfer index for math-to-physics and math-to-economics contexts.](image)

P1: No, students will perform with similar Transfer Indices on both Transfer Categories, demonstrating a lack of transfer. $\bar{x}_{\text{physics}} = \bar{x}_{\text{economics}}$
2. Is students’ scientific accuracy score on their first exam, as measured by the graphing rubric developed from a compilation of expert answer keys, a function of their Transfer Index score, as measured using the Roberts et al. (2007) transfer formula for the Test on Graphs and Transfer Category—M to P and M to E? The analysis is based on two linear regressions and their difference in slopes for one group with two predictors. Power of 0.95 or higher assuming a small effect size (e.g., $f^2 = 0.11$) is estimated to require 121 participants. More than 121 participants completed exam one.

$H_2$: If students perform with higher transfer scores initially, they will demonstrate higher scientific accuracy, based on the rubric score on the graphing exam questions, because students who can transfer demonstrate an ability to think abstractly and see the underlying problem structure (Bassok & Holyoak, 1989; De Bock et al., 2011; Gick & Holyoak, 1983; Holyoak & Koh, 1987; Menis, 1987; Nicoll & Franscisco, 2001; Ngu & Yeung, 2012; Ngu et al., 2015; Terwel et al., 2009).

The distributions for scientific accuracy on exam one are shown below and approximates a normal distribution. Transfer Indices distributions can be seen above in question 1. The dependent variable is the continuous variable of scientific accuracy (scores from 0-11) on the graphing question on exam 1. The continuous (0-100%) independent variable is Transfer Index score (0-100%), grouped by Transfer Category.
P.2a: Yes, students’ scientific accuracy will be a function of Transfer Index score.

\[ \text{Scientific Accuracy on Exam 1 Based on Incoming Transfer Index} \]

![Figure 12. Predicted graph of scientific accuracy as a function of transfer index on exam 1.](image)

H.2b: If students demonstrate a certain level of ability to transfer as measured by their Transfer Index, then they will show an increase in their scientific accuracy because there may be robust misconceptions or an inability to focus on all aspects of graphing until students have already reached a certain level of capability (Bowen et al., 1999; Leinhardt et al., 1990; Moschkovich, 1998).

P.2b: Yes, students will show higher scientific accuracy scores on the graphing exam questions after a certain level of transfer ability.

\[ \text{Scientific Accuracy on Exam 1 Based on Incoming Transfer Index} \]

![Figure 13. Alternate predicted graph of scientific accuracy as a function of transfer index on exam 1.](image)

3. Is scientific graph accuracy, as measured by the graphing rubric developed from a compilation of expert answer keys, a function of time, based on each graphing question across the three exams? The analysis is based on repeated measures, within factor ANOVA, which has a continuous dependent variable with three levels of an independent variable. Power of 0.95 or higher assuming a small effect size (e.g., \( f = 0.33 \)) and a correlation among repeated measures of 0.1, is estimated to require 45 participants. More than 45 participants completed all three exams.

H.3: If students receive and learn from feedback on their previous exams they will show increased performance in subsequent exams because the feedback will show them how to
The distributions for scientific graph accuracy for all three exams are shown below and approximate normal distributions. The dependent variable is the continuous variable of scientific accuracy (scores from 0-11). The independent variable is time, across three within-subject exam levels.

Figure 14. Distribution of scientific accuracy on exam 1.

Figure 15. Distribution of scientific accuracy on exam 2.

Figure 16. Distribution of scientific accuracy on exam 3.
P3: Yes, scientific accuracy will be a function of time; students will show an increase in scientific accuracy across the three exams.

Figure 17. Predicted graph of scientific accuracy as a function of time.

3.5.5.2 Premeasure correlations to transfer.

Other measures have been shown to predict performance in chemistry: scientific reasoning (Bird, 2010; Cantu & Herron, 1978; Cracolice & Busby, 2015; Lawson & Renner, 1975; Lewis & Lewis, 2010), prior content knowledge and alternate conceptions (Cracolice & Busby, 2015; Garnett, Garnett, & Hackling, 1995; Hale, 2000; Nakhleh, 1992), and intelligence (Neisser et al., 1996). We therefore pilot students' ability to accurately read a textbook and collect student self-reported data on their prior experience with story problems and inquiry labs to investigate if there are any correlations to their ability to transfer.

If transfer is an issue for college chemistry students, we want to see how measures— that have been shown to affect performance— are related to students' ability to transfer math-graphing skills to other contexts in this section.

4. Is Transfer Index score, as measured using the Roberts et al. (2007) transfer formula for the Test on Graphs, a function of incoming math-graphing ability, as measured by the TOGS, and Transfer Category – M to P or M to E? The analysis is based on two linear regressions and their difference in slopes. Power of 0.95 or higher assuming a small effect size (e.g., $f^2 = 0.11$) is estimated to require 121 participants. More than 121 participants completed both the Test on Graphs and the TOGS assessments.

H4: If students demonstrate higher basic graphing skills, they will not necessarily show higher scores in transfer because, while having prior knowledge is necessary for transfer to occur (Bassok & Holyoak, 1989; Menis, 1987; Potgieter et al., 2008; Scott, 2012), it does not ensure transfer. Abstracted schemas must still be constructed to link the prior knowledge to the target problem, and data has shown that having basic math graphing does not mean one can transfer (Beichner, 1994; Cunningham, 2005; Planinic et al., 2008; Roberts et al., 2007).

The distributions for the Transfer Indices are shown in question one. The TOGS distribution is shown below and approximates normal distribution. To investigate the research question, the
continuous dependent variable of Transfer Index (0-100%) is correlated to the continuous independent TOGS score variable (0-26) across Transfer Category.

![Frequency of Each Possible TOGS Score](image)

**Figure 18.** Distribution of prior math-graphing skills.

$P_4$: No, Transfer Index score will not be a function of high school math-graphing ability.

![Transfer Index Based on High-School Math-Graphing Skills](image)

**Figure 19.** Predicted graph of transfer index as a function of prior math-graphing skills.

5. Is Transfer Index, as measured using the Roberts et al. (2007) transfer formula for the *Test on Graphs*, a function of scientific reasoning, as measured by the CTSR, and Transfer Category – M to P or M to E? The analysis is based on two linear regressions and their difference in slopes. Power of 0.95 or higher assuming a small effect size (e.g., $f^2 = 0.11$) is estimated to require 121 participants. More than 121 participants completed both the *Test on Graphs* and the CTSR assessments.

$H_5$: If students have higher scientific reasoning ability, they will produce higher scores on the graphing transfer domains because scientific reasoning has been shown to correlate to ability to transfer (Dori & Sasson, 2008; Kapur, 2014; Lappalainen & Rosqvist, 2015; Menis, 1987; Nicoll & Francisco, 2001; Roberts et al., 2007; Sasson & Dori, 2012).

The distributions for the Transfer Indices are shown in question one. The CTSR distribution is shown below and meets the assumption of a normal distribution. To investigate the research
question, the continuous dependent variable of Transfer Index (0-100%) is correlated to the continuous independent CTSR score variable (0-12) across Transfer Category.

![Frequency of Each Possible CTSR Score](image)

*Figure 20.* Distribution of scientific reasoning scores.

P₅: Yes, Transfer Index score will be a function of scientific reasoning.

![Transfer Index Based on Scientific Reasoning](image)

*Figure 21.* Predicted graph of transfer index as a function of scientific reasoning.

6. Is Transfer Index, as measured using the Roberts et al. (2007) transfer formula for the *Test on Graphs*, a function of students’ chemical misconceptions, as measured by the CCI, and Transfer Category – M to P or M to E? The analysis is based on two linear regressions and their difference in slopes. Power of 0.95 or higher assuming a small effect size (e.g., $f^2 = 0.11$) is estimated to require 121 participants. More than 121 participants completed both the *Test on Graphs* and the CCI assessments.

H₀: If students come into general chemistry with fewer misconceptions about chemistry concepts they will produce higher scores on transfer because the students will already understand abstract concepts, meaning they will not be context bound (Beauford, 2009; Catrambone & Holyoak, 1989; Johnson & Rutherford, 2010; Planinic et al., 2012; Roberts et al., 2007).

The distributions for the Transfer Indices are shown in question one. The CCI distribution is shown below and meets the assumption of a normal distribution. To investigate the research
question, the continuous dependent variable of Transfer Index (0-100%) is correlated to the continuous independent CCI score variable (0-16) across Transfer Category.

![Frequency of Each Possible CCI Score](image)

*Figure 22. Distribution of chemistry content knowledge and alternate conceptions.*

P₆: Yes, Transfer Index score will be a function of chemical misconceptions; students with fewer misconceptions (higher CCI score) will be show higher scores on transfer.

![Transfer Index Based on Chemistry Misconceptions](image)

*Figure 23. Predicted graph of transfer index as a function of alternate chemical conceptions.*

7. Is Transfer Index, as measured using the Roberts et al. (2007) transfer formula for the *Test on Graphs*, a function of students’ intelligence, as measured by the SPM+, and Transfer Category – M to P or M to E? The analysis is based on two linear regressions and their difference in slopes. Power of 0.95 or higher assuming a small effect size (e.g., $r^2 = 0.11$) is estimated to require 121 participants. More than 121 participants completed both the *Test on Graphs* and the SPM+ assessments.

$H_7$: If students have higher IQ, they will not perform higher on transfer because, while higher general intelligence has been linked to greater mathematical achievement (McGrew & Wendling, 2010), it has not been shown to influence performance in chemistry, and mathematical achievement alone is not enough for transfer to occur (Beichner, 1994; Cunningham, 2005; Planinic et al., 2008; Roberts et al., 2007).

The distributions for the Transfer Indices are shown in question one. The SPM+ distribution is shown below and meets the assumption of a normal distribution. To investigate the research
question, the continuous dependent variable of Transfer Index (0-100%) is correlated to the continuous independent SPM+ score variable (0-60) across Transfer Category.

![Frequency of Each Possible SPM+ Score](image)

*Figure 24. Distribution of intelligence.*

\( P_7: \) No, Transfer Index score will not be a function of IQ.

![Transfer Index Based on Intelligence](image)

*Figure 25. Predicted graph of transfer index as a function of intelligence.*

8. Is Transfer Index score, as measured using the Roberts et al. (2007) transfer formula for the *Test on Graphs*, a function of each of the previous dependent variables: incoming math-graphing ability as measured by the TOGS, scientific reasoning as measured by the CTSR, chemical misconceptions, as measured by the CCI, intelligence as measured by the SPM+, and Transfer Category – M to P or M to E? The analysis is based on two multiple linear regressions and their difference in slopes. Power of 0.95 or higher assuming a small effect size (e.g., \( f^2 = 0.11 \)) is estimated to require 121 participants. More than 121 participants completed both the *Test on Graphs* and all assessments.

\( H_5: \) If students demonstrate higher basic graphing skills, they will not necessarily show higher scores in transfer because, while having prior knowledge is necessary for transfer to occur (Bassok & Holyoak, 1989; Menis, 1987; Potgieter et al., 2008; Scott, 2012), it does not ensure transfer. Abstracted schemas must still be constructed to link the prior knowledge to the target problem, and data has shown that having basic math graphing does not mean one can transfer (Beichner, 1994; Cunningham, 2005; Planinic et al., 2008; Roberts et al., 2007).
If students have higher scientific reasoning ability, they will produce higher scores on the graphing transfer domains because scientific reasoning has been shown to correlate to ability to transfer (Dori & Sasson, 2008; Kapur, 2014; Lappalainen & Rosqvist, 2015; Menis, 1987; Nicoll & Francisco, 2001; Roberts et al., 2007; Sasson & Dori, 2012).

If students come into general chemistry with fewer misconceptions about chemistry concepts they will produce higher scores on transfer because the students will already understand abstract concepts, meaning they will not be context bound (Beauford, 2009; Catrambone & Holyoak, 1989; Johnson & Rutherford, 2010; Planinic et al., 2012; Roberts et al., 2007).

If students have higher IQ, they will not perform higher on transfer because, while higher general intelligence has been linked to greater mathematic achievement (McGrew & Wendling, 2010), it has not been shown to influence performance in chemistry, and mathematical achievement alone is not enough for transfer to occur (Beichner, 1994; Cunningham, 2005; Planinic et al., 2008; Roberts et al., 2007).

The distributions for the Transfer Indices are shown in question one and the distributions for the other assessments are seen in questions 4–7.

P8: No, Transfer Index score will not be a function of high school math-graphing ability or IQ, but it will be a function of scientific reasoning and chemical misconceptions; students with fewer misconceptions (higher CCI score) will be show higher scores on transfer.

9. Is Transfer Index, as measured using the Roberts et al. (2007) transfer formula for the Test on Graphs, and percent story problems, as assessed by the student self-reported percentages from the demographics questionnaire, a function of story problem type—math, physics, or chemistry—and Transfer Category—M to P or M to E? The analysis is based on two sets of four linear regressions and comparing their differences in slopes. Power of 0.95 or higher assuming a small effect size (e.g., \( f^2 = 0.11 \)) was estimated to require 121 participants. More than 121 participants completed both the Test on Graphs and the demographics questionnaire.

H0: Students with more story problem experience will score higher in transfer because story problem solving requires greater logical reasoning, which is correlated to transfer (Dori & Sasson, 2008; Kapur, 2014; Nicoll & Francisco, 2001; Sasson & Dori, 2012, 2015).

The distributions for the Transfer Indices are shown in question one. The percent story problem distributions are shown below and meet the assumption of a normal distribution. To investigate the research question, the continuous dependent variables of Transfer Index (0-100%) and % Story Problem score (0-100%) are compared based on the three types of story problem and Transfer Category.
Figure 26. Distribution of percent story problems in high school based on course.

P9: Yes, Transfer Index Score will be a function of percent story problems in high school.

Figure 27. Predicted graph of transfer index as a function of percent story problems in high school.

Figure 28. Predicted graph of percent story problems in high school as a function of course type.
10. Is Transfer Index, as measured using the Roberts et al. (2007) transfer formula for the *Test on Graphs*, a function of high school experience with inquiry labs, as measured by the student self-reported percentages from the demographic questionnaire by type, and Transfer Category—M to P or M to E? The analysis is based on two sets of two linear regressions and comparing their differences in slopes. Power of 0.95 or higher assuming a small effect size (e.g., $f^2 = 0.11$) was estimated to require 121 participants. There were 165 students who completed both the *Test on Graphs* and the demographics questionnaire.

$H_{10}$: If students have had greater inquiry experience, they will show higher transfer scores because students will have constructed conceptual understanding and developed higher reasoning skills, which are correlated to transfer (Cantu & Herron, 1978; Dori & Sasson, 2008; Kapur, 2014; Lappalainen & Rosqvist, 2015; Lawson & Renner, 1975; Marek & Cavallo, 1997; Menis, 1987; Nicoll & Francisc, 2001; Piaget, 1970, 1997; Roberts et al., 2007; Sasson & Dori, 2012).

The distributions for the Transfer Indices are shown in question one. The percent inquiry labs distribution is shown below and meet the assumption of a normal distribution. To investigate the research question, the continuous dependent variable of Transfer Index (0-100%) is compared based on the continuous independent variable of Inquiry Labs (0-100%) across two within-subject types—Chemistry and Physics—and Transfer Category. Inquiry lab percent was made continuous by taking averages of each category percent.
P10: Yes, Transfer Index score will be a function of percent inquiry labs students experienced in high school.

![Graph of Transfer Index Based on % Inquiry Labs Done in High School](image)

*Figure 31.* Predicted graph of transfer index as a function of percent inquiry labs in high school.

### 3.5.5.3 Instructional treatments.

In addition to possible predictive student characteristics, if transfer is an issue, can any specific instructional treatments improve ability to transfer? If students are given specific direction on how to graph, either strictly mathematically or via a chemistry analogy, will those different treatments affect how students construct graphs from data and interpret the concept presented as measured by lab reports and exam questions?

11. Is students’ percentage of spontaneous graphing in laboratory, as measured by

\[
\frac{\text{# graphs drawn in lab question A}}{\text{total graphs possible}} \times 100
\]

a function of the graphing instructional treatment they received at the beginning of the course? Is this also affected by whether participants were given explicit, prompted, graphing instruction for their first laboratory? Two sets of questions on the first week’s lab was given to two groups of participants. One set of questions investigated what students do spontaneously when asked to describe a pattern shown in their data – no prompt. The other set of questions provided complete instructions about what to graph to see how accurately students could construct a graph with guidance – prompt. The analysis is based on a $2 \times 3$, between-subject ANOVA, which has a continuous dependent variable of percent graphs drawn in lab, with three groups of instructional treatments for one independent variable, and two levels of being prompted, or not, for the second independent variable. Power of 0.95 or higher assuming a small effect size (e.g., $f = 0.33$), is estimated to require 147 participants. More than 147 participants completed all the labs requiring graphs to be drawn.

H11: Students who received instructional treatment with active construction of graphs will produce a higher percentage of subsequent graphs in lab than those with passive graph interpretation. Both of those groups will produce a higher percentage of graphs in lab than the students who received a worked example instructional treatment. Construction has been shown to draw attention to underlying structure and thus improve transfer (Ngu & Yeung, 2012; Ngu et al., 2015; Stern, Aprea, & Ebner, 2004; Terwel et al., 2009). Passive interpretation was also shown to improve transfer as it still drew attention to structure (Stern, Aprea, & Ebner, 2004), however, worked examples have been shown to
not improve transfer so will act as a control (Ngu & Yeung, 2012; Ngu, Yeung, & Phan, 2015; Stern et al., 2004).

Having additional explicit instruction, via prompted laboratory questions will produce a higher percentage of subsequent graphs in lab compared to those participants with an open-ended instruction. This is due to additional practice and instruction in the domain of chemistry graphing to gain graphical literacy (Bassok & Holyoak, 1989; Beauford, 2009; Becker and Towns, 2012; Bowen & Roth, 1998; Bowen et al., 1999; Kaminski & Sloutsky, 2013; Kapur, 2014; Waight & Abd-El-Khalick, 2010).

The distribution for percent graphs drawn in lab is shown below. It meets the assumption of a normal distribution. To investigate the research question, the continuous dependent variable of percent graphs drawn spontaneously in lab (0-100%) is compared based on three groups of the dependent variable, graphing instructional treatment (Active Construction—55 students, Passive Interpretation—59 students, Worked Example—61 students).

![Figure 32. Distribution of percent graphs drawn in laboratory.](image)

P11: Yes, percent spontaneous graphing in lab will be a function of instructional treatment. Students with active graphing instruction will produce a higher percentage of subsequent graphs in lab than those with passive interpretation instruction. Both groups will produce a higher percentage of subsequent graphs than those who received worked example instruction, which acts as the control.

![Figure 33. Predicted graph of percent graphs drawn as a function of instructional treatment.](image)
P_{11}: Yes, percent spontaneous graphing in lab will be a function participants being prompted with explicit graphing instruction their first week of lab as compared to those who were not prompted.

![Figure 34. Predicted graph of percent graphs drawn as a function of receiving a prompt first week of lab.](chart)

12. Is students’ scientific accuracy of graphing questions, as measured by the graphing rubric developed from a compilation of expert answer keys, a function of instructional treatment and three levels of time—Exam 1, 2, and 3? The analysis is based on a 3×3 repeated measures ANOVA, with one between category and one within category. Power of 0.95 or higher assuming a small effect size (e.g., $f = 0.33$) and a correlation among repeated measures of 0.1, is estimated to require 54 participants. More than 54 participants completed all three exams.

$H_{12}$: Students who received instructional treatment with active construction of graphs will produce a higher scientific accuracy of subsequent graphs on exams than those with passive graph interpretation. Both of those groups will produce a higher percentage of graphs in lab than the students who received a worked example instructional treatment. Construction has been shown to draw attention to underlying structure and thus improve transfer (Ngu & Yeung, 2012; Ngu et al., 2015; Stern et al., 2004; Terwel et al., 2009). Passive interpretation was also shown to improve transfer because it drew attention to structure (Stern et al., 2004); however, worked examples have been shown to not improve transfer (Ngu & Yeung, 2012; Ngu et al., 2015; Stern et al., 2004).

The distributions for scientific graph accuracy are shown in question three for all three exams. To investigate the research question, the continuous dependent variable of scientific accuracy (0-11) is compared based on the independent variables of three groups of instructional treatments (Active Construction—55 students, Passive Interpretation—59 students, Worked Example—61 students) across three exams.

$P_{12}$: Yes, scientific accuracy will be a function of instruction treatment across the three exams. Students with active graphing instruction will produce a greater scientific accuracy on exams than those with passive interpretation instruction. Both groups will produce greater scientific accuracy than those who received worked example instruction, which acts as the control.
3.6 Qualitative Research

3.6.1 Participants.

Clinical interviews were conducted with purposeful selection of students in the second half of the semester. Two students from three levels of performance (low, medium, high) on the Test on Graphs were asked to participate in the corresponding clinical interviews. There was a total of 48 points possible on the Test on Graphs instrument. A histogram of frequency of scores was divided into thirds, so scores between 0–16 were considered low, between 17–32 were considered medium, and between 33–48 were considered high.

Students who missed the last four quizzes in a row for the lecture portion of the course were removed from the pool, with the assumption they were no longer regularly attending the course. Names with their Test on Graphs score were put on strips of paper, folded, and placed in a hat. Another individual, not the researcher, pulled names from the hat randomly and those students were emailed to determine if they would consent to an interview. Between four and five students from each level of performance agreed to be interviewed, resulting in 13 total participants.

3.6.2 Research design.

This portion of the research was a qualitative phenomenological study. The purpose of this phenomenological study was to understand the phenomenon of transfer; to gain further understanding of how students in a first semester general chemistry course interpret graphs that represent a physical relationship in a chemistry context using mathematical skills. The design of this study was meant to explore the lived experience of specific participants within the phenomenon of graphical interpretation in chemistry. The goal of this study was to recognize and draw out themes within the experienced phenomenon.

3.6.2.1 Central questions and sub-questions.

The specific research question that this section of the study answers is:

How do college general chemistry students reason through the construction and interpretation of a graphical representation, including the algebraic expression, of a physical relationship in a
chemistry context; do they recognize that their mathematical skills are the underlying structure for the chemistry graphs?

Several sub-questions include, in continuation from the quantitative questions:

13. What math skills do the students possess?

14. What do students think about when they see a table of abstract math values?

15. What do students think about when they see a graph of abstract math values?

16. What do students do to determine the equation of a line on a graph of abstract math values?

17. What do students think about when they see a table of chemistry values – a math value with a unit?

18. What do students think about when they see a graph of chemistry values?

19. What do students do to determine the equation of a line on a graph of chemistry values?

20. What do students recognize as the underlying structure of the chemistry graph calculations?

21. What differences do students recognize between the two contexts?

22. What relationships do students recognize in chemistry graphs?

23. What are students’ general understanding of graphs—its purpose?

24. What skills do students apply to both math and chemistry graphs?

25. What did students learn about graphing this semester?

### 3.6.2.2 Procedures.

For data collection, face-to-face interviews were conducted with each participant during the second half of the semester. Interviews took about 30 minutes. The audio of all interviews was recorded and notes were taken simultaneously. The interview notes include the interviewer’s observations of non-verbal communication expressed by the participant. The researcher referred to audio recordings as necessary for clarity while coding results.

To develop trustworthiness and accuracy of the findings, a rich description was derived from the interviews, accurate themes provided, and shared characteristics explained to lead to transferability. Member checking, where established themes and rich description were presented back to the participants to determine if they find the results accurate, were utilized during the interview process to help ensure credibility. Notes were sent to a fellow researcher for peer review to provide additional trustworthiness through the other researcher’s perspectives and to aid in the interpretation of the data. Any contradictory or discrepant information that is counter to the themes was also presented to ensure the reality of the experienced phenomenon.
Qualitative validity was further established, as researcher bias was monitored to reveal the researcher’s position and potential assumptions that may influence the interpretation. As a college graduate, there is a need to recognize that the researcher too experienced difficulties in learning and did not want to appear sympathetic to student difficulties. Conversely, while still a student, the researcher is still at a more advanced level of education and does not want to belittle or come across as superior. Due to personal experience with this phenomenon, it was important to be conscientious of leading questions, anticipating responses, or interpreting responses from the researcher’s own viewpoint and experiences. Specifically, as it relates to transfer, the researcher took care not assume that those who performed at higher levels on the transfer instrument would answer the interview questions on graphing with more depth of insight, particularly those questions that were meant to determine if transfer did take place during the course.

Qualitative reliability was established via double-checking transcripts to ensure no obvious mistakes were made during transcription.

3.6.3 Data analysis.

Step 1
The analysis procedure for this qualitative phenomenological study includes first recognizing and setting aside the researcher’s personal bias prior to collecting data. This bias is expressed above. This bracketing allows for a closer experience of the phenomenon.

Step 2
All data was read through to obtain a general sense of the overall meaning of the data, and then organized and sorted into categories. To do so, each document was read and thoughts where written for each concerning the underlying meaning. A list of all topics was made and similar topics clustered together.

Step 3
Detailed analysis began with coding. Each of the topics above received an abbreviated code and the codes were written next to the relevant text. Each category was labeled with a term based in the language of the participants. The data collected from the face-to-face interviews was organized into specific statements. According to Moustakas (1994), these significant statements are referred to as “horizontalization of the data” and each has equal worth (as sited in Creswell, 2007, p. 159). The statements were grouped within larger theme statements referred to as “meaning units” (p. 159).

Step 4
The researcher wrote a description of what the participants experienced within the phenomenon followed by writing a description of how the experience happened. These are referred to as “textural description” and “structural description” (p. 159).

Step 5
An overall description of the phenomenon tied together the textural and structural descriptions. This portion is capturing the “essence” (p. 159) of the phenomenon (Moustakas, 1994, as sited in Creswell 2007).
3.6.3.1 Delimitations.

The participants of this mixed methods study were University of Montana-Missoula College students enrolled in the 2016 Fall term of first semester general chemistry. This mixed methods study was comprised of undergraduate students. Participants include traditional and non-traditional students of any major enrolled in CHMY 141 (College Chemistry I).

3.6.3.2 Limitations.

Quantitative research has several potential limitations to its validity. The participants of the experiment may be influenced from outside sources that result in a change in maturity apart from the experiment as the experiment occurs over an extended period. As with any college course, students may drop out at any point during the semester, so results may have been skewed. Final outcomes for those students are unknown and inconclusive. While we attempted to keep the control and treatment groups separate, students within the same course could interact outside of class and may have influenced the results within the groups. Treatments were not random, but based on time of laboratory, which students select for themselves. This implies that results cannot be applied to a larger population, only suggested.

However, there is no difference in reasoning ability across times, so it is claimed that each group within the time periods is equivalent. Each section of students also includes males and females we believe to be representative of students in other college general chemistry courses. All information gained from assessments is only as good as the instruments themselves. Most the instruments are shown to be valid and reliable and have been pilot tested.

The nature of qualitative research is to focus on each subjects’ own unique experience. Because of this, the findings of this qualitative study are not able to be generalized. However, the human experience and phenomenon of transfer of math-graphing skills to chemistry context was transferable. Potential lack of transferability could arise from selecting participants who, though having trouble with transfer, may be unable to verbally articulate the phenomenon. Another limitation may have included the relationship between the participant and researcher. If a trusting relationship is not achieved between the researcher and participant, the researcher may not have fully gain the participant’s interpretation of his or her learning experience. Information gleaned from interviews was also indirect, as it was filtered through the views of the participants. In addition, the information was presented outside a natural setting, and the presence of the researcher may have biased responses. Each participant shows varying degrees of articulation and perception.

Intercoder agreement was not established at >80% (Miles & Huberman, 1994); however, the advisor to the primary investigator was asked to cross-check the researcher's codes and provided feedback to improve the researcher’s coding direction.
Chapter 4: Results

The overarching goal of this research was to determine if participants demonstrated the ability to transfer math-graphing skills to a science context. The first phase of this study was quantitative. Several assessments were administered and data were collected and analyzed. Specifically, the quantitative research questions posed were within these four categories:

1. Compare ability to transfer math-graphing skills to two other domains.
2. Relate ability to transfer graphing skills to scientific accuracy of graphs constructed on chemistry exams.
3. Relate scientific reasoning ability, prior content knowledge, intelligence, textbook reading, experience with story problems, and experience with inquiry labs to ability to transfer math-graphing skills into science context.

The second phase of this study was qualitative. Interview questions were used to probe participants’ understanding of graphs and their ability to transfer graphing skills into a chemistry context.

4.1 Quantitative Results

Participants were given five assessments at the beginning of the first semester of a general chemistry course to establish baseline levels of skills that have been shown to measure aspects of thought relevant to math transfer. These were the: Classroom Test of Scientific Reasoning (CTSR), Chemical Concepts Inventory (CCI), Raven’s Standard Progressive Matrices Plus (SPM+), Textbook Reading Pilot (TRP), and Test of Graphing Skills (TOGS). They are described in detail in Section 3.5.3 Research instruments. The students completed these in their laboratory sections during the first two weeks of the 15-week semester. Other instruments were administered throughout the semester: Scientific accuracy of graphs constructed in lab or on exams based on chemistry expert rubrics, and Transfer Index, which is the comparative scores on math-graphing abilities to the two science domains on the Test on Graphs.

The twelve quantitative research questions that were asked were described, with a literature-based hypothesis and prediction, in Section 3.5 Quantitative Research. A review of each quantitative research question follows, including the question and prediction originally discussed in Section 3.5.5 Research questions and data analysis plan. The graphs included with the original prediction were not created with real data; they are simply predicted, hypothetical results. Actual quantitative statistical analyses were done in R, a widely-used free statistical program and language that allows for statistical analysis and graphing, and double-checked in Statistical Package for the Social Sciences (SPSS), as well as discussed and reviewed with a statistical expert. For comparative code and data in R refer to Appendix Q – Data from R. Results from each analysis follow the predictions for each question. Tables generally were taken from SPSS and graphics from R. This choice was made based on aesthetics from both programs.

When appropriate, graphs show error bars with ±1 standard error (SE), which is equivalent to a 68% confidence interval (CI) (Cumming & Finch, 2005). When using ±1 SE, observing a gap between the error bars only indicates a level of significance related to the p-value, when working
4.1.1 Context impacts graphing ability.

Differences between average scores out of 16 for each of the three areas of graphing skills: math, economics, and physics, were compared and are shown in Figure 36. This analysis provides an overall picture of students’ graphing skills in these contexts prior to analyzing their transfer index scores and correlations. The question is: Will there be a difference between any of the mean context scores, as measured by the sum of scores for each context – math, economics, and physics – on the Test on Graphs?

The null hypothesis, $H_0$, states that there will be no difference between mean context scores. An alternative is predicted, specifically that participants will demonstrate highest mean scores in math context, then economics and physics. This is because it has been observed in the literature that students have difficulty applying their math-graphing skills to other contexts (Beichner, 1994; Dori & Sasson, 2008; Planinic et al., 2012; Potgieter et al., 2008; Roberts et al., 2007; Stern et al., 2004). Math scores are expected to be the highest because students tend to be context bound (Beauford, 2009; Catrambone & Holyoak, 1989; Johnson & Rutherford, 2010; Planinic et al., 2012; Roberts et al., 2007), making it difficult for them to recognize the same underlying structure on both the math and application domains (Becker & Towns, 2012; Bassok & Holyoak, 1989; Catrambone & Holyoak, 1989; Hester et al., 2014; Johnson & Rutherford, 2010; Ngu & Yeung, 2012). This means that while they may perform at a higher level in the math domain alone, they will have similar difficulty applying those math-graphing skills to other contexts.

![Figure 36. Predicted graph of mean transfer index score as a function of each category. The data depicted here are made up and meant to strictly provide a visual prediction.](image)
To test the hypothesis, an analysis was done based on repeated measures, within factor ANOVA, which has a continuous dependent variable with three levels of an independent variable. Power of 0.95 or higher assuming a small effect size (e.g., $f = 0.33$) and a correlation among repeated measures of 0.1, was estimated to require 45 participants. More than 45 participants completed all three exams. Table 20 below shows descriptive statistics from this analysis, including number of participants for each group and means.

Table 20

*Descriptive Statistics*

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Math</td>
<td>9.70</td>
<td>3.916</td>
<td>181</td>
</tr>
<tr>
<td>Economics</td>
<td>6.18</td>
<td>3.374</td>
<td>181</td>
</tr>
<tr>
<td>Physics</td>
<td>5.70</td>
<td>3.804</td>
<td>181</td>
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</table>

A graphical representation of mean scores as a function of context is shown in Figure 37 below. Because Transfer Category is a within-subject variable, the error bars do not give a visual depiction of significant difference.

![Figure 37. Graph of mean transfer score as a function of context for math, economics, and physics.](image)

The statistics in Table 21 show we can reject the null hypothesis that there will be no difference in mean context scores as a function of context ($F = 176.558, p < 0.001$). There is a medium effect of 49.5% variance in mean scores explained by graphing context (*partial eta squared* = 0.495).
Table 21

Tests of Within-Subjects Effects

<table>
<thead>
<tr>
<th>Source</th>
<th>Type III Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
<th>Partial Eta Squared</th>
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<td>context</td>
<td>Greenhouse-Geisser</td>
<td>1724.523</td>
<td>1.724</td>
<td>1000.320</td>
<td>176.558</td>
<td>.000</td>
</tr>
<tr>
<td>Error(context)</td>
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<td>1758.144</td>
<td>310.315</td>
<td>5.666</td>
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</tbody>
</table>

Since Table 21 only indicates the presence of a mean difference without showing where the difference lies, a post hoc Tukey test was conducted. The pairwise comparisons table (Table 22) suggests that the means of math context differs from economics context ($p < 0.001$) and physics context ($p < 0.001$). There is also a difference between economics context and physics context ($p = 0.009$).

Table 22

Multiple Comparisons of Means: Tukey Contrasts

<table>
<thead>
<tr>
<th>(I) context</th>
<th>(J) context</th>
<th>Mean Difference (I-J)</th>
<th>Std. Error</th>
<th>Sig.</th>
<th>95% Confidence Interval for Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3.514*</td>
<td>.237</td>
<td>.000</td>
<td>3.045 - 3.982</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-3.514*</td>
<td>.237</td>
<td>.000</td>
<td>-3.982 - -3.045</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>-4.000*</td>
<td>.267</td>
<td>.000</td>
<td>-4.527 - -3.473</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>.486*</td>
<td>.185</td>
<td>.009</td>
<td>.121 - .851</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>-4.000*</td>
<td>.267</td>
<td>.000</td>
<td>-4.527 - -3.473</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-4.86*</td>
<td>.185</td>
<td>.009</td>
<td>-.851 - -.121</td>
</tr>
</tbody>
</table>

Note. 1 is math context, 2 is economics context, and 3 is physics context.

This supports the hypothesis that participants would score the highest in the math graphing context followed by economics context and physics context, although differences were also seen between economics and physics. Context does impact graphing ability. This matches with literature findings that students have difficulty applying their math-graphing skills to other contexts (Beichner, 1994; Dori & Sasson, 2008; Planinic et al., 2012; Potgieter et al., 2008; Roberts et al., 2007; Stern et al., 2004) because they tend to be context bound (Beauford, 2009; Catrambone & Holyoak, 1989; Johnson & Rutherford, 2010; Planinic et al., 2012; Roberts et al., 2007). However, it was found that the economics and physics contexts were also different. This is likely because an economics context is more commonly dealt with in everyday life as compared to physics, so participants show more familiarity with the context and, as a result, performed higher in economics than physics. Planinic et al. (2013) found that there was an increase in difficulty for students going from math to other context questions (economics) to physics.

Since there are differences in general performances for each of these contexts, the research questions consider more detail about transfer between the contexts, correlations of specific abilities to transfer ability, and effect of graphing transfer instructional treatments on ability to
transfer. Correlation tables will not be presented in the body of this document, instead, refer to Appendix R – Correlations Data.

4.1.2 Question 1: Difference between transfer categories.

Will there be a difference in participants’ ability to transfer, as measured by the Transfer Index score using the Roberts et al. (2007) transfer formula for the Test on Graphs, depending on the Transfer Category, math to physics or math to economics, based on a paired samples t-test?

The null hypothesis, $H_0$, states that there will be no difference between transfer index score means as a function of transfer category. The alternative is not predicted.

$P_1$: No, participants will perform with similar Transfer Indices on both Transfer Categories, demonstrating a lack of transfer. The graph depicting this prediction is shown below in Figure 1.

![Figure 38](image)

Figure 38. Predicted graph of mean transfer index score as a function of each transfer category. The data depicted here are made up and meant to strictly provide a visual prediction. The prediction, in this case, matches the null hypothesis.

To test the hypothesis, an analysis was done using a paired samples t-test, which incorporated within subject grouping. Power of 0.95 or higher assuming a small effect size (e.g., $f = 0.33$) for a two-tailed t-test was estimated to require 122 participants. More than 122 participants completed the Test on Graphs. Table 23 below shows descriptive statistics from this analysis, including number of participants for each group and means.

Table 23

<table>
<thead>
<tr>
<th>T-Test Paired Samples Statistics</th>
<th>Mean</th>
<th>N</th>
<th>Std. Deviation</th>
<th>Std. Error Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pair 1 MP TI</td>
<td>39.3750</td>
<td>160</td>
<td>24.31046</td>
<td>1.92191</td>
</tr>
<tr>
<td>Pair 1 ME TI</td>
<td>42.5000</td>
<td>160</td>
<td>21.50033</td>
<td>1.69975</td>
</tr>
</tbody>
</table>

*Note. MP stands for Math to Physics transfer category. ME stands for Math to Economics transfer category. TI stands for Transfer Index.*
A graphical representation of Transfer Index Score as a function of Transfer Category is shown in Figure 39 showing that the actual data differs from the predicted outcome. Because Transfer Category is a within-subject variable, the error bars do not give a visual depiction of significant difference. Refer to the t-test in Table 24 for the p-value.

![Graph of mean transfer index score as a function of transfer index category. Standard error bars are of +/- 1 SE.](image)

**Figure 39.** Graph of mean transfer index score as a function of transfer index category. Standard error bars are of +/- 1 SE.

The statistics in Table 24 indicate we can reject the null hypothesis that there will be no difference between Transfer Index scores as a function of Transfer Category. There was evidence for an average difference between math-to-physics and math-to-economics scores ($t_{159} = -2.644$, $p = 0.009$). On average, math to physics scores were 3.125 points lower than math to economics (95% CI [-5.46, -0.79]).

Table 24

<table>
<thead>
<tr>
<th>Paired Samples Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paired Differences</td>
</tr>
<tr>
<td>--------------------</td>
</tr>
<tr>
<td>Pair 1 MP TI - ME TI</td>
</tr>
</tbody>
</table>

**Sig. (2-tailed)**

<table>
<thead>
<tr>
<th>Pair 1</th>
<th>MP TI - ME TI</th>
<th>.009</th>
</tr>
</thead>
</table>

*Note.* MP stands for Math to Physics transfer category. ME stands for Math to Economics transfer category. TI stands for Transfer Index.
These results are looking at not just the raw category scores, but the ability to transfer math to the contexts of economics and physics. Finding a difference between math-to-economics and math-to-physics transfer scores matches with the initial findings that there was a difference not only between math scores and other context scores, but also between economics and physics. It was hypothesized that there would be no difference since students tend to be context bound (Beauford, 2009; Catrambone & Holyoak, 1989; Johnson & Rutherford, 2010; Planinic et al., 2012; Roberts et al., 2007), however, if economics is a more familiar context it would make sense that students would have an easier time seeing and transferring the underlying math skills to economics than to physics. Context is not limited to physical components, but also refers to the expectations and perceptions people have of the problem-solving task, which will influence access to prior knowledge (Bassok & Holyoak, 1989; Beauford, 2009; Hester et al., 2014; Holyoak, 1985; Nemirovsky, 2011). If students have more familiarity with a context there will have easier access to the knowledge for how to solve the problem.

4.1.3 Question 2: Scientific accuracy as a function of transfer.

Is participants’ scientific accuracy score on their first exam, as measured by the graphing rubric developed from a compilation of expert answer keys, a function of their Transfer Index score, as measured using the Roberts et al. (2007) transfer formula for the Test on Graphs and Transfer Category—math to physics and math to economics?

The null hypothesis, $H_0$, states that scientific accuracy will not be a function of transfer index score. Two potential alternatives are predicted below.

$P_{2a}$: Yes, participants’ scientific accuracy will be a function of Transfer Index score.

$P_{2b}$: Yes, participants will show higher scientific accuracy scores on the graphing exam questions after a certain level of transfer ability.

Figure 40. Predicted graph of scientific accuracy on the first exam as a function of transfer index score. This could a linear relationship as shown here.
Figure 41. Predicted graph of scientific accuracy on the first exam as a function of transfer index score. It could be that a certain score on transfer is required before an increase in scientific accuracy is seen.

To test the hypothesis, an analysis was done using two linear regressions and comparing the difference in slopes for one group with two predictors. Power of 0.95 or higher assuming a small effect size (e.g., $f^2 = 0.11$) was estimated to require 121 participants. More than 121 participants completed exam one. Table 25 below shows descriptive statistics from this analysis, including number of participants for each group and means.

Table 25

Regression Descriptive Statistics

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA1</td>
<td>3.81</td>
<td>2.016</td>
<td>149</td>
</tr>
<tr>
<td>MPT1</td>
<td>39.6393</td>
<td>24.46397</td>
<td>149</td>
</tr>
<tr>
<td>METI</td>
<td>42.7013</td>
<td>21.53332</td>
<td>149</td>
</tr>
</tbody>
</table>

Note. SA1 stands for scientific accuracy on exam 1. MP stands for Math to Physics transfer category. ME stands for Math to Economics transfer category. TI stands for Transfer Index.

A graphical representation of scientific accuracy on Exam 1 as a function of Transfer Index Score can be seen in Figure 42.
Figure 42. Scientific accuracy on Exam 1 as a function of transfer index score. This is for both math-to-economics and math-to-physics transfer categories. There is no difference between transfer categories and it appears that there is a linear relationship, like the first predicted outcome, between scientific accuracy and transfer index.

Based on the statistics from Table 26, we can reject the null that scientific accuracy is not a function of transfer ($F = 6.311, p = 0.013$).

Table 26

ANOVA

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regression</td>
<td>24.755</td>
<td>1</td>
<td>24.755</td>
<td>6.311</td>
</tr>
<tr>
<td>Residual</td>
<td></td>
<td>576.600</td>
<td>147</td>
<td>3.922</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>601.356</td>
<td>148</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Dependent Variable: Scientific Accuracy on Exam 1
b. Predictors: (Constant), Math-to-Physics Transfer Index

The effect size is given by $R^2$ shown in Table 27. This shows the predictor variables of math-to-economics transfer index and math-to-physics transfer index account for 4.1% variance in the scientific accuracy score on Exam 1 ($R^2 = 0.041$, $adjusted R^2 = 0.028$). Effect sizes for linear regression statistics will be reported using both $R$–squared and adjusted $R$–squared values. $R$–squared are more commonly known, but the adjusted $R$–squared values do not falsely inflate the explanatory power of the predictor variables.
Table 27

Model Summary

<table>
<thead>
<tr>
<th>Model</th>
<th>R</th>
<th>R Square</th>
<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
<th>R Square Change</th>
<th>Change Statistics</th>
<th>F Change</th>
<th>df1</th>
<th>df2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.203</td>
<td>.041</td>
<td>.028</td>
<td>1.987</td>
<td>.041</td>
<td>3.144</td>
<td>2</td>
<td>146</td>
<td></td>
</tr>
</tbody>
</table>

Change Statistics

<table>
<thead>
<tr>
<th>Model</th>
<th>Sig. F Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.046</td>
</tr>
</tbody>
</table>

a. Predictors: (Constant), Math-to-Economics Transfer Index, Math-to-Physics Transfer Index
b. Dependent Variable: Scientific Accuracy on Exam 1

Table 28 shows that for every one-point increase in math-to-physics transfer index we can expect, on average, an increase of 0.018 points in scientific accuracy. For every one-point increase in math-to-economics transfer index, we can expect, on average a decrease of 0.002 points in scientific accuracy. If there is a zero score for transfer index math-to-physics and math-to-economics, we would expect scientific accuracy, on average, to be equal to approximately 3.17 (constant = 3.169, MPTI = 0.018, METI = -0.002).

Table 28

Coefficients

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
<th>95.0% Confidence Interval for B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>Std. Error</td>
<td>Beta</td>
</tr>
<tr>
<td>1</td>
<td>(Constant)</td>
<td>3.169</td>
<td>.363</td>
</tr>
<tr>
<td>MPTI</td>
<td>.018</td>
<td>.011</td>
<td>.217</td>
</tr>
<tr>
<td>METI</td>
<td>-.002</td>
<td>.012</td>
<td>-.018</td>
</tr>
</tbody>
</table>

Note. MP stands for Math to Physics transfer category. ME stands for Math to Economics transfer category. TI stands for Transfer Index.

Scientific accuracy is a function of transfer; transfer index scores do provide a small effect on scientific accuracy of a chemistry graphing question. This supports the first hypothesis, that if students perform with higher transfer scores initially, they will demonstrate higher scientific accuracy, based on the rubric score on the graphing exam questions, because students who can transfer demonstrate an ability to think abstractly and see the underlying problem structure (Bassok & Holyoak, 1989; De Bock et al., 2011; Gick & Holyoak, 1983; Holyoak & Koh, 1987; Menis, 1987; Nicoll & Francisco, 2001; Ngu & Yeung, 2012; Ngu et al., 2015; Terwel et al., 2009).
4.1.4 Question 3: Scientific accuracy as a function of exam time.

Is scientific graph accuracy, as measured by the graphing rubric developed from a compilation of expert answer keys, a function of time, based on each graphing question across the three exams?

The null hypothesis, $H_0$, states that scientific accuracy will not be a function of time. The alternative is predicted below.

$P_3$: Yes, scientific accuracy will be a function of time; participants will show an increase in scientific accuracy across the three exams.

To test the hypothesis, a repeated measure, within factor ANOVA was conducted. This has a continuous dependent variable with three levels of an independent variable. Power of 0.95 or higher assuming a small effect size (e.g., $f = 0.33$) and a correlation among repeated measures of 0.1, was estimated to require 45 participants. More than 45 participants completed all three exams as seen in Table 29.

Table 29

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA1</td>
<td>3.98</td>
<td>2.028</td>
<td>133</td>
</tr>
<tr>
<td>SA2</td>
<td>5.24</td>
<td>2.243</td>
<td>133</td>
</tr>
<tr>
<td>SA3</td>
<td>4.74</td>
<td>2.399</td>
<td>133</td>
</tr>
</tbody>
</table>

*Note. SA stands for scientific accuracy on exams. The numbers following SA stand for exam 1, 2, or 3.*

A graphical representation of scientific accuracy as a function of time can be seen in Figure 44. Time is a within-subject variable so the error bars do not give a visual depiction of significant difference. Refer to Table 30 for $p$-values and effect size.
The statistics in Table 30 show we can reject the null hypothesis that scientific accuracy is not a function of time ($F = 14.885, p < 0.001$). There is a small effect of 10.1% variance in scientific accuracy explained by time ($\text{partial eta squared} = 0.101$).

Table 30

Tests of Within-Subjects Effects

<table>
<thead>
<tr>
<th>Source</th>
<th>Type III Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
<th>Partial Eta Squared</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error(Exam)</td>
<td>Greenhouse-Geisser</td>
<td>953.779</td>
<td>246.533</td>
<td>3.869</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Since Table 30 only indicates the presence of a mean difference without showing where the difference lies, a post hoc Tukey test was conducted. The pairwise comparisons table (Table 31) suggests that the means of Exam 2 differs from Exam 1 ($p < 0.001$) and Exam 3 differs from Exam 1 ($p = 0.003$). There is no evidence for a difference between Exam 2 and Exam 3.

Table 31

Multiple Comparisons of Means: Tukey Contrasts

|          | Estimate | Std. Error | z value | Pr(>|z|) |
|----------|----------|------------|---------|---------|
| E2 - E1  == 0 | 1.2632 | 0.2331 | 5.419 | <0.001 *** |
| E3 - E1  == 0 | 0.7594 | 0.2331 | 3.258 | 0.0033 ** |
| E3 - E2  == 0 | -0.5038 | 0.2331 | -2.161 | 0.0780 . |

Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
(Adjusted p values reported -- single-step method)
The hypothesis was supported that scientific accuracy is a function of time. It appears that students who received and learned from feedback on their previous exams showed an increased performance in subsequent exams because the feedback showed them how to improve (Benjamin, 2003; Pashler et al., 2005; Pastötter et al., 2010). However, there was no difference between the second and third exam so perhaps students did not continue to utilize the feedback or perhaps they reached a maximum improvement in their scientific reasoning within the timeframe.

4.1.5 Question 4: Transfer as a function of high school graphing ability.

Is Transfer Index score, as measured using the Roberts et al. (2007) transfer formula for the Test on Graphs, a function of incoming math-graphing ability, as measured by the Test of Graphing Skills (TOGS), and Transfer Category–math to physics or math to economics?

The null hypothesis, \( H_0 \), states that transfer will not be a function of high school graphing ability. The alternative is not predicted.

\[ P_4 : \text{No, Transfer Index score will not be a function of high school math-graphing ability.} \]

![Predicted graph of transfer as a function of high school graphing skills](image)

Figure 45. Predicted graph of transfer as a function of high school graphing skills. No correlation is the predicted result.

To test the hypothesis, an analysis was done using two linear regressions and comparing their difference in slopes. Power of 0.95 or higher assuming a small effect size (e.g., \( f^2 = 0.11 \)) was estimated to require 121 participants. More than 121 participants completed both the Test on Graphs and the Test of Graphing Skills (TOGS) assessments as seen in Table 32 below.

Table 32

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOGS</td>
<td>23.11</td>
<td>2.451</td>
<td>157</td>
</tr>
<tr>
<td>MP TIScore</td>
<td>39.371</td>
<td>24.43743</td>
<td>157</td>
</tr>
<tr>
<td>ME TIScore</td>
<td>42.4363</td>
<td>21.60469</td>
<td>157</td>
</tr>
</tbody>
</table>

*Note. TOGS stands for Test of Graphing Skills. MP stands for Math to Physics transfer category. ME stands for Math to Economics transfer category. TI stands for Transfer Index.*
A graphical representation can be seen in Figure 46. It indicates that a minimum score of 13 out of the 26 points possible (50%) in general graphing skills, is necessary to transfer graphing skills in either transfer category.

![Figure 46](image)

**Figure 46.** Transfer as a function of high school graphing. This is based on the Test of Graphing Skills (TOGS) and transfer category. Both math-to-economics and math-to-physics correlations are depicted here. It is seen that there is a correlation and that a minimum score of 13 on the TOGS, i.e. 50%, is required to transfer math-graphing skills.

The statistics shown in Table 33 indicate we can reject the null that transfer index is not a function of high school graphing skills (MPTI: \( F = 23.746, p < 0.001 \); METI: \( F = 32.258, p < 0.001 \)).

**Table 33**

*ANOVA with Math to Physics*

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>12376.491</td>
<td>1</td>
<td>12376.491</td>
<td>23.746</td>
<td>.000b</td>
</tr>
<tr>
<td>Residual</td>
<td>80784.835</td>
<td>155</td>
<td>521.192</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>93161.326</td>
<td>156</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*a. Dependent Variable: Math-to-Physics Transfer Index Score  
b. Predictors: (Constant), Test of Graphing Skills (TOGS)*
*ANOVA with Math to Economics*

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>12543.418</td>
<td>1</td>
<td>12543.418</td>
<td>32.258</td>
<td>.000b</td>
</tr>
<tr>
<td>Residual</td>
<td>60271.570</td>
<td>155</td>
<td>388.849</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>72814.988</td>
<td>156</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Dependent Variable: Math-to-Economics Transfer Index Score

b. Predictors: (Constant), Test of Graphing Skills (TOGS)

Effect size is given by $R^2$, shown in Table 34. It indicates the predictor variable of high school graphing ability accounts for 13.3% variance in math-to-physics transfer index ($R^2 = 0.133$, adjusted $R^2 = 0.127$). The predictor variable of high school graphing ability accounts for 17.2% variance in math-to-economics transfer index ($R^2 = 0.172$, adjusted $R^2 = 0.167$).

Table 34

*Model Summary of Math to Physics*

<table>
<thead>
<tr>
<th>Model</th>
<th>R</th>
<th>R Square</th>
<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.364a</td>
<td>.133</td>
<td>.127</td>
<td>22.82964</td>
</tr>
</tbody>
</table>

a. Predictors: (Constant), Test of Graphing Skills (TOGS)

*Model Summary of Math to Economics*

<table>
<thead>
<tr>
<th>Model</th>
<th>R</th>
<th>R Square</th>
<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.415a</td>
<td>.172</td>
<td>.167</td>
<td>19.71925</td>
</tr>
</tbody>
</table>

a. Predictors: (Constant), Test of Graphing Skills (TOGS)

Table 35 shows that, for every one-point increase in Test of Graphing Skills (TOGS), we can expect, on average, a 3.634-point increase in math-to-physics transfer index ($MPTI = 3.634$). For every one-point increase in TOGS we can expect, on average, a 3.658-point increase in math-to-economics transfer index ($METI = 3.658$).

Table 35

*Coefficients for Math to Physics*

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
<th>t</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>Std. Error</td>
<td>Beta</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>(Constant) -44.606</td>
<td>17.329</td>
<td>-2.574</td>
<td>.011</td>
</tr>
<tr>
<td></td>
<td>TOGS 3.634</td>
<td>.746</td>
<td>.364</td>
<td>4.873</td>
</tr>
</tbody>
</table>

a. Dependent Variable: Math-To-Physics Transfer Index Score
Coefficients for Math to Economics

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
<th>t</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>Std. Error</td>
<td>Beta</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>(Constant)</td>
<td>-42.105</td>
<td>14.968</td>
<td>-2.813</td>
</tr>
<tr>
<td></td>
<td>TOGS</td>
<td>3.658</td>
<td>.644</td>
<td>.415</td>
</tr>
</tbody>
</table>

a. Dependent Variable: Math-to-Economics Transfer Index Score

The predicted result of transfer not being a function of high school graphing ability was rejected. It was hypothesized that, students will not necessarily show higher scores in transfer with higher high school graphing skills because, while having prior knowledge is necessary for transfer to occur (Bassok & Holyoak, 1989; Menis, 1987; Potgieter et al., 2008; Scott, 2012), it does not ensure transfer. Abstracted schemas must still be constructed to link the prior knowledge to the target problem, and data has shown that having basic math graphing does not mean one can transfer (Beichner, 1994; Cunningham, 2005; Planinic et al., 2008; Roberts et al., 2007). These results show that at least a 50% general math graphing prior knowledge ability is required for transfer to occur.

4.1.6 Question 5: Transfer as a function of scientific reasoning ability.

Is Transfer Index, as measured using the Roberts et al. (2007) transfer formula for the Test on Graphs, a function of scientific reasoning, as measured by the Classroom Test of Scientific Reasoning (CTSR), and Transfer Category–math to physics or math to economics?

The null hypothesis, $H_0$, states that transfer will not be a function of scientific reasoning ability. The alternative is predicted below.

$P_5$: Yes, Transfer Index score will be a function of scientific reasoning.

![Figure 47. Predicted graph of transfer as a function of scientific reasoning ability. This is based on the Classroom Test of Scientific Reasoning (CTSR).](image)

To test the hypothesis, an analysis was done using two linear regressions, comparing their difference in slopes. Power of 0.95 or higher assuming a small effect size (e.g., $f^2 = 0.11$) was estimated to require 121 participants. More than 121 participants completed both the Test on Graphs and the Classroom Test of Scientific Reasoning (CTSR) assessments as seen in Table 36.
Table 36

Descriptive Statistics

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTSR</td>
<td>7.92</td>
<td>2.536</td>
<td>158</td>
</tr>
<tr>
<td>MP TIScore</td>
<td>39.2801</td>
<td>24.38629</td>
<td>158</td>
</tr>
<tr>
<td>ME TIScore</td>
<td>42.3259</td>
<td>21.58041</td>
<td>158</td>
</tr>
</tbody>
</table>

Note. CTSR stands for Classroom Test of Scientific Reasoning. MP stands for Math to Physics transfer category. ME stands for Math to Economics transfer category. TI stands for Transfer Index.

A graphical representation Transfer Index Score as a function of scientific reasoning ability can be seen in Figure 48.

![Transfer Index Score vs CTSR Score](image)

Figure 48. Transfer as a function of scientific reasoning ability. This is based on the Classroom Test of Scientific Reasoning (CTSR) and transfer category. Both math-to-economics and math-to-physics as shown here.

The statistics shown in Table 37 indicate we can reject the null that transfer index is not a function of scientific reasoning ability (MPTI: $F = 51.266, p < 0.001$; METI: $F = 62.905, p < 0.001$).
Table 37

**ANOVA with Math to Physics**

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regression</td>
<td>23093.687</td>
<td>1</td>
<td>23093.687</td>
<td>51.266</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>70272.858</td>
<td>156</td>
<td>450.467</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>93366.545</td>
<td>157</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Dependent Variable: Math-to-Physics Transfer Index Score  
b. Predictors: (Constant), Classroom Test of Scientific Reasoning (CTSR)

**ANOVA with Math to Economics**

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regression</td>
<td>21011.078</td>
<td>1</td>
<td>21011.078</td>
<td>62.905</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>52106.011</td>
<td>156</td>
<td>334.013</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>73117.089</td>
<td>157</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Dependent Variable: Math-to-Economics Transfer Index Score  
b. Predictors: (Constant), Classroom Test of Scientific Reasoning (CTSR)

Effect size is given by \( R^2 \), shown in Table 38. It indicates the predictor variable of scientific reasoning ability accounts for 24.7% variance in math-to-physics transfer index \( (R^2 = 0.247, \text{ adjusted } R^2 = 0.243) \). The predictor variable of high school graphing ability accounts for 28.7% variance in math-to-economics transfer index \( (R^2 = 0.287, \text{ adjusted } R^2 = 0.283) \).

Table 38

**Model Summary of Math to Physics**

<table>
<thead>
<tr>
<th>Model</th>
<th>R</th>
<th>R Square</th>
<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.497&lt;sup&gt;a&lt;/sup&gt;</td>
<td>.247</td>
<td>.243</td>
<td>21.22421</td>
</tr>
</tbody>
</table>

a. Predictors: (Constant), Classroom Test of Scientific Reasoning (CTSR)

**Model Summary of Math to Economics**

<table>
<thead>
<tr>
<th>Model</th>
<th>R</th>
<th>R Square</th>
<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.536&lt;sup&gt;a&lt;/sup&gt;</td>
<td>.287</td>
<td>.283</td>
<td>18.27602</td>
</tr>
</tbody>
</table>

a. Predictors: (Constant), Classroom Test of Scientific Reasoning (CTSR)

Table 39 shows that, for every one-point increase in Classroom Test of Scientific Reasoning (CTSR), we can expect, on average, a 4.782-point increase in math-to-physics transfer index \( (MPTI = 4.782, t = 7.160, p < 0.001) \). For every one-point increase in CTSR, we can expect on average, a 4.780-point increase in math-to-economics transfer index \( (METI = 4.780, t = 7.931, p < 0.001) \).
Table 39

Coefficients for Math to Physics

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
<th>t</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>Std. Error</td>
<td>Beta</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>(Constant)</td>
<td>1.418</td>
<td>5.551</td>
<td>.255</td>
</tr>
<tr>
<td></td>
<td>CTSR</td>
<td>4.782</td>
<td>.668</td>
<td>.497</td>
</tr>
</tbody>
</table>

a. Dependent Variable: Math-to-Physics Transfer Index Score

Coefficients for Math to Economics

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
<th>t</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>Std. Error</td>
<td>Beta</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>(Constant)</td>
<td>6.212</td>
<td>4.780</td>
<td>1.300</td>
</tr>
<tr>
<td></td>
<td>CTSR</td>
<td>4.561</td>
<td>.575</td>
<td>.536</td>
</tr>
</tbody>
</table>

a. Dependent Variable: Math-to-Economics Transfer Index Score

Transfer is a function of scientific reasoning. This finding supports literature results that scientific reasoning correlates to ability to transfer (Dori & Sasson, 2008; Kapur, 2014; Lappalainen & Rosqvist, 2015; Menis, 1987; Nicoll & Francisco, 2001; Roberts et al., 2007; Sasson & Dori, 2012).

4.1.7 Question 6: Transfer as a function of chemical misconceptions.

Is Transfer Index, as measured using the Roberts et al. (2007) transfer formula for the Test on Graphs, a function of participants’ chemical misconceptions, as measured by the Chemistry Concepts Inventory (CCI), and Transfer Category–math to physics or math to economics?

The null hypothesis, $H_0$, states that transfer will not be a function of chemical misconceptions. The alternative is predicted below.

$P_0$: Yes, Transfer Index score will be a function of chemical misconceptions; participants with fewer misconceptions (higher CCI score) will be show higher scores on transfer.
Figure 49. Predicted graph of transfer index as a function of chemical misconceptions. This is based on the Chemistry Concepts Inventory (CCI). The CCI measures misconceptions so a higher score demonstrates a greater lack of chemistry misconceptions.

To test the hypothesis, an analysis was done using two linear regressions and comparing their difference in slopes. Power of 0.95 or higher assuming a small effect size (e.g., $f^2 = 0.11$) was estimated to require 121 participants. More than 121 participants completed both the Test on Graphs and the Chemistry Concepts Inventory (CCI) assessments as seen in Table 40.

Table 40

Descriptive Statistics

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCI</td>
<td>6.73</td>
<td>3.063</td>
<td>158</td>
</tr>
<tr>
<td>MP TIScore</td>
<td>39.3196</td>
<td>24.44959</td>
<td>158</td>
</tr>
<tr>
<td>ME TIScore</td>
<td>42.4842</td>
<td>21.62487</td>
<td>158</td>
</tr>
</tbody>
</table>

Note. CCI stands for Chemistry Concepts Inventory. MP stands for Math to Physics transfer category. ME stands for Math to Economics transfer category. TI stands for Transfer Index.

A graphical representation of Transfer Index Score as a function of chemical misconceptions can be seen in Figure 50.
Figure 50. Transfer as a function of chemical misconceptions. This is based on the Chemistry Concepts Inventory (CCI) and transfer category. The higher the CCI score the greater the lack of misconceptions. Both math-to-economics and math-to-physics categories are shown here.

The statistics in Table 41 indicate we can reject the null that transfer index is not a function of lack of chemical misconceptions (MPTI: $F = 54.838$, $p < 0.001$; METI: $F = 39.276$, $p < 0.001$).

Table 41

**ANOVA with Math to Physics**

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>24410.504</td>
<td>1</td>
<td>24410.504</td>
<td>54.838</td>
<td>.000b</td>
</tr>
<tr>
<td>Residual</td>
<td>69441.356</td>
<td>156</td>
<td>445.137</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>93851.859</td>
<td>157</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Dependent Variable: Math-to-Physics Transfer Index Score
b. Predictors: (Constant), Chemistry Concepts Inventory (CCI)

**ANOVA with Math to Economics**

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>14766.792</td>
<td>1</td>
<td>14766.792</td>
<td>39.276</td>
<td>.000b</td>
</tr>
<tr>
<td>Residual</td>
<td>58651.918</td>
<td>156</td>
<td>375.974</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>73418.710</td>
<td>157</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Dependent Variable: Math-to-Economics Transfer Index Score
b. Predictors: (Constant), Chemistry Concepts Inventory (CCI)

Effect size is given by $R^2$, shown in Table 42. It indicates the predictor variable of lack of chemical misconceptions accounts for 26.0% variance in math-to-physics transfer index ($R^2 =$
0.260, \textit{adjusted }R^2 = 0.255). The predictor variable of lack of chemical misconceptions accounts for 20.1\% variance in math-to-economics transfer index \((R^2 = 0.201, \textit{adjusted }R^2 = 0.196).\)

Table 42

\textit{Model Summary of Math to Physics}

\begin{center}
\begin{tabular}{|c|c|c|c|}
\hline
Model & R & R Square & Adjusted R Square & Std. Error of the Estimate \\
\hline
1 & .510\textsuperscript{a} & .260 & .255 & 21.09827 \\
\hline
\end{tabular}
\end{center}

\textbf{a. Predictors: (Constant), Chemistry Concepts Inventory (CCI)}

\textit{Model Summary of Math to Economics}

\begin{center}
\begin{tabular}{|c|c|c|c|}
\hline
Model & R & R Square & Adjusted R Square & Std. Error of the Estimate \\
\hline
1 & .448\textsuperscript{a} & .201 & .196 & 19.39004 \\
\hline
\end{tabular}
\end{center}

\textbf{a. Predictors: (Constant), Chemistry Concepts Inventory (CCI)}

Table 43 shows that, for every one-point increase in the Chemistry Concepts Inventory (CCI), we can expect, on average, a 4.070-point increase in math-to-physics transfer index \((MPTI = 4.070, t = 7.405, p = 0.000).\) If there is a zero score on the Chemistry Concepts Inventory (CCI) a score of about 12 can still be achieved for math-to-physics transfer index \((constant = 11.934, t = 2.939, p = 0.004).\) For every one-point increase in the Chemistry Concepts Inventory (CCI), we can expect, on average, a 3.166-point increase in math-to-economics transfer index \((METI = 3.166, t = 6.267, p = 0.000).\) If there is a zero score on the Chemistry Concepts Inventory (CCI) a score of about 21 can still be achieved for math-to-economics transfer index \((constant = 21.184, t = 5.676, p = 0.000).\)

Table 43

\textit{Coefficients for Math to Physics}

\begin{center}
\begin{tabular}{|c|c|c|c|c|c|}
\hline
Model & Unstandardized Coefficients & Standardized Coefficients & \textit{t} & \textit{Sig.} \\
& B & Std. Error & Beta & & \\
\hline
1 & (Constant) & 11.934 & 4.061 & 2.939 & .004 \\
CCI & 4.070 & .550 & .510 & 7.405 & .000 \\
\hline
\end{tabular}
\end{center}

\textbf{a. Dependent Variable: Math-to-Physics Transfer Index Score}

\textit{Coefficients for Math to Economics}

\begin{center}
\begin{tabular}{|c|c|c|c|c|}
\hline
Model & Unstandardized Coefficients & Standardized Coefficients & \textit{t} & \textit{Sig.} \\
& B & Std. Error & Beta & & \\
\hline
1 & (Constant) & 21.184 & 3.732 & 5.676 & .000 \\
CCI & 3.166 & .505 & .448 & 6.267 & .000 \\
\hline
\end{tabular}
\end{center}

\textbf{a. Dependent Variable: Math-to-Economics Transfer Index Score}
Transfer is a function of lack of chemical misconceptions. If students come into general chemistry with fewer misconceptions about chemistry concepts they will produce higher scores on transfer because the students will already understand abstract concepts, meaning they will not be context bound (Beauford, 2009; Catrambone & Holyoak, 1989; Johnson & Rutherford, 2010; Planinic et al., 2012; Roberts et al., 2007).

4.1.8 Question 7: Transfer as a function of intelligence.

Is Transfer Index, as measured using the Roberts et al. (2007) transfer formula for the Test on Graphs, a function of participants’ intelligence, as measured by the Raven’s Standard Progressive Matrices Plus (SPM+), and Transfer Category—math to physics or math to economics?

The null hypothesis, $H_0$, states that transfer will not be a function of intelligence. The alternative is not predicted.

$H_0$: No, Transfer Index score will not be a function of IQ.

![Graph](image)

Figure 51. Predicted graph of transfer index as a function of intelligence. This is based on the Standard Progressive Matrices Plus (SPM+) instrument. This is depicting no correlation.

To test the hypothesis, an analysis was done using two linear regressions and comparing their difference in slopes. Power of 0.95 or higher assuming a small effect size (e.g., $f^2 = 0.11$) was estimated to require 121 participants. More than 121 participants completed both the Test on Graphs and the SPM+ assessments as seen in Table 44.

Table 44

<table>
<thead>
<tr>
<th>Descriptive Statistics</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPM</td>
<td>43.65</td>
<td>4.932</td>
<td>162</td>
</tr>
<tr>
<td>MP TIScore</td>
<td>38.9275</td>
<td>24.43336</td>
<td>162</td>
</tr>
<tr>
<td>ME TIScore</td>
<td>42.1682</td>
<td>21.57555</td>
<td>162</td>
</tr>
</tbody>
</table>

*Note.* SPM stands for Standard Progressive Matrices Plus. MP stands for Math to Physics transfer category. ME stands for Math to Economics transfer category. TI stands for Transfer Index.
A graphical representation of transfer index score as a function of intelligence can be seen in Figure 52.

Figure 52. Transfer as a function of intelligence. This is based on the Standard Matrices Plus (SPM+) instrument and transfer category. It does not follow the predicted results of no correlation. Both math-to-economics and math-to-physics are shown here. Additionally, there appears to be a minimum intelligence requirement of about 50%, based on this instrument, before transfer can occur.

The statistics shown in Table 45 indicate we can reject the null that transfer index is not a function of intelligence (MPTI: $F = 28.041, p < 0.001$; METI: $F = 27.746, p < 0.001$).

Table 45

ANOVA with Math to Physics

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>14332.847</td>
<td>1</td>
<td>14332.847</td>
<td>28.041</td>
<td>.000^b</td>
</tr>
<tr>
<td>Residual</td>
<td>81782.363</td>
<td>160</td>
<td>511.140</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>96115.210</td>
<td>161</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Dependent Variable: Math-to-Physics Transfer Index Score
b. Predictors: (Constant), Raven’s Standard Progressive Matrices Plus (SPM+)

ANOVA with Math to Economics

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>11076.051</td>
<td>1</td>
<td>11076.051</td>
<td>27.746</td>
<td>.000^b</td>
</tr>
<tr>
<td>Residual</td>
<td>63870.178</td>
<td>160</td>
<td>399.189</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>74946.229</td>
<td>161</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Dependent Variable: Math-to-Economics Transfer Index Score
b. Predictors: (Constant), Raven’s Standard Progressive Matrices Plus (SPM+)
Effect size is given by $R^2$, shown in Table 46. It indicates the predictor variable of intelligence accounts for 14.9% variance in math-to-physics transfer index ($R^2 = 0.149, \text{ adjusted } R^2 = 0.144$). The predictor variable of intelligence accounts for 14.8% variance in math-to-economics transfer index ($R^2 = 0.148, \text{ adjusted } R^2 = 0.142$).

Table 46

*Model Summary of Math to Physics*

<table>
<thead>
<tr>
<th>Model</th>
<th>$R$</th>
<th>$R$ Square</th>
<th>Adjusted $R$ Square</th>
<th>Std. Error of the Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.386*</td>
<td>.149</td>
<td>.144</td>
<td>22.60840</td>
</tr>
</tbody>
</table>

a. Predictors: (Constant), Raven’s Standard Progressive Matrices Plus (SPM+)

*Model Summary of Math to Economics*

<table>
<thead>
<tr>
<th>Model</th>
<th>$R$</th>
<th>$R$ Square</th>
<th>Adjusted $R$ Square</th>
<th>Std. Error of the Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.384*</td>
<td>.148</td>
<td>.142</td>
<td>19.97971</td>
</tr>
</tbody>
</table>

a. Predictors: (Constant), Raven’s Standard Progressive Matrices Plus (SPM+)

Table 47 shows that, for every one-point increase in Raven’s Standard Progressive Matrices Plus (SPM+), we can expect, on average, a 1.913-point increase in math-to-physics transfer index ($MPTI = 1.913, t = 5.295, p < 0.001$). For every one-point increase in Raven’s Standard Progressive Matrices Plus (SPM+), we can expect, on average, a 1.682-point increase in math-to-economics transfer index ($METI = 1.682, t = 5.267, p < 0.001$). According to the graph, one would need at least a score of 29 to transfer.

Table 47

*Coefficients of Math to Physics*

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
<th>t</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$B$</td>
<td>Std. Error</td>
<td>Beta</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>$(\text{Constant})$</td>
<td>-44.582</td>
<td>15.870</td>
<td>-2.809</td>
</tr>
<tr>
<td></td>
<td>SPM</td>
<td>1.913</td>
<td>.361</td>
<td>.386</td>
</tr>
</tbody>
</table>

a. Dependent Variable: Math-to-Physics Transfer Index Score

*Coefficients of Math to Economics*

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
<th>t</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$B$</td>
<td>Std. Error</td>
<td>Beta</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>$(\text{Constant})$</td>
<td>-31.243</td>
<td>14.025</td>
<td>-2.228</td>
</tr>
<tr>
<td></td>
<td>SPM</td>
<td>1.682</td>
<td>.319</td>
<td>.384</td>
</tr>
</tbody>
</table>

a. Dependent Variable: Math-to-Economics Transfer Index Score

Transfer is a function of intelligence defined as an ability to recognize patterns. This is not what was predicted because, while higher general intelligence has been linked to greater mathematical
achievement (McGrew & Wendling, 2010), it has not been shown to influence performance in chemistry, and mathematical achievement alone is not enough for transfer to occur (Beichner, 1994; Cunningham, 2005; Planinic et al., 2008; Roberts et al., 2007). However, the intelligence required to have a certain level of mathematical achievement is also required for transfer to occur. In addition, there is a minimum required intelligence of about 29 out of 60 (about 50%), based on this instrument, before transfer can occur.

4.1.9 Question 8: Multiple linear regression.

Is Transfer Index score, as measured using the Roberts et al. (2007) transfer formula for the Test on Graphs, a function of each of the previous dependent variables: incoming math-graphing ability as measured by the Test of Graphing Skills (TOGS), scientific reasoning as measured by the Classroom Test of Scientific Reasoning (CTSR), chemical misconceptions, as measured by the Chemistry Concepts Inventory (CCI), intelligence as measured by the Raven’s Standard Progressive Matrices Plus (SPM+), and Transfer Category–math to physics or math to economics?

The null hypothesis, \( H_0 \), states that transfer will not be a function of any of the predictor variables: high school math-graphing ability, scientific reasoning, chemical misconceptions, or IQ. An alternative is predicted below.

\[ P_8: \text{No, Transfer Index score will not be a function of high school math-graphing ability or IQ, but it will be a function of scientific reasoning and chemical misconceptions; students with fewer misconceptions (higher CCI score) will be show higher scores on transfer.} \]

No graphical representation of a multiple linear regression can be shown. To test the hypothesis, an analysis was done using two multiple linear regressions and comparing their difference in slopes. Power of 0.95 or higher assuming a small effect size (e.g., \( f^2 = 0.11 \)) was estimated to require 121 participants. More than 121 participants completed both the Test on Graphs and all assessments, as seen in Table 48 along with other descriptive statistics.

Table 48

Descriptive Statistics with Math to Physics

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>MP TIScore</td>
<td>39.3145</td>
<td>24.58016</td>
<td>155</td>
</tr>
<tr>
<td>SPM+</td>
<td>43.77</td>
<td>4.997</td>
<td>155</td>
</tr>
<tr>
<td>TOGS</td>
<td>23.12</td>
<td>2.461</td>
<td>155</td>
</tr>
<tr>
<td>CCI</td>
<td>6.74</td>
<td>3.083</td>
<td>155</td>
</tr>
<tr>
<td>CTSR</td>
<td>7.92</td>
<td>2.528</td>
<td>155</td>
</tr>
</tbody>
</table>

Note. MP stands for Math to Physics transfer category. TI stands for Transfer Index. SPM+ stands for Standard Progressive Matrices Plus, TOGS stands for Test of Graphing Skills, CCI stands for Chemistry Concepts Inventory, and CTSR stands for Classroom Test of Scientific Reasoning.
Descriptive Statistics with Math to Economics

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>ME TIScore</td>
<td>42.4194</td>
<td>21.73234</td>
<td>155</td>
</tr>
<tr>
<td>SPM+</td>
<td>43.77</td>
<td>4.997</td>
<td>155</td>
</tr>
<tr>
<td>TOGS</td>
<td>23.12</td>
<td>2.461</td>
<td>155</td>
</tr>
<tr>
<td>CCI</td>
<td>6.74</td>
<td>3.083</td>
<td>155</td>
</tr>
<tr>
<td>CTSR</td>
<td>7.92</td>
<td>2.528</td>
<td>155</td>
</tr>
</tbody>
</table>

Note. ME stands for Math to Economics transfer category. TI stands for Transfer Index. SPM+ stands for Standard Progressive Matrices Plus, TOGS stands for Test of Graphing Skills, CCI stands for Chemistry Concepts Inventory, and CTSR stands for Classroom Test of Scientific Reasoning.

The statistics shown in Table 49 indicate we can reject the null that transfer index is not a function of the predictor variables (MPTI: \( F = 20.151, p < 0.001 \); METI: \( F = 20.370, p < 0.001 \)).

Table 49

ANOVA with Math to Physics

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>32522.532</td>
<td>4</td>
<td>8130.633</td>
<td>20.151</td>
<td>.000</td>
</tr>
<tr>
<td>Residual</td>
<td>60521.823</td>
<td>150</td>
<td>403.479</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>93044.355</td>
<td>154</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Dependent Variable: Math-to-Physics Transfer Index Score
b. Predictors: (Constant), CTSR, SPM+, CCI, TOGS

ANOVA with Math to Economics

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>25601.969</td>
<td>4</td>
<td>6400.492</td>
<td>20.370</td>
<td>.000</td>
</tr>
<tr>
<td>Residual</td>
<td>47131.398</td>
<td>150</td>
<td>314.209</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>72733.367</td>
<td>154</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Dependent Variable: Math-to-Economics Transfer Index Score
b. Predictors: (Constant), CTSR, SPM+, CCI, TOGS

Effect size is given by \( R^2 \), shown in Table 50. It indicates the predictor variables of scientific reasoning, intelligence, lack of chemical misconceptions, and high school graphing skills, account for 35.0% variance in math-to-physics transfer index (\( R^2 = 0.350 \), adjusted \( R^2 = 0.332 \)) and 35.2% variance in math-to-economics transfer index (\( R^2 = 0.352 \), adjusted \( R^2 = 0.335 \)).
Table 50

Model Summary of Math to Physics

<table>
<thead>
<tr>
<th>Model</th>
<th>R</th>
<th>R Square</th>
<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
<th>Change Statistics</th>
<th>Sig. F Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>.591</td>
<td>.350</td>
<td>.332</td>
<td>20.08678</td>
<td>.350</td>
<td>20.151</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Change Statistics</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Model</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.000</td>
</tr>
</tbody>
</table>

a. Predictors: (Constant), CTSR, SPM+, CCI, TOGS
b. Dependent Variable: Math-to-Physics Transfer Index Score

Model Summary of Math to Economics

<table>
<thead>
<tr>
<th>Model</th>
<th>R</th>
<th>R Square</th>
<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
<th>Change Statistics</th>
<th>Sig. F Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>.593</td>
<td>.352</td>
<td>.335</td>
<td>17.72595</td>
<td>.352</td>
<td>20.370</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Change Statistics</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.000</td>
</tr>
</tbody>
</table>

a. Predictors: (Constant), CTSR, SPM+, CCI, TOGS
b. Dependent Variable: Math-to-Economics Transfer Index Score

Table 51 shows that, we do not have evidence that intelligence has an effect on transfer, given the inclusion of other predictors in the model (MPTI = 0.695, t = 1.796, p = 0.074; METI = 0.500, t = 1.466, p = 0.145). We also do not have evidence that high school graphing skills has an effect on transfer, given the inclusion of other predictors in the model (MPTI = 0.649, t = 0.764, p = 0.446; METI = 1.011, t = 1.350, p = 0.179).

However, Table 51 also shows that both chemistry misconceptions and scientific reasoning do have an effect on transfer, even with the other predictors included in the model. For every one-point increase in CCI, we can expect, on average, a 2.471-point increase in math-to-physics transfer index (MPTI = 2.471, t = 3.778, p = 0.000) and a 1.352-point increase in math-to-economics transfer index (METI = 1.352, t = 2.343, p = 0.020). For every one-point increase in CTSR, we can expect, on average, a 2.140-point increase in math-to-physics transfer index (MPTI = 2.140, t = 2.297, p = 0.023) and a 2.692-point increase in math-to-economics transfer index (METI = 2.692, t = 3.275, p = 0.001).
### Table 51

**Coefficients for Math to Physics**

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
<th>t</th>
<th>Sig.</th>
<th>95.0% Confidence Interval for B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>Std. Error</td>
<td>Beta</td>
<td></td>
<td>Lower Bound</td>
</tr>
<tr>
<td>1</td>
<td>(Constant)</td>
<td>-39.679</td>
<td>18.575</td>
<td>-2.136</td>
<td>.034</td>
</tr>
<tr>
<td></td>
<td>SPM+</td>
<td>.695</td>
<td>.387</td>
<td>.141</td>
<td>1.796</td>
</tr>
<tr>
<td></td>
<td>TOGS</td>
<td>.649</td>
<td>.849</td>
<td>.065</td>
<td>.764</td>
</tr>
<tr>
<td></td>
<td>CCI</td>
<td>2.471</td>
<td>.654</td>
<td>.310</td>
<td>3.778</td>
</tr>
<tr>
<td></td>
<td>CTSR</td>
<td>2.140</td>
<td>.932</td>
<td>.220</td>
<td>2.297</td>
</tr>
</tbody>
</table>

When all predictor variables that were individually discussed previously, are considered collectively, only scientific reasoning ability and lack of chemical misconceptions influence ability to transfer. Intelligence and prior high school graphing knowledge do not show evidence of influencing transfer. Even when considered individually, scientific reasoning and lack of chemical misconceptions had about twice as much effect on transfer variance compared to intelligence and prior high school graphing knowledge. This indicates that, above all else, these two factors must be nurtured and developed early on so that subsequent education is not lost or minimized for students.

### 4.1.10 Question 9: Transfer as a function of percent story problems in high school.

Is Transfer Index, as measured using the Roberts et al. (2007) transfer formula for the Test on Graphs, and percent story problems, as assessed by the student self-reported percentages from the demographics questionnaire, a function of story problem type—math, physics, or chemistry—and Transfer Category—math to physics or math to economics?

The null hypothesis, H₀, states that transfer will not be a function of percent story problems participants experienced in high school. The alternative is predicted below.

P₀: Yes, Transfer Index Score will be a function of percent story problems in high school.
To test the hypothesis, an analysis was done using two sets of four linear regressions and comparing their differences in slopes. Power of 0.95 or higher assuming a small effect size (e.g., $f^2 = 0.11$) was estimated to require 121 participants. More than 121 participants completed both the Test on Graphs and all assessments, as seen in Table 52 along with other descriptive statistics.

Table 52

**Descriptive Statistics with Math to Physics**

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>MP TI</td>
<td>39.39</td>
<td>24.387</td>
<td>159</td>
</tr>
<tr>
<td>ave%SP</td>
<td>39.34</td>
<td>17.505</td>
<td>159</td>
</tr>
<tr>
<td>M % story problems</td>
<td>39.50</td>
<td>18.134</td>
<td>159</td>
</tr>
<tr>
<td>P % story problems</td>
<td>30.73</td>
<td>35.860</td>
<td>159</td>
</tr>
<tr>
<td>C % SP ave</td>
<td>47.78</td>
<td>23.429</td>
<td>159</td>
</tr>
</tbody>
</table>

*Note. MP stands for Math to Physics transfer category. TI stands for Transfer Index. Ave%SP stands for average percent story problems across math, physics, and chemistry in high school. M % story problems stands for percent math story problems, P % story problems stands for percent physics story problems, and C % SP ave stands for average percent chemistry story problems across three years of high school.*

**Descriptive Statistics with Math to Economics**

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>ME TI</td>
<td>42.53</td>
<td>21.565</td>
<td>159</td>
</tr>
<tr>
<td>ave%SP</td>
<td>39.34</td>
<td>17.505</td>
<td>159</td>
</tr>
<tr>
<td>M % story problems</td>
<td>39.50</td>
<td>18.134</td>
<td>159</td>
</tr>
<tr>
<td>P % story problems</td>
<td>30.73</td>
<td>35.860</td>
<td>159</td>
</tr>
<tr>
<td>C % SP ave</td>
<td>47.78</td>
<td>23.429</td>
<td>159</td>
</tr>
</tbody>
</table>

*Note. ME stands for Math to Economics transfer category. TI stands for Transfer Index. Ave%SP stands for average percent story problems across math, physics, and chemistry in high school. M % story problems stands for percent math story problems, P % story problems stands for percent physics story problems, and C % SP ave stands for average percent chemistry story problems across three years of high school.*

Graphical representation of transfer index as a function of percent story problems can be seen in Figure 54 and Figure 55.
Figure 54. Math-to-economics transfer index as a function of percent story problems. These are story problems experienced in high school and story problem category (SPcat). The categories are overall average percent story problems across chemistry, math, and physics, the average percent of chemistry story problems from up to three years of high school chemistry, the percent of math story problems, and the percent of physics story problems.

Figure 55. Math-to-physics transfer index as a function of percent story problems. These are experienced in high school and story problem category (SPcat). The categories are overall average percent story problems across chemistry, math, and physics, the average percent of chemistry story problems from up to three years of high school chemistry, the percent of math story problems, and the percent of physics story problems.

Considering the univariate statistics shown in Table 53 we cannot reject the null that transfer index is not a function of math, physics, chemistry average, or overall average percent story problems experienced in high school (MPTI: $F_{\text{Math}} = 2.940, p = 0.088$; $F_{\text{Chem Ave}} = 1.758, p = 0.187$; $F_{\text{Ave}} = 0.275, p = 0.601$; METI: $F_{\text{Math}} = 5.480, p = 0.020$; $F_{\text{Physics}} = 1.998, p = 0.160$; $F_{\text{Chem Ave}} = 1.953, p = 0.164$; $F_{\text{Ave}} = 0.207, p = 0.649$). However, we can reject the null in the specific case of math-to-physics transfer index being a function of percent physics story problems ($F_{\text{Physics}} = 6.443, p = 0.012$) and math-to-economics transfer index being a function of percent math story problems ($F_{\text{Math}} = 5.480, p = 0.020$).
### Math to Physics (Dependent Variable) Univariate ANOVAs

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regression</td>
<td>1727.448</td>
<td>1</td>
<td>1727.448</td>
<td>2.940</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>92237.765</td>
<td>157</td>
<td>587.502</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>93965.212</td>
<td>158</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**a. Predictors:** (Constant), **Math percent story problems**

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regression</td>
<td>3704.101</td>
<td>1</td>
<td>3704.101</td>
<td>6.443</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>90261.112</td>
<td>157</td>
<td>574.912</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>93965.212</td>
<td>158</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**b. Predictors:** (Constant), **Physics percent story problems**

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regression</td>
<td>1040.635</td>
<td>1</td>
<td>1040.635</td>
<td>1.758</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>92924.578</td>
<td>157</td>
<td>591.876</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>93965.212</td>
<td>158</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**c. Predictors:** (Constant), **Chemistry average percent story problems**

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regression</td>
<td>164.230</td>
<td>1</td>
<td>164.230</td>
<td>.275</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>93800.982</td>
<td>157</td>
<td>597.458</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>93965.212</td>
<td>158</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**d. Predictors:** (Constant), **Overall average percent story problems**

### Math to Economics (Dependent Variable) Univariate ANOVAs

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regression</td>
<td>2478.176</td>
<td>1</td>
<td>2478.176</td>
<td>5.480</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>70996.667</td>
<td>157</td>
<td>452.208</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>73474.843</td>
<td>158</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**a. Predictors:** (Constant), **Math percent story problems**

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regression</td>
<td>923.143</td>
<td>1</td>
<td>923.143</td>
<td>1.998</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>72551.700</td>
<td>157</td>
<td>462.113</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>73474.843</td>
<td>158</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**b. Predictors:** (Constant), **Physics percent story problems**
Model | Sum of Squares | df | Mean Square | F  | Sig.  
--- | --- | --- | --- | --- | --- 
1 Regression | 902.537 | 1 | 902.537 | 1.953 | .164<sup>b</sup> 
Residual | 72572.306 | 157 | 462.244 | | | 
Total | 73474.843 | 158 | | | |  

c. Predictors: (Constant), Chemistry average percent story problems  

Model | Sum of Squares | df | Mean Square | F  | Sig.  
--- | --- | --- | --- | --- | --- 
1 Regression | 96.949 | 1 | 96.949 | .207 | .649<sup>b</sup> 
Residual | 73377.893 | 157 | 467.375 | | | 
Total | 73474.843 | 158 | | | |  

d. Predictors: (Constant), Overall average percent story problems  

Effect size is given by $R^2$, shown in Table 54. It indicates the predictor variable of percent physics story problems account for 3.9% variance in math-to-physics transfer index ($R^2 = 0.039$, adjusted $R^2 = 0.033$) and the predictor variable of percent math story problems account for 3.4% variance in math-to-economics transfer index ($R^2 = 0.034$, adjusted $R^2 = 0.028$).  

Table 54  

[Math to Physics Transfer Index (Dependent Variable) Univariate Model Summary](#)  

| Model | R | R Square | Adjusted R Square | Std. Error of the Estimate | R Square Change | F Change | df1 | df2 | Sig. F Change |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | .199<sup>a</sup> | .039 | .033 | 23.977 | .039 | 6.443 | 1 | 157 | .012 |

a. Predictors: (Constant), Physics percent story problems  

[Math to Economics Transfer Index (Dependent Variable) Univariate Model Summary](#)  

| Model | R | R Square | Adjusted R Square | Std. Error of the Estimate | R Square Change | F Change | df1 | df2 | Sig. F Change |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | .184<sup>a</sup> | .034 | .028 | 21.265 | .034 | 5.480 | 1 | 157 | .020 |

a. Predictors: (Constant), Math percent story problems  

Table 55 shows that, for every one-point increase in math-to-physics transfer index, we can expect, on average, a 0.135-point increase in math-to-physics transfer index ($\text{Physics \% SP} = 0.135, t = 2.538, p = 0.012$). For every one-point increase in math percent story problems, we can expect, on average, a 0.218-point decrease in math-to-economics transfer index ($\text{coefficient M\%} = -0.218, t = -2.341, p = 0.020$).
Table 55

Math to Physics (Dependent Variable) Univariate Coefficients

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
<th>95.0% Confidence Interval for B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>Std. Error</td>
<td>Beta</td>
</tr>
<tr>
<td>1</td>
<td>(Constant)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P % story problems</td>
<td>.135</td>
<td>.053</td>
<td>.199</td>
</tr>
<tr>
<td>a. Predictors: (Constant), Physics percent story problems</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Math to Economics (Dependent Variable) Univariate Coefficients

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
<th>95.0% Confidence Interval for B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>Std. Error</td>
<td>Beta</td>
</tr>
<tr>
<td>1</td>
<td>(Constant)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M % story problems</td>
<td>-.218</td>
<td>.093</td>
<td>-.184</td>
</tr>
<tr>
<td>a. Predictors: (Constant), Math percent story problems</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The statistics shown in Table 56 are for the multivariate regression if all percent story problem variables are considered in the same model. It indicates we can reject the null that transfer index is not a function of math percent story problems, physics percent story problems, or average chemistry percent story problems (MPTI: $F = 4.876, p = 0.003$; METI: $F = 3.802, p = 0.012$). In the following tables, SPSS removed the overall average percent story problems variable, as seen in the excluded variables portion of Table 58. This is due to the correlation between the variables—one or more of the other variables already account for the influence of average percent story problems so including it would be including a redundant predictor variable.

Table 56

ANOVA with Math to Physics

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regression</td>
<td>8103.298</td>
<td>3</td>
<td>2701.099</td>
<td>4.876</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>85861.914</td>
<td>155</td>
<td>553.948</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>93965.212</td>
<td>158</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Dependent Variable: Math-to-Physics Transfer Index</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b. Predictors: (Constant), Chemistry average % story problems, Math % story problems, Physics % story problems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
ANOVA with Math to Economics

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Regression</td>
<td>5036.522</td>
<td>3</td>
<td>1678.841</td>
<td>3.802</td>
<td>.012b</td>
</tr>
<tr>
<td>Residual</td>
<td>68438.321</td>
<td>155</td>
<td>441.538</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>73474.843</td>
<td>158</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Dependent Variable: Math-to-Economics Transfer Index
b. Predictors: (Constant), Chemistry average % story problems, Math % story problems, Physics % story problems

Effect size is given by $R^2$, shown in Table 57. It indicates the predictor variables of math percent story problems, physics percent story problems, and average chemistry percent story problems account for approximately 7% variance in math-to-economics transfer index ($R^2 = 0.069$, *adjusted $R^2 = 0.051$). The predictor variables of math % story problems, physics % story problems, and average chemistry % story problems account for approximately 9% variance in math-to-physics transfer index ($R^2 = 0.086$, *adjusted $R^2 = 0.069$).

Table 57

Model Summary of Math to Physics

<table>
<thead>
<tr>
<th>Model</th>
<th>R</th>
<th>R Square</th>
<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
<th>Change Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$F$ Change $df_1$ $df_2$ Sig. $F$ Change</td>
</tr>
<tr>
<td>1</td>
<td>.294a</td>
<td>.086</td>
<td>.069</td>
<td>23.536</td>
<td>.086</td>
</tr>
</tbody>
</table>

a. Predictors: (Constant), Chemistry average % story problems, Math % story problems, Physics % story problems
b. Dependent Variable: Math-to-Physics Transfer Index

Model Summary of Math to Economics

<table>
<thead>
<tr>
<th>Model</th>
<th>R</th>
<th>R Square</th>
<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
<th>Change Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$F$ Change $df_1$ $df_2$ Sig. $F$ Change</td>
</tr>
<tr>
<td>1</td>
<td>.262a</td>
<td>.069</td>
<td>.051</td>
<td>21.013</td>
<td>.069</td>
</tr>
</tbody>
</table>

a. Predictors: (Constant), Chemistry average % story problems, Math % story problems, Physics % story problems
b. Dependent Variable: Math-to-Economics Transfer Index

Table 58 shows that, for every one-point increase in physics percent story problems, we can expect, on average, a 0.170-point increase in math-to-physics transfer index (*coefficient MPTI* = 0.170, $t = 3.157, p = 0.002$). For every one-point increase in math percent story problems, we can expect, on average, a 0.228-point decrease in math-to-economics transfer index (*coefficient METI* = -0.228, $t = -2.459, p = 0.015$). For every point increase in physics percent story problems we can expect 0.099-point increase in math-to-economics transfer index (*coefficient METI* = 0.099, $t = 2.053, p = 0.042$). We do not have evidence that chemistry % story problems from high school influences transfer index score. Similar tables for the predictor variables that did not have an effect on the dependent variables can be found in Appendix S – Extra Data Tables.
Table 58

**Coefficients of Math to Physics**

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
<th>t</th>
<th>Sig.</th>
<th>95.0% Confidence Interval for B</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>Std. Error</td>
<td>Beta</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Constant)</td>
<td>49.764</td>
<td>5.716</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M % story problems</td>
<td>-.205</td>
<td>.104</td>
<td>-.152</td>
<td></td>
<td></td>
<td>-.410</td>
<td>.001</td>
</tr>
<tr>
<td>P % story problems</td>
<td>.170</td>
<td>.054</td>
<td>.250</td>
<td></td>
<td></td>
<td>.064</td>
<td>.277</td>
</tr>
<tr>
<td>C % SP ave</td>
<td>-.157</td>
<td>.082</td>
<td>-.151</td>
<td>-.193</td>
<td></td>
<td>-.320</td>
<td>.005</td>
</tr>
</tbody>
</table>

a. Dependent Variable: Math-to-Physics Transfer Index

**Excluded Variables**

<table>
<thead>
<tr>
<th>Model</th>
<th>Beta In</th>
<th>t</th>
<th>Sig.</th>
<th>Partial Correlation</th>
<th>Tolerance</th>
<th>VIF</th>
<th>Minimum Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Constant)</td>
<td>.</td>
<td></td>
<td></td>
<td></td>
<td>.000</td>
<td></td>
<td>.000</td>
</tr>
</tbody>
</table>

a. Predictors in the Model: (Constant), Chemistry average % story problems, Math % story problems, Physics % story problems

**Coefficients with Math to Economics**

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
<th>t</th>
<th>Sig.</th>
<th>95.0% Confidence Interval for B</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>Std. Error</td>
<td>Beta</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Constant)</td>
<td>54.411</td>
<td>5.103</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M % story problems</td>
<td>-.228</td>
<td>.093</td>
<td>-.192</td>
<td></td>
<td></td>
<td>-.412</td>
<td>-.045</td>
</tr>
<tr>
<td>P % story problems</td>
<td>.099</td>
<td>.048</td>
<td>.164</td>
<td></td>
<td></td>
<td>.004</td>
<td>.194</td>
</tr>
<tr>
<td>C % SP ave</td>
<td>-.123</td>
<td>.073</td>
<td>-.134</td>
<td>-.168</td>
<td></td>
<td>-.268</td>
<td>.022</td>
</tr>
</tbody>
</table>

a. Dependent Variable: Math-to-Economics Transfer Index

**Excluded Variables**

<table>
<thead>
<tr>
<th>Model</th>
<th>Beta In</th>
<th>t</th>
<th>Sig.</th>
<th>Partial Correlation</th>
<th>Tolerance</th>
<th>VIF</th>
<th>Minimum Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Constant)</td>
<td>.</td>
<td></td>
<td></td>
<td></td>
<td>.000</td>
<td></td>
<td>.000</td>
</tr>
</tbody>
</table>

a. Predictors in the Model: (Constant), Chemistry average % story problems, Math % story problems, Physics % story problems

Transfer is a function of percent story problems students were exposed to in high school, specifically physics story problems. Story problem solving requires greater logical reasoning, so it makes sense that students with more story problem experience will score higher in transfer, as
scientific, or logical, reasoning is correlated to transfer (Dori & Sasson, 2008; Kapur, 2014; Nicoll & Francisco, 2001; Sasson & Dori, 2012, 2015).

4.1.11 Question 10: Transfer as a function of percent inquiry labs in high school.

Is Transfer Index, as measured using the Roberts et al. (2007) transfer formula for the Test on Graphs, a function of high school experience with inquiry labs, as measured by the student self-reported percentages from the demographic questionnaire by type, and Transfer Category—math to physics or math to economics?

The null hypothesis, $H_0$, states that transfer will not be a function of percent inquiry labs participants experienced in high school. The alternative is predicted below.

$P_{10}$: Yes, Transfer Index score will be a function of percent inquiry labs participants experienced in high school.

![Figure 56](image)

*Figure 56. Predicted graph of transfer index as a function of percent inquiry labs. These were self-reported percentages experienced in high school. Inquiry refers to going from data to concepts. The original prediction was done considering the percentages as a categorical variable. However, in the actual analysis they were changed to average percentages and treated as a continuous variable.*

To test the hypothesis, an analysis was done using two sets of two linear regressions and comparing their differences in slopes. Power of 0.95 or higher assuming a small effect size (e.g., $f^2 = 0.11$) was estimated to require 121 participants. More than 121 participants completed both the Test on Graphs and all assessments, as seen in Table 59 along with other descriptive statistics.

Table 59

<table>
<thead>
<tr>
<th>Descriptive Statistics of Math to Physics</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>MP TI</td>
<td>39.48</td>
<td>24.437</td>
<td>158</td>
</tr>
<tr>
<td>C Inq Lab Ave %</td>
<td>46.65</td>
<td>28.827</td>
<td>158</td>
</tr>
<tr>
<td>P Inq Lab Ave %</td>
<td>20.13</td>
<td>26.331</td>
<td>158</td>
</tr>
</tbody>
</table>

*Note. MP stands for Math to Physics transfer category. TI stands for Transfer Index. C Inq Lab Ave % stands for the average percent of inquiry-style laboratories students had in all their years of high school chemistry. P Inq Lab Ave % stands for the average percent of inquiry-style laboratories students had in all their years of high school physics.*
Descriptive Statistics of Math to Economics

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>ME TI</td>
<td>42.56</td>
<td>21.629</td>
<td>158</td>
</tr>
<tr>
<td>C Inq Lab Ave %</td>
<td>46.65</td>
<td>28.827</td>
<td>158</td>
</tr>
<tr>
<td>P Inq Lab Ave %</td>
<td>20.13</td>
<td>26.331</td>
<td>158</td>
</tr>
</tbody>
</table>

*Note.* ME stands for Math to Economics transfer category. TI stands for Transfer Index. C Inq Lab Ave % stands for the average percent of inquiry-style laboratories students had in all their years of high school chemistry. P Inq Lab Ave % stands for the average percent of inquiry-style laboratories students had in all their years of high school physics.

Graphical representations of transfer index as a function of percent inquiry labs in high school can be seen in Figure 57 and Figure 58.

*Figure 57.* Math-to-economics transfer category transfer index as a function of percent inquiry labs. These were experienced in high school and inquiry lab category (InqLabcat). The categories are average percent inquiry labs in up to three years of high school chemistry and average percent of physics inquiry labs.

*Figure 58.* Math-to-physics transfer category transfer index as a function of percent inquiry labs. These were experienced in high school and inquiry lab category (InqLabcat). The categories are average percent inquiry labs in up to three years of high school chemistry and average percent of physics inquiry labs.
Considering the univariate statistics shown in Table 60 we cannot reject the null that transfer index is not a function of average physics percent inquiry labs and average chemistry percent inquiry labs experienced in high school (MPTI: $F_{\text{ChemAve}} = 0.086, p = 0.769$; METI: $F_{\text{PhysicsAve}} = 1.431, p = 0.233; F_{\text{ChemAve}} = 0.685, p = 0.409$). However, we can reject the null in the specific case of math-to-physics transfer index being a function of percent average physics percent inquiry labs ($F_{\text{PhysicsAve}} = 4.628, p = 0.033$).

Table 60

**Math to Physics (Dependent Variable) Univariate ANOVAs**

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regression</td>
<td>2701.505</td>
<td>1</td>
<td>2701.505</td>
<td>4.628</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>91055.418</td>
<td>156</td>
<td>583.689</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>93756.922</td>
<td>157</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Predictors: (Constant), **Average percent physics inquiry labs**

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regression</td>
<td>51.784</td>
<td>1</td>
<td>51.784</td>
<td>.086</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>93705.138</td>
<td>156</td>
<td>600.674</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>93756.922</td>
<td>157</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

b. Predictors: (Constant), **Average percent chemistry inquiry labs**

**Math to Economics (Dependent Variable) Univariate ANOVAs**

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regression</td>
<td>667.485</td>
<td>1</td>
<td>667.485</td>
<td>1.431</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>72781.882</td>
<td>156</td>
<td>466.551</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>73449.367</td>
<td>157</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Predictors: (Constant), **Average percent physics inquiry labs**

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regression</td>
<td>321.034</td>
<td>1</td>
<td>321.034</td>
<td>.685</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>73128.333</td>
<td>156</td>
<td>468.771</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>73449.367</td>
<td>157</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

b. Predictors: (Constant), **Average percent chemistry inquiry labs**

Effect size is given by $R^2$, shown in Table 61. It indicates the predictor variable of average percent physics inquiry labs account for 2.9% variance in math-to-physics transfer index ($R^2 = 0.029$, adjusted $R^2 = 0.023$).
Table 61

**Math to Physics Transfer Index (Dependent Variable) Univariate Model Summary**

<table>
<thead>
<tr>
<th>Model</th>
<th>R</th>
<th>R Square</th>
<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
<th>R Square Change</th>
<th>F Change</th>
<th>df1</th>
<th>df2</th>
<th>Sig. F Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.170</td>
<td>.029</td>
<td>.023</td>
<td>24.160</td>
<td>.029</td>
<td>4.628</td>
<td>1</td>
<td>156</td>
<td>.033</td>
</tr>
</tbody>
</table>

a. Predictors: (Constant), Average percent physics inquiry labs

Table 62 shows that, for every one-point increase in math-to-physics transfer index, we can expect, on average, a 0.135-point increase in math-to-physics transfer index (Physics % SP = 0.135, t = 2.538, p = 0.012). Similar tables for the predictor variables that did not have an effect on the dependent variables can be found in Appendix S – Extra Data Tables.

Table 62

**Math to Physics (Dependent Variable) Univariate Coefficients**

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
<th>t</th>
<th>Sig.</th>
<th>95.0% Confidence Interval for B Lower Bound</th>
<th>Upper Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>Std. Error</td>
<td>Beta</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>(Constant)</td>
<td>36.307</td>
<td>2.422</td>
<td>14.990</td>
<td>.000</td>
<td>31.523</td>
</tr>
<tr>
<td>P Inq Lab Ave %</td>
<td>.158</td>
<td>.073</td>
<td>.170</td>
<td>2.151</td>
<td>.033</td>
<td>.013</td>
</tr>
</tbody>
</table>

a. Predictors: (Constant), Average percent physics inquiry labs

The statistics shown in Table 63 are for the multivariate regression if all percent inquiry lab variables are considered in the same model. It indicates we cannot reject the null that transfer index is not a function of physics average percent inquiry labs and chemistry average percent inquiry labs (MPTI: F = 2.606, p = 0.077; METI: F = 1.332, p = 0.267).

Table 63

**ANOVA of Math to Physics**

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regression</td>
<td>3049.721</td>
<td>2</td>
<td>1524.861</td>
<td>2.606</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>90707.201</td>
<td>155</td>
<td>585.208</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>93756.922</td>
<td>157</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Dependent Variable: Math-to-Physics Transfer Index
b. Predictors: (Constant), Physics average % inquiry labs, Chemistry average % inquiry labs
ANOVA of Math to Economics

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>1241.128</td>
<td>2</td>
<td>620.564</td>
<td>1.332</td>
<td>.267</td>
</tr>
<tr>
<td>Residual</td>
<td>72208.240</td>
<td>155</td>
<td>465.860</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>73449.367</td>
<td>157</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Dependent Variable: Math-to-Economics Transfer Index
b. Predictors: (Constant), Physics average % inquiry labs, Chemistry average % inquiry labs

Similarly, to self-reported percent story problems in high school, there is evidence that percent physics inquiry labs students experienced in high school affects their transfer from math to physics contexts. Working with “data to concepts” labs would allow students to construct conceptual understanding and develop higher reasoning skills, which are skills correlated to transfer (Cantu & Herron, 1978; Dori & Sasson, 2008; Kapur, 2014; Lappalainen & Rosqvist, 2015; Lawson & Renner, 1975; Marek & Cavallo, 1997; Menis, 1987; Nicoll & Francisco, 2001; Piaget, 1970, 1997; Roberts et al., 2007; Sasson & Dori, 2012). This also provides support that students require prior knowledge and practice in the contexts they are doing the transfer problems (Bassok & Holyoak, 1989; Becker & Towns, 2012; Menis, 1987; Potgieter et al., 2008; Scott, 2012; Shah & Hoeffner, 2002), as well as that students are context bound (Beauford, 2009; Catrambone & Holyoak, 1989; Johnson & Rutherford, 2010; Planinic et al., 2012; Roberts et al., 2007). The physics labs only helped with math to physics transfer, not math to economics.


Is participants’ percentage of spontaneous graphing in laboratory, as measured by
\[
\frac{\# \text{ graphs drawn when the lab questions prompted it}}{\text{total graphs possible}} \times 100\%\],
a function of the graphing instructional treatment they received at the beginning of the course? For seven of the laboratories, questions in the laboratory manual prompted students to graph the data they collected to see and quantify the relationship between variables. Students were not told explicitly that they must graph so here the interest was to see if they followed the prompting of the lab question, especially after receiving specific graphing instructional treatments the second week of class. Each of three versions of treatments provided students with basic graphing definitions, an opportunity to work through a math-graphing scenario, and subsequent application in a chemistry context. In version one, students were presented with a table of data and asked to construct a graph representing the relationship – active graphing example. In version two, the students were presented with a graph already depicting the relationship and asked several questions about why the graph was constructed the way it was – passive graphing example. In version three, students were presented with a worked example of how a graph was constructed but no reflective questions were asked – worked graphing example. This was the control group, as worked examples have been show, with regards to transfer, to be ineffective (Ngu & Yeung, 2012; Ngu et al., 2015).

The null hypothesis, \( H_0 \), states that percent graphs drawn in laboratory will not be a function of instructional treatment. The alternative is predicted below.

\( P_{11} \): Yes, percent spontaneous graphing in lab will be a function of instructional treatment. Participants with active graphing instruction will produce a higher percentage of subsequent graphs in lab than those with passive interpretation instruction. Both groups will produce a higher...
percentage of subsequent graphs than those who received worked example instruction, which acts as the control.

![Percentage of Spontaneously Drawn Graphs in Lab](image1)

*Figure 59. Predicted graph of the percent of spontaneously drawn graphs as a function of instructional treatment. These graphs were constructed during the semester of lab, out of a potential of seven labs.*

Of additional interest was whether, during the first lab on week one, students who received explicit, prompted, graphing instruction would demonstrate an interaction effect with instructional treatment on the percent of spontaneously drawn graphs in lab. Two sets of questions on the first week’s lab was given to two groups of participants. One set of questions investigated what students do spontaneously when asked to describe a pattern shown in their data – no prompt. The other set of questions provided complete instructions about what to graph to see how accurately students could construct a graph with guidance – prompt.

The null hypothesis, $H_0$, states that being prompted with explicit graphing instruction the first week of laboratory will not be a function of percent spontaneously drawn graphs drawn throughout the semester in lab. The alternative is predicted below.

$P_{11}$: Yes, percent spontaneous graphing in lab will be a function of participants being prompted with explicit graphing instruction their first week of lab as compared to those who were not prompted.

![Percent of Spontaneously Drawn Graphs in Lab based on a Prompted 1st Week Lab](image2)

*Figure 60. Predicted graph of the percent of spontaneously drawn graphs as a function of receiving explicit graphing prompts. The graphs were drawn during the semester of lab, out of a potential of seven labs.*
The analysis was based on a $2 \times 3$, between-subject ANOVA, which has a continuous dependent variable of percent graphs drawn in lab, with three groups of instructional treatments for one independent variable, and two levels of being prompted, or not, for the second independent variable. Power of 0.95 or higher assuming a small effect size (e.g., $f = 0.33$), was estimated to require 147 participants. More than 147 participants completed all the labs requiring graphs to be drawn as seen in Table 64.

### Table 64

**Descriptive Statistics**

<table>
<thead>
<tr>
<th>Prompt</th>
<th>Instructional Tx</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>A</td>
<td>54.622</td>
<td>25.3724</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>53.741</td>
<td>28.5374</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>52.613</td>
<td>32.0139</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>53.345</td>
<td>29.4471</td>
<td>79</td>
</tr>
<tr>
<td>Y</td>
<td>A</td>
<td>74.286</td>
<td>24.9369</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>78.947</td>
<td>24.1198</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>63.158</td>
<td>30.6083</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>73.913</td>
<td>26.2485</td>
<td>92</td>
</tr>
<tr>
<td>Total</td>
<td>A</td>
<td>67.857</td>
<td>26.5195</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>69.976</td>
<td>28.2861</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>55.952</td>
<td>31.7038</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>64.411</td>
<td>29.5370</td>
<td>171</td>
</tr>
</tbody>
</table>

*Note.* Dependent Variable: % of Graphs. N stands for no prompt the first week of lab and Y stands for yes, prompt, the first week of lab. A refers to active construction instructional treatment, P for passive interpretations instructional treatment, and W for worked example instructional treatment.

The interaction plot in Figure 61 shows that participants who received a prompt from their first week labs consistently had higher mean percent spontaneous graphing in subsequent labs across all treatments. Both independent variables of instructional treatment and prompt are between-subject variables, so the error bars can be used as a visual depiction of significant difference. Refer to Table 65 for $p$-values and effect size.
Figure 61. Percent spontaneously drawn graphs as a function of instructional treatment and prompted instruction. The graphs were drawn during the semester of lab, out of a potential of seven labs, and instructional treatment was given the second week of the course. Those who received a prompted lab produced a higher percent of spontaneously drawn graphs in lab across all treatments.

Table 65 indicates that there is evidence for a main effect for prompt ($F = 16.723, p < 0.001$) with a partial eta squared of 0.092. No main effect was found for instructional treatment ($F = 1.336, p = 0.266$) or an interaction effect of prompt and instructional treatment ($F = 0.938, p = 0.393$).

Table 65

Tests of Between-Subjects Effects

<table>
<thead>
<tr>
<th>Source</th>
<th>Type III Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
<th>Partial Eta Squared</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrected Model</td>
<td>21198.657a</td>
<td>5</td>
<td>4239.731</td>
<td>5.503</td>
<td>.000</td>
<td>.143</td>
</tr>
<tr>
<td>Intercept</td>
<td>597463.021</td>
<td>1</td>
<td>597463.021</td>
<td>775.529</td>
<td>.000</td>
<td>.825</td>
</tr>
<tr>
<td>Prompt</td>
<td>12883.298</td>
<td>1</td>
<td>12883.298</td>
<td>16.723</td>
<td>.000</td>
<td>.092</td>
</tr>
<tr>
<td>InstructionalTx</td>
<td>2058.149</td>
<td>2</td>
<td>1029.074</td>
<td>1.336</td>
<td>.266</td>
<td>.016</td>
</tr>
<tr>
<td>Prompt * InstructionalTx</td>
<td>1445.389</td>
<td>2</td>
<td>722.695</td>
<td>.938</td>
<td>.393</td>
<td>.011</td>
</tr>
<tr>
<td>Error</td>
<td>127114.984</td>
<td>165</td>
<td>770.394</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>857755.102</td>
<td>171</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Corrected Total</td>
<td>148313.641</td>
<td>170</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. R Squared = .143 (Adjusted R Squared = .117)
b. Dependent Variable: % of Graphs
To see where specific differences occurred, a Tukey Honest Significant Difference post hoc test was done. Table 66 shows that there is only an average mean difference in spontaneous graphing between Passive Interpretation treatment and Worked Example treatment \((mean\ difference = 14.023, p = 0.018)\). There is no evidence for other mean differences.

Table 66

*Post Hoc Tests for Instructional Treatment*

<table>
<thead>
<tr>
<th>(I) Instructional Tx</th>
<th>(J) Instructional Tx</th>
<th>Mean Difference (I-J)</th>
<th>Std. Error</th>
<th>Sig.</th>
<th>95% Confidence Interval Lower Bound</th>
<th>95% Confidence Interval Upper Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>P</td>
<td>-2.119</td>
<td>5.2795</td>
<td>.915</td>
<td>-14.605</td>
<td>10.368</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>11.905</td>
<td>5.2588</td>
<td>.064</td>
<td>-.533</td>
<td>24.342</td>
</tr>
<tr>
<td>P</td>
<td>A</td>
<td>2.119</td>
<td>5.2795</td>
<td>.915</td>
<td>-10.368</td>
<td>14.605</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>14.023*</td>
<td>5.0890</td>
<td>.018</td>
<td>1.988</td>
<td>26.059</td>
</tr>
<tr>
<td>W</td>
<td>A</td>
<td>-11.905</td>
<td>5.2588</td>
<td>.064</td>
<td>-24.342</td>
<td>.533</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>-14.023*</td>
<td>5.0890</td>
<td>.018</td>
<td>-26.059</td>
<td>-1.988</td>
</tr>
</tbody>
</table>

Based on observed means. Tukey HSD
The error term is Mean Square(Error) = 770.394.
Dependent variable: % Graphs

Results showed that there was no evidence for an instructional treatment main effect, however, there was still a difference between the passive interpretation and worked example treatments. It had been hypothesized that students who received instructional treatment with active construction of graphs would produce a higher percentage of subsequent graphs in lab than those with passive graph interpretation and that both of those groups would produce a higher percentage of graphs in lab than the students who received a worked example instructional treatment. This is because construction has been shown to draw attention to underlying structure and thus improve transfer (Ngu & Yeung, 2012; Ngu et al., 2015; Stern et al., 2004; Terwel et al., 2009). Passive interpretation was also shown to improve transfer as it still draws attention to structure (Stern et al., 2004), however, worked examples have been shown to not improve transfer (Ngu & Yeung, 2012; Ngu et al., 2015; Stern et al., 2004). The latter part of the hypothesis was supported in that both the active construction and passive interpretation showed higher percent spontaneously drawn graphs than those who received the worked example treatment. This indicates that both the active and passive treatments did help draw participants’ attention to underlying structure and improve transfer. With worked example acting as a control, it can be assumed that with the instruction in the laboratory question prompting students to draw a graph to quantify the pattern, a baseline of 60% spontaneous graphing can be expected.

Whether students were prompted with explicit chemistry graphing instruction during their first lab did show a main effect. Students who had this additional practice in the chemistry domain seemed to gain graphical literacy (Bassok & Holyoak, 1989; Beauford, 2009; Becker and Towns, 2012; Bowen & Roth, 1998; Bowen et al., 1997; Kaminski & Sloutsky, 2013; Kapur, 2014; Waight & Abd-El-Khalick, 2010).

Is participants’ scientific accuracy of graphing questions, as measured by the graphing rubric developed from a compilation of expert answer keys, a function of instructional treatment and three levels of time—Exam 1, 2, and 3?

The null hypothesis, $H_0$, states that scientific accuracy will not be a function of instructional treatment. The alternative is predicted below.

$P_{12}$: Yes, scientific accuracy will be a function of instruction treatment across the three exams. Participants with active graphing instruction will produce a greater scientific accuracy on exams than those with passive interpretation instruction. Both groups will produce greater scientific accuracy than those who received worked example instruction, which acts as the control.

![Figure 62](chart.png)

*Figure 62.* Predicted graph of scientific accuracy as a function of instructional treatment and time. Time is based on all three exams.

To test this hypothesis, an analysis was based on a $3 \times 3$ repeated measures ANOVA, with one between category and one within category. Power of 0.95 or higher assuming a small effect size (e.g., $f = 0.33$) and a correlation among repeated measures of 0.1, was estimated to require 54 participants. More than 54 participants completed all three exams as seen in Table 67.
Table 67

*Descriptive Statistics*

<table>
<thead>
<tr>
<th>Instructional Tx</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exam 1 SA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>4.45</td>
<td>2.165</td>
<td>38</td>
</tr>
<tr>
<td>P</td>
<td>3.34</td>
<td>2.026</td>
<td>50</td>
</tr>
<tr>
<td>W</td>
<td>3.94</td>
<td>1.769</td>
<td>31</td>
</tr>
<tr>
<td>Total</td>
<td>3.85</td>
<td>2.049</td>
<td>119</td>
</tr>
<tr>
<td>Exam 2 SA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>5.45</td>
<td>2.165</td>
<td>38</td>
</tr>
<tr>
<td>P</td>
<td>4.76</td>
<td>1.912</td>
<td>50</td>
</tr>
<tr>
<td>W</td>
<td>5.55</td>
<td>2.392</td>
<td>31</td>
</tr>
<tr>
<td>Total</td>
<td>5.18</td>
<td>2.139</td>
<td>119</td>
</tr>
<tr>
<td>Exam 3 SA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>4.76</td>
<td>2.410</td>
<td>38</td>
</tr>
<tr>
<td>P</td>
<td>4.46</td>
<td>2.159</td>
<td>50</td>
</tr>
<tr>
<td>W</td>
<td>5.10</td>
<td>2.749</td>
<td>31</td>
</tr>
<tr>
<td>Total</td>
<td>4.72</td>
<td>2.397</td>
<td>119</td>
</tr>
</tbody>
</table>

*Note.* "SA" stands for scientific accuracy. “A” refers to active construction instructional treatment, “P” for passive interpretations instructional treatment, and “W” for worked example instructional treatment.

An interaction plot in Figure 63 was obtained to help visualize the exam by instructional treatment interaction and it is evident from the plot that the greatest difference, for the between-subject variable, occurs between the passive interpretation and worked examples treatments. This supports the data found in question 11. Instructional treatment is a between-subject variable so the error bars can be used as a visual representation of significance. However, exam is a within-subject variable so for significance values refer to Table 68.

*Figure 63. Scientific accuracy as a function of instructional treatment and time.*
A 3 × 3 repeated measures ANOVA was performed, where instructional treatment was the between-subject factor having three levels, and exam was the within-subjects factor having three levels. Table 68, for the within-subject effects, shows that an exam effect was found ($F = 14.260$, $p < 0.001$) with a small effect (partial eta-squared = 0.109) and there was no evidence of an interaction effect ($F = 0.618$, $p = 0.636$). Looking at the between-subjects effect portion of Table 69, an instructional treatment effect was also not found ($F = 2.994$, $p = 0.054$).

Table 68

*Test of Within-Subject Effects*

<table>
<thead>
<tr>
<th>Source</th>
<th>Type III Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
<th>Partial Eta Squared</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exam</td>
<td>Greenhouse-Geisser</td>
<td>106.357</td>
<td>1.828</td>
<td>58.184</td>
<td>14.260</td>
<td>.000</td>
</tr>
<tr>
<td>Exam * InstructionalTx</td>
<td>Greenhouse-Geisser</td>
<td>9.212</td>
<td>3.656</td>
<td>2.520</td>
<td>.618</td>
<td>.636</td>
</tr>
<tr>
<td>Error(Exam)</td>
<td>Greenhouse-Geisser</td>
<td>865.202</td>
<td>212.041</td>
<td>4.080</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 69

*Tests of Between-Subject Effects*

<table>
<thead>
<tr>
<th>Source</th>
<th>Type III Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
<th>Partial Eta Squared</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>7411.787</td>
<td>1</td>
<td>7411.787</td>
<td>1078.114</td>
<td>.000</td>
<td>.903</td>
</tr>
<tr>
<td>InstructionalTx</td>
<td>41.171</td>
<td>2</td>
<td>20.585</td>
<td>2.994</td>
<td>.054</td>
<td>.049</td>
</tr>
<tr>
<td>Error</td>
<td>797.474</td>
<td>116</td>
<td>6.875</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Transformed Variable: Average

Tukey post hoc tests, shown in Table 70, confirmed no differences between instructional treatments. Paired samples t-tests were done to test for differences between the within-subject factor of exam. Table 71 shows significant differences were found between each pair of exams ($E_1 – E_2 p < 0.001$, $E_1 – E_3 p = 0.002$, $E_2 – E_3 p = 0.029$).
Table 70

*Post Hoc Tests for Instructional Treatment*

<table>
<thead>
<tr>
<th>(I) Instructional Tx</th>
<th>(J) Instructional Tx</th>
<th>Mean Difference</th>
<th>Std. Error</th>
<th>Sig.</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(I-J)</td>
<td></td>
<td></td>
<td>Lower Bound</td>
</tr>
<tr>
<td>A</td>
<td>P</td>
<td>.70</td>
<td>.326</td>
<td>.085</td>
<td>-.07</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>.03</td>
<td>.366</td>
<td>.997</td>
<td>-.84</td>
</tr>
<tr>
<td>P</td>
<td>A</td>
<td>-.70</td>
<td>.326</td>
<td>.085</td>
<td>-1.47</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>-.67</td>
<td>.346</td>
<td>.130</td>
<td>-1.50</td>
</tr>
<tr>
<td>W</td>
<td>A</td>
<td>-.03</td>
<td>.366</td>
<td>.997</td>
<td>-.90</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>.67</td>
<td>.346</td>
<td>.130</td>
<td>-.15</td>
</tr>
</tbody>
</table>

Based on observed means. Tukey HSD.
The error term is Mean Square(Error) = 2.292.

Table 71

*Paired Samples T-tests*

<table>
<thead>
<tr>
<th>Pair</th>
<th>Exam 1 SA - Exam 2 SA</th>
<th>Exam 1 SA - Exam 3 SA</th>
<th>Exam 2 SA - Exam 3 SA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Std. Deviation</td>
<td>Mean</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Std. Error</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td>95% Confidence Interval</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>of the Difference</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lower</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Upper</td>
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<td></td>
<td>df</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Sig. (2-tailed)</td>
</tr>
<tr>
<td>Pair 1</td>
<td>-1.336</td>
<td>2.805</td>
<td>.257</td>
</tr>
<tr>
<td></td>
<td>-1.845</td>
<td>-.827</td>
<td></td>
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<tr>
<td></td>
<td>-5.196</td>
<td>118</td>
<td></td>
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<tr>
<td></td>
<td>.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pair 2</td>
<td>-.874</td>
<td>3.024</td>
<td>.277</td>
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<tr>
<td></td>
<td>-1.423</td>
<td>-.325</td>
<td></td>
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<tr>
<td></td>
<td>-3.153</td>
<td>118</td>
<td></td>
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<tr>
<td></td>
<td>.002</td>
<td></td>
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</tr>
<tr>
<td>Pair 3</td>
<td>.462</td>
<td>2.284</td>
<td>.209</td>
</tr>
<tr>
<td></td>
<td>.048</td>
<td>.877</td>
<td></td>
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<tr>
<td></td>
<td>2.207</td>
<td>118</td>
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<td></td>
<td>.029</td>
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</tr>
</tbody>
</table>

A main effect was only found for exams, which was already seen in research question three. No main instructional treatment effect was found or an interaction effect. This seems to indicate that the practice with the chemistry context graphs and feedback had more influence on students’ scientific accuracy than instruction that drew attention to underlying structure of the graphs. Scientific accuracy was about the details of the graphing—did they draw a straight line through 0,0 for a directly proportional relationship, could they calculate the slope, and could they interpret its meaning? This brings up the question, did participants try to focus more on memorizing the steps than understanding the underlying structure. As students performed at 50% or less, on average, for all exams and all instructional treatments it does seem that there was a general lack of understanding taking place.
4.2 Quantitative Discussion

The following table summarizes the quantitative findings based on the percent variance each finding explains. See Table 72. The order of the findings is based on increased percent variance explained. All findings are listed although certain findings were not significant. Those that were significant are marked with an asterisk. The highest percent variance explained supports other literature findings that context does influence ability to transfer. It was found that almost 50% variance is explained by context mattering when transferring math-graphing skills. Contexts that participants were more familiar with were correlated to greater success with transfer. Refer to Table 72 number 16.

Table 72

Summary of Quantitative Results

<table>
<thead>
<tr>
<th>Order</th>
<th>Quantitative Finding</th>
<th>Percent Variance Explained</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Difference between transfer index categories</td>
<td>–</td>
<td>*0.009</td>
</tr>
<tr>
<td>2</td>
<td>Percent spontaneous graphing as a function of instructional treatment*prompt</td>
<td>1.1</td>
<td>0.393</td>
</tr>
<tr>
<td>3</td>
<td>Scientific accuracy as a function of instructional treatment*time</td>
<td>1.1</td>
<td>0.636</td>
</tr>
<tr>
<td>4</td>
<td>Percent spontaneous graphing as a function of instructional treatment</td>
<td>1.6</td>
<td>0.266</td>
</tr>
<tr>
<td>5</td>
<td>Transfer as a function of percent inquiry labs in high school: Math-to-physics as a function of physics labs (Univariate model)</td>
<td>2.9</td>
<td>*0.033</td>
</tr>
<tr>
<td>6</td>
<td>Scientific accuracy as a function of transfer</td>
<td>4.1</td>
<td>*0.013</td>
</tr>
<tr>
<td>7</td>
<td>Scientific accuracy as a function of instructional treatment</td>
<td>4.9</td>
<td>0.054</td>
</tr>
<tr>
<td>8</td>
<td>Transfer as a function of percent story problems in high school (Multivariate model)</td>
<td>6.9–8.6</td>
<td>*0.003–0.012</td>
</tr>
<tr>
<td>9</td>
<td>Percent spontaneous graphing as a function of prompt</td>
<td>9.2</td>
<td>*0.000</td>
</tr>
<tr>
<td>10</td>
<td>Scientific accuracy as a function of time</td>
<td>10.1</td>
<td>*0.000</td>
</tr>
<tr>
<td>11</td>
<td>Transfer as a function of high school graphing ability</td>
<td>13.3–17.2</td>
<td>*0.000</td>
</tr>
<tr>
<td>12</td>
<td>Transfer as a function of intelligence</td>
<td>14.8–14.9</td>
<td>*0.000</td>
</tr>
<tr>
<td>13</td>
<td>Transfer as a function of chemical misconceptions</td>
<td>20.1–26.0</td>
<td>*0.000</td>
</tr>
<tr>
<td>14</td>
<td>Transfer as a function of scientific reasoning ability</td>
<td>24.7–28.7</td>
<td>*0.000</td>
</tr>
<tr>
<td>15</td>
<td>Transfer as a function of: high school graphing ability, scientific reasoning, chemical misconceptions, and intelligence (Multiple linear regression)</td>
<td>35.0–35.2</td>
<td>*0.000</td>
</tr>
<tr>
<td>16</td>
<td>Graphing ability as a function of context</td>
<td>49.5</td>
<td>*0.000</td>
</tr>
</tbody>
</table>

Note. All quantitative findings are listed in increasing order of percent variance explained. The percent variance is either based on $R^2$ or partial eta squared values. The significance (p-value) is also listed as some of the variances explained are not actually significant findings. Those that are significant are indicated by a “*” next to the significance value. There is no variance explained for the difference between transfer categories as the analysis was done with a paired t-test, not a regression or ANOVA. For #15 the bolded variables are the two that showed significant impact.

Results looking at scientific accuracy was about the details of the graphing. Refer to Table 72 numbers 3, 6, 7, and 10. Did they draw a straight line through 0,0 for a directly proportional relationship, could they calculate the slope, and could they interpret its meaning? Attention to these details of graphical construction and interpretation in a chemistry context and the meaning of those details, i.e., scientific accuracy, is a function of transfer. When participants understood the underlying structure, they demonstrated greater scientific accuracy. As well, scientific accuracy improved when students learned from feedback. However, there seemed to be a ceiling of improvement in scientific accuracy on the second exam that did not even reach 50%. Additionally, when we looked at scientific accuracy and instructional treatment, we found no main instructional treatment effect and no interaction effect between instructional treatment and
time. This seems to indicate that practice with the chemistry context graphs and feedback on exams had more influence on students’ scientific accuracy than instruction that drew attention to underlying structure of the graphs. We believe that students may be more focused on memorizing the steps than they are in understanding what they are graphing, why, and what the graph represents.

When looking at predictor variables and their correlations to transfer, it was found that transfer is a function of prior knowledge, scientific reasoning, lack of chemical misconceptions, and intelligence, when considered individually. Refer to Table 72 numbers 11–14. This follows what already has been shown in the literature. Prior knowledge, and access to prior knowledge, are necessary for transfer to occur (Bassok & Holyoak, 1989; Becker & Towns, 2012; Menis, 1987; Potgieter et al., 2008; Scott, 2012; Shah & Hoeffner, 2002). Scientific reasoning correlates to transfer (Dori & Sasson, 2008; Kapur, 2014; Lappalainen & Rosqvist, 2015; Menis, 1987; Nicoll & Francisco, 2001; Roberts et al., 2007; Sasson & Dori, 2012). A lack of misconceptions means a greater understanding of abstract concepts and less contextual binding (Beaurod, 2009; Catrambone & Holyoak, 1989; Johnson & Rutherford, 2010; Planinic et al., 2012; Roberts et al., 2007) Adaptive intelligence links to pattern recognition (Holyoak, 1985; Neisser et al., 1996).

However, when all predictor variables are considered collectively, only scientific reasoning ability and lack of chemical misconceptions influence ability to transfer. Intelligence and prior high school graphing knowledge do not show evidence of influencing transfer. Even when considered individually, scientific reasoning and lack of chemical misconceptions had twice as much effect on transfer variance compared to intelligence and prior high school graphing knowledge. Refer to Table 72 numbers 11–15. This indicates that, above all else, these two factors must be nurtured and developed early on so that subsequent education is not lost or minimized for students.

Additionally, students need exposure to story problems and inquiry laboratories in high school. Refer to Table 72 numbers 5 and 8. Problem solving requires logical reasoning, so it makes sense that students with more story problem experience will score higher in transfer because scientific, or logical, reasoning is correlated to transfer (Dori & Sasson, 2008; Kapur, 2014; Nicoll & Francisco, 2001; Sasson & Dori, 2012, 2015). While this study did not show an effect of inquiry labs on transfer, working with “data to concepts” labs would allow students to construct conceptual understanding and develop scientific reasoning skills, which are skills correlated to transfer (Cantu & Herron, 1978; Dori & Sasson, 2008; Kapur, 2014; Lappalainen & Rosqvist, 2015; Lawson & Renner, 1975; Marek & Cavallo, 1997; Menis, 1987; Nicoll & Francisco, 2001; Piaget, 1970, 1997; Roberts et al., 2007; Sasson & Dori, 2012).

Regarding instructional treatments, no main effect was found. However, looking at Table 66 and Figure 61, both the active construction and passive interpretation instructional treatments helped improve percent spontaneously drawn graphs in lab and there was a significant difference between passive interpretation and worked example treatments. This is likely due to having participants’ attention drawn to the underlying structure of the problems (Ngu & Yeung, 2012; Ngu et al., 2015; Stern et al., 2004; Terwel et al., 2009). Students who were prompted with explicit chemistry graphing instruction during their first lab also showed higher transfer ability regarding percent spontaneously drawn graphs during lab. This additional, prompted, practice in the chemistry domain seemed to help participants gain graphical literacy (Bassok & Holyoak, 1989; Beaurod, 2009; Becker and Towns, 2012; Bowen & Roth, 1998; Bowen et al., 1997; Kaminski & Sloutsky, 2013; Kapur, 2014; Waight & Abd-El-Khalick, 2010). Refer to Table 72 numbers 2, 4, and 9. Overall, it appears that receiving an explicit prompt, with how to graph and
why, improved participants’ ability to recognize the need to graph and transfer those skills to other lab settings to a greater degree than any of the instructional treatments.

4.3 Qualitative Results

Information from the quantitative phase was explored further in a second qualitative phase. Qualitative interviews were used to probe participants’ understanding of graphs and their ability to transfer graphing skills into science context with 13 purposefully selected participants. Participants were selected based on total score from the transfer instrument. There was a total of 48 points possible; between four and five participants with “high,” “medium,” and “low” scores were chosen. Low scores were between 0–16, medium scores were between 17–32, and high scores were between 33–48.

Initially, participants were shown tables of data, with increasing, directly proportional values between the dependent and independent variables in math and chemistry contexts. See Figure 64. This was primarily to determine if they (a) could see a pattern between the variables and (b) thought a graph would be helpful to quantify the pattern. Participants were then shown graphs in math and chemistry contexts to determine if they (a) could see a relationship between the variables and (b) could determine how to quantify the relationship. See Appendix O – Interview Questions for the full interview.

Additionally, participants were asked several attitude questions about graphs, as well as questions about graphing during their semester of laboratories. The laboratories were designed to provide participants the opportunity to measure data in a guided inquiry format: data precedes concept introduction. Participants collect data, and from those data they synthesize their own concepts, which are later verified in lecture. Most of the labs were designed in a similar fashion where participants make qualitative observations of the materials, and interactions of materials, prior to collecting quantitative data. This encourages participants to explore what might be happening at the particulate level before they collect quantitative data.

Here are examples of the exposure participants had to graphing, how to graph, and the meaning of graphical equations. Participants were asked to describe the pattern they observed from the data collection as part of the data analysis phase of most of the laboratory exercises. To do so, the laboratory instructions recommended they graph the data and come up with an algebraic expression to describe the pattern. Of the 12 wet labs given throughout the semester, seven required at least one graph to be constructed and interpreted. All seven graphing labs investigated directly proportional relationships between chemistry variables. One lab also required an inverse proportional relationship to be graphed. Participants were also given laboratory graphing questions on three of their four midterm exams. In all cases, participants were provided feedback about how to graph and what to look for when collecting and interpreting data.

Furthermore, in the lecture portion of the course, "How do Scientists Use Algebra to Reason and Calculate?" was discussed in Lesson 1. This included reviewing definitions of algebra, variable, direct proportionality, and inverse proportionality. Direct and inverse proportionality were also explained symbolically and graphically, including the requirement for a direct proportionality to pass through (0,0) on a graph.

All excerpts of responses will use pseudonyms for the participants. The terms “high”, “medium”, or “low,” will also be recorded next to the participant’s pseudonym. While the researcher was unaware of which level each participant placed into based on their pre-transfer score while conducting the interviews and coding and analysis following the interviews, the terms indicating
their pre-transfer level will be included in this section to add richness to the results. The researcher’s questions will be indicated by an “R.” For a summary of all main qualitative findings refer to Table 73, Table 74, and Table 75.

4.3.1 Graphing conceptions.

Several attitude and conception questions were asked of the 13 participants during the interview: What did they see as the purpose of a graph and why? Did they find graphs useful? During lab how often did you work with variables related to each other? How did you know they were related? How did you decide to show the relationships? Did you think to solve a lab relationship right away or did you need to be prompted, and why?

Ten of the 13 participants, 77%, saw the purpose of graphing as providing a visual representation of the data with three mentioning that graphs are a way to think about the data differently. Mike (medium) had a typical response:

R: What do you see as the purpose of a graph?
M: It paints a picture that’s easier to see the relationship.
R: Why is that?
M: You can see the relationship physically rather than looking at a list of numbers.

All 13 participants said that they found graphs useful, three of whom specified especially in science. Georgia (medium) had a typical response:

R: Do you personally find graphs useful?
G: Yes, although I don’t enjoy making them. They are more a visual thing than just numbers in a group.

Dan’s (low) response was also typical:

R: Do you personally find graphs useful?
D: Yes, very. You don’t have to think about what the data is doing, you can just see it. Get hints and clues to what’s happening.

For the participants that mentioned graphs were especially useful in science Abby’s (medium) response included a personal distinction:

R: Do you personally find graphs useful?
A: Yeah; in science, yes.
R: Why is that?
A: In science, you have to answer questions based on the graph, whereas in math you just need to be able to graph.

We wanted students to recognize that they worked with related variables in lab frequently. When asked, 100% of participants recognized that they worked with variables related to one another throughout the semester. Erik (low) had a typical response:

R: When you were in lab how often did you find you were working with variables that were related to one another?
E: Fair amount, if not all the time.
Four participants recognized the variables were related during lab because they were told to use a graph; three recognized the pattern for a chemical reason, and 11, 85%, from the data collection process. Georgia’s (medium) response for a chemical reason was typical, while Kelly (high) gave a typical response for those recognizing a relationship during data collection.

R: When you were in lab how often did you find you were working with variables that were related to one another?
G: All the time. Almost every week.
R: What made you realize the values were related?
G: Any time we did a reaction and had to find masses before and after.
R: How did you decide to show those relationships?
G: Table and then a graph.

Kelly:
R: When you were in lab how often did you find you were working with variables that were related to one another?
K: Pretty much every lab.
R: What made you realize the values were related?
K: A change in one leading to a change in another. That was usually the point of the lab too – notice the changes and relationship
R: How did you decide to show those relationships?
K: Tables when doing the experiment and graphs after to see what the relationship was.

All 13 participants stated that, right away or after making a table, they would quantify the relationship seen in lab by using a graph. This indicates that everyone realized the purpose of collecting data and graphing was to see the relationship.

To explore this observation that all participants would graph the data to see the relationship, they were asked if they thought to graph right away or if they needed to be prompted. Seven participants, 54%, said that graphing the data was automatic for them during lab, whereas two participants said they needed to be prompted, two participants said it depended on the lab, and two participants said they would graph to reinforce a trend already seen in the data table, not necessarily graph automatically. These responses were mixed and Dan (low) gives a good example of a typical response:

R: Have you had an experiment where you envisioned solving it with a graph right away or did you need to be prompted?
D: A couple of times figure I would have to but most of the time I needed to be prompted. First three labs maybe not prompted.
R: Why was that? Why did you not need to be prompted the for the first three labs?
D: The relationship looked directly proportional.

To better understand what students thought about when they worked with data tables they were shown data tables and asked: What do you think when you see this table? What sort of calculations might you do with these data? Would you look for relationships between the values, and how? If you graphed the data what might it look like? Why might you think a table of data should be graphed?
4.3.2 Tables.

Participants were shown a math context table followed by a chemistry context table. Each table displays values that increase numerically and are directly proportional. The math table was given to them and then they were asked several questions. The purpose of these questions was to determine (a) if participants could recognize that a pattern was being expressed in the data of the table and from that, (b) if they realized a graph would help them quantify the pattern. After the math context questions participants were shown a chemistry context table and asked similar questions. Could they recognize that a pattern was being expressed in the data of the table and from that, could they see that a graph would help them quantify the pattern? This also probed the transfer concept; were participants able to conceptualize the same theme in the chemistry context table as the math table? Figure 64 shows the tables used in the interviews.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>y</td>
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<tr>
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</tr>
<tr>
<td>5.00</td>
<td>11.75</td>
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</tr>
</tbody>
</table>

Figure 64. Tables of data for math and chemistry contexts. Table A is the math context table participants were shown during their interview. Table B is the chemistry context table participants were shown during their interview.

4.3.2.1 Math table results.

When working with the math table, all 13 participants realized that (a) there was a pattern in the data of the table and that (b) a graph would help them quantify that pattern, which was what we were hoping to find. All 13 specifically stated that they thought of a graph when they saw the math table. Finn (low) gave a typical response:

R: What do you think when you see this table?
F: X and y axes, different points, like on a graph. Looks like a direct proportion.

When asked more specifically what calculations they might do from such a table all 13 participants also mentioned aspects of a graph, including slope, y-intercept, and equation of the line. More questions were asked to get an idea of why a student would look for such a relationship in the first place and how they would determine such a relationship. Abby (medium) gave a typical response, and Harry’s (medium) response had typical aspects while generally going into more depth:

R: What do you think about when you see this table?
A: A graph. How x relates to y. Both increase.
R: How about calculations? What sort of calculations might you imagine being done with these?
A: Finding slope, if it’s a direct or inverse proportionality.
R: How about relationships between the values? Why might you look for any?
A: To see if it’s a direct or inverse proportionality. To see the effect of x on y or y on x.
R: How would you look for them?
A: Graph it and find the slope and write the equation for the line.

Harry:
R: What do you think about when you see this table?
H: Direct proportionality between x and y.
R: How about calculations? What sort of calculations might you imagine being done with these?
H: You could calculate slope. It would be a straight line with a slope of about 2.35. You could also calculate y from x.
R: How about relationships between the values? Why might you look for any?
H: It’s important to look for relationships if you’re trying to calculate output with an input. You can calculate other values base on the relationship.
R: How would you look for them?
H: I divided 2.35 by 1 etc. and all seemed to be about the same, which would also give the slope.

Participants overall stated that the reason they would look for the relationship between variables was to determine the pattern. One student, in addition to looking for a pattern, said he or she would look for a relationship in response to a test requirement.

When asked what such a graph of this data would look like they all 13 participants recognized that it would be an increasing straight line; one student even realized it would be a direct proportion. A typical response was given by Callie (high):

R: How might a graph look with this data?
C: X and y go up incrementally. It would be a straight line with a positive slope in a positive quadrant (indicating both x and y axes would be in the positive quadrant).

When asked what features about the table made them think to graph the data, three participants said they saw the variables “x” and “y”. In addition, nine stated generally that they thought of a graph to provide a visualization of the relationship. Two stated they thought of a graph because they were trained to do so. Again, Callie (high) gave a typical response for a visualization of the relationship:

R: What would make you think a table of data should be graphed?
C: If there’s important information and you’re looking for a pattern, especially if the pattern isn’t easily seen in numbers.

Beth (low) gave a typical response for seeing variables as a reason to graph the data:

R: What would make you think a table of data should be graphed?
B: I saw an x and y, which usually indicates a graph.

Similar questions were asked when participants were presented with the chemistry context table.
4.3.2.2 Chemistry table results.

Unlike with the math table results, the results here show that participants did not recognize the same underlying mathematical structure in the chemistry context table as the math table. For recognition of the pattern from the data three of the 13 participants (23%) said they recognized a pattern compared to the 100% for the math table. Callie (high) responded as seeing a pattern. She also noticed the variables, as further discussed below:

R: What stands out to you on this table?
C: It’s a mole ratio table. Has real world values. X and y are constantly increasing. It’s more random but there’d be at least a best fit line.

The three who did recognize a pattern from the chemistry data also noticed something about either the variables or values of the table. Nine of the 13 participants, 69%, mentioned something about the variables, and eight of the 13, 62%, mentioned the values. Ian (high) gave a typical response for both:

R: What stands out to you on this table?
I: Both involve Hg and both are in moles. Also, all the numbers are really small amounts.

For quantification of the pattern five participants said they would graph. Five others alluded to a graph by mentioning a proportion or calculating the relationship between the mercury(II) oxide and mercury when asked specifically what calculations they might do from such a table. This gives a total of 77% compared to the 100% for the math table. Abby (medium) gave a representative response incorporating all three of those types of calculations:

R: What sort of calculations might you be asked to do?
A: Find a mole to mole ratio with the slope of the line on the line of best fit, or how the amount of HgO affects the amount of Hg.
R: What sort of relationships might exist between the variables?
A: As one increases so does the other, maybe proportionally.

Six participants mentioned specific chemical calculations, such as a chemical equation, percent composition, or amount of oxygen lost. Erik’s (low) response was typical of these participants:

R: What sort of calculations might you be asked to do?
E: Could find how much oxygen is lost. Could also find grams of each substance.
R: What sort of relationships might exist between the variables?
E: Mass relationship. How much, percent lost oxygen, could find the percent composition.

Looking more in depth into participants’ understanding of the relationships that might exist and whether they saw graphs as useful quantification of those relationships there was a greater diversity of responses.

When asked specifically about the type of relationship that would exist between the variables, seven participants responded that a relationship would exist, essentially a restatement of the question. Three participants mentioned a proportion could be found, and eight participants provided a chemical reason, such as limiting reactant, finding the amount of oxygen, or determining percent composition, and one student stated a graph, which was not relevant to this question. The chemical reasons mentioned were not directly relevant to the graph. Georgia
(medium), one of the three participants who mentioned a proportion did specify a mole ratio. Her dialogue is as follows:

R: What stands out to you on this table?
G: Different substances. Mercury is less than the mercury oxide.
R: What sort of calculations might you be asked to do?
G: Determine how much oxygen is lost.
R: What sort of relationships might exist between the variables?
G: Probably goes with the chemical equation and mole ratios here.
R: Would a graph be useful to use with this data?
G: Yes, because then you could see if the mole ratios were correct.

When asked directly if a graph would be useful with the chemistry table of data, one participant said no, three said maybe, and nine said yes. Asked why, nine who had responded with an affirmative stated that a graph would help with visualization and six stated a graph would help with determining a proportion. A follow up question about what the graph would show resulted in five participants still saying a relationship, with no specification, and two a proportion. Beth (low) was the atypical response of no within an otherwise typical response:

R: What sort of relationships might exist between the variables?
B: Depending on what you’re doing with the substances might be a relationship. Looks like HgO has slightly more than Hg.
R: Would a graph be useful to use with this data?
B: No, I don’t think so.
R: Why is that?
B: The numbers are too close so it’d be hard to tell. It’s easier to see with the table.
R: What would a graph show you about this data?
B: A relationship between the two.

Participants were then asked about the aspects of a table they look for to help them determine if a graph would be useful. Six participants discussed the values in the table, whether they were big or small numbers for example, and eight mentioned the presence of a relationship or trend. Two participants said they look at the variables and two participants said they did not know what to look for in a table to determine if a graph would be helpful. Kelly (high) and Ian (high) had typical responses. Kelly thought graphing was less useful if the numbers did not obviously display a trend, whereas Ian thought a graph would be helpful if that was the case.

Kelly:

R: What aspects of a table do you look for that clues you in that something should be graphed versus just getting the principle from the table?
K: Usually if there’s a trend. The numbers are close together so it’s harder to see if it’s a bunch of random numbers and if you can’t see the relationship it doesn’t make as much sense to graph.

Ian:

R: What aspects of a table do you look for that clues you in that something should be graphed versus just getting the principle from the table?
I: When there’s not a definite relationship or there may not be a definite straight line. Just to get a general understanding of how the two work together.
Once questions about tables were finished and thoughts collected about recognition of patterns in data and using graphs to quantify such data, questions were then asked of graphs themselves.

4.3.3 Graphs.

To understand the phenomenon of transfer through graphical interpretation, participants were first shown a graph with no context (Figure 65) to determine their understanding of the different parts of a graph: Line of best fit, slope, and y-intercept. General understanding of these aspects had to be established before determining if the participants could then transfer that understanding from a math to chemistry context.

![No context graph](image)

*Figure 65. No context graph. Graph of a linear relationship that is not a direct proportion and given with no context. Quantification of the relationship would be done using the equation of a straight line, \( y = mx + b \).*

Following the no context graph, participants were shown a math graph constructed from the data they had been shown in the math table. See Figure 66. The data resulted in data points that fell in a perfect line, as is commonly seen in math and chemistry textbooks. The purpose of this graph was to determine (a) if they could see that a relationship was expressed in the graph and (b) how they would quantify the relationship. Further questions were asked to determine how the participants knew a relationship was expressed.

![Math context graph](image)

*Figure 66. Math context graph. This was shown to participants during their interview.*

The chemistry graph was shown to them last, also constructed from the data from the chemistry table. See Figure 67. These data did not fall in a straight line, as is more commonly seen in lab when participants are collecting data themselves. No line of best fit was drawn for either the math or chemistry graphs to determine if participants would recognize that step as necessary. The
The purpose of the chemistry graph was to determine (a) if participants could see that a relationship was expressed in the graph and (b) how they would quantify the relationship. Further questions were asked to determine how the participants knew a relationship was expressed and if they understood the chemical representation of the mathematically-expressed relationship.

Figure 67. Chemistry context graph. This was shown to participants during their interview.

Comparing how participants responded to the math and the chemistry graph questions provided insight into their ability to transfer the math skills required to determine a graphical relationship in the math context to a chemistry context.

As a follow up, participants were asked the names of the mathematical tools they used to quantify the relationship in the graphs. They were also asked if any aspect of the laboratory course helped them to utilize those tools.

4.3.3.1 No context graph results.

The results showed that all 13 participants recognized that to quantify the pattern they needed to find the slope of the line. Eight participants also mentioned the need for a y-intercept. Of the 13 participants, eight stated that they knew to solve for the slope because the line was linear and five said they were taught to solve for the slope and intercept. Four of the five participants who said they were taught to do this also gave details for solving slope.

Regarding determination of the y-intercept, eight said they would look at the graph and read where the line crosses the y-axis. Two participants mentioned the slope calculation, and three different participants mentioned the point-slope formula. Three participants said they would determine the y-intercept where x = 0, and two participants did not give a clear answer. Ian (high) and Lisa (medium) give typical responses:

R: How would you go about solving the equation of this line?
I: It’s linear so start by associating with \( y = mx + b \). B isn’t zero so it’d actually have to be a number.
R: Can you guide me through your thought process on how you decided on that?
I: I noticed that linear line, \( y = mx + b \). I tried to think how to solve but since there are no numbers just general \( y = mx + b \) so I could only find the y-intercept and that’s not 0,0 this time so it’s above that point.
Lisa:

R: How would you go about solving the equation of this line?
L: Find points on the line, y2 - y1/x2 - x1 to find slope. Then put the slope in y = mx + b. Use the point where the line hits the y-axis at x = 0.
R: Can you guide me through your thought process on how you decided on that?
L: Just learned it since I was a child. I think of the point slope form or y = mx + b when asked to find an equation.
R: What about the y-intercept?
L: To find the intercept use the one with zero in it so it plugs in nicely.

After obtaining insight into participants’ understanding of a graph’s line of best fit equation they were asked about the math context graph. No line of best fit was provided for them this time, although the points fell in a directly proportional line if one was drawn.

4.3.3.2 Math context graph results.

The results showed that twelve participants (92%) recognized there was a pattern between x and y. One of those participants mentioned it would be a proportional relationship, and five of the twelve specified, correctly, that it would be a directly proportional relationship (38%). Erik (low) said he was not sure; he saw a correlation but was not sure it was a relationship. It appears he understands there is a pattern and how to quantify it, but misunderstands the term relationship. His response is shown below for clarification:

R: Is there a relationship between these variables?
E: Looks like there’s a correlation, not sure about relationship.
R: Can you guide me through your thought process on how you decided that?
E: Could be a slope, points aren’t scattered randomly. Could be an increase at a constant rate, there aren’t outliers.
R: How would you go about determining a relationship on a graph like this?
E: Find the slope, draw line of best fit and see how close the points are to the line of best fit. That usually shows a relationship.

All 13 participants referred to the data being linear or proportional as rationale for knowing there was a relationship between the variables. Eight of those participants mentioned that the variables increased at a constant rate, six referred to it being a straight line, and two mentioned that the relationship would be a direct proportion. Two participants said they knew there was a relationship because the variables were graphed together.

To quantify the pattern, six participants mentioned using the line of best fit and ten discussed the slope of the line (77%). One participant said the relationship could be determined because both variables increase. Georgia (medium) and Mike (medium) provide typical responses:

R: Is there a relationship between these variables?
G: Yes.
R: Can you guide me through your thought process on how you decided that?
G: They’re on a graph so have to be related some way. They have a slope that seems very constant.
R: How would you go about determining a relationship on a graph like this?
G: Find the slope and find the ratio, kind of one in the same.
Mike:

R: Is there a relationship between these variables?
M: Yeah, seems like a strong positive correlation between x and y. As x increases y increases and it looks like it starts at the origin if you go back so it’s directly proportional.
R: Can you guide me through your thought process on how you decided that?
M: Looked at x to see what it increases by and then y to see how it increases as x increases, something like 2.2 or 2.3, like the table before.
R: How would you go about determining a relationship on a graph like this?
M: Look at the slope and see what direction it’s going. You can tell if it’s a strong positive or negative correlation based on the direction of the slope.

A chemistry context graph of the data from the chemistry table was shown next. It also did not include a line of best fit and the points were not perfectly linear, just as would be the case in the participants’ data collected in lab.

**4.3.3.3 Chemistry context graph results.**

The results showed that nine participants recognized there was a relationship between the variables and two participants stated it was, or seemed to be, a directly proportional relationship. Three said there seemed to be a relationship. Two of the participants mentioned there were outliers and three said the relationship was less clear than the relationship on the math graph. When asked how they knew there was a relationship, twelve participants stated there was an increasing line or trend, and three mentioned chemical reasons, such as chemical reaction, limiting reactants, and mass relationship. Seven of the participants also mentioned outliers and experimental error. Beth (low), Harry (medium), and John (high) provide representative responses to all the varying thoughts about the relationship present in this graph:

Beth:

R: Is there a relationship between these variables?
B: Yes, but it is more scattered. There are two outliers you could say.
R: Can you guide me through your thought process on how you decided that?
B: There’s not a clear straight line but there is increasing variables. Not all over the place but they increase.

Harry:

R: Is there a relationship between these variables?
H: There seems to be a directly proportional relationship but fairly weak. There are some outliers but if you draw a line of best fit there’s still a fairly directly proportional trend to it.
R: Can you guide me through your thought process on how you decided that?
H: I looked for points in a line (rotated the graph so looking down from the origin). The points seem straight and if they’re off it’s probably just from experimental error.

John:

R: Is there a relationship between these variables?
J: Yes, but more unclear.
R: Can you guide me through your thought process on how you decided that?
J: Same thing (meaning same as what he did with the math graph). Mental line of best fit but it looks also like it tables off. Could just be experimental error. Also looks like x and y are going up by constant amounts. Going with linear because it’s a mass relationship.
To quantify the pattern, eight participants mentioned using the line of best fit and five discussed the slope of the line. Only one of those five did not mention the line of best fit. Three participants discussed chemical information: previous information on Hg and HgO, finding percent oxygen lost, and converting units on the axes to see a different chemical relationship. Two participants did not know how to quantify the relationship and mentioned the presence of outliers and one said they would see what the values were doing. Continuing to look at Beth’s (low) conversation, as well as Dan’s (low), gives representative responses:

**R:** How would you determine the relationship exists here?
**B:** I don’t know. Finding slope would be harder. Not a definite line so it wouldn’t be as accurate.
**R:** Can you guide me through your thought process on how you decided on that?
**B:** It’s still a graph so has to be some sort of \( y = mx + b \) slope. The graph clearly indicates a relationship – the dots.

**Dan:**

**R:** How would you determine the relationship exists here?
**D:** Put in a line of best fit, take the equation. Convert one of the axes to something other than moles to see a different relationship.
**R:** Can you guide me through your thought process on how you decided on that?
**D:** By looking at it and previous experience with looking at graphs.

Participants were then asked to solve for the relationship by quantifying it and explaining the meaning. They were provided a ruler, extra paper, and anything else they might need to determine the relationship. Results showed that 11 participants correctly drew the line of best fit, all 13 mentioned the need to solve for the slope, and nine correctly had the y-intercept at zero where \( x \) equaled zero. Conversely, two participants did not draw the line of best fit correctly, after mentioning the need to solve for the slope one student used the incorrect formula, and four participants did not know why they chose 0,0 as a point. Regarding recognition of the correct mole to mole ratio and meaning of the quantified relationship, nine participants correctly answered, five, one of which had originally answered correctly but later contradicted him or herself, did not. The five who did not fully understand the meaning of the relationship had solved the mathematical equation correctly but did not round to a whole number as would be necessary for a mole ratio. Ian (high), Harry (medium), and Callie (high) have typical responses:

**Ian:**

**R:** So, what is the relationship here? Go ahead and calculate it, and try to explain to me everything you are doing as you go. Just think out loud.
**I:** Assume 0,0 is always a point – not sure why. Try to catch 1st and last point too with the ruler. Draw the line. Look for points that are easy to grab since I like to skip work however possible – points on the line. Practically would call the ratio 1-to-1 (doing mental math). For change in y and change in x I calculated 0.935 and say 0.94 ratio to 1. \( Y = 0.94x \). This means slightly more x than y. HgO has oxygen and the other doesn’t so the other 0.6% would be oxygen.
Harry:
  R: So, what is the relationship here? Go ahead and calculate it, and try to explain to me everything you are doing as you go. Just think out loud.
  H: Try to draw line of best fit so none of the points are too far off the line so the average is least, use the ruler. It appears the line would have a slope of 1 (looked at where the points crossed). Use change in y over change in x. So \( y = x \), or amount of \( y \) (Hg) = amount of \( x \) (HgO).

Callie:
  R: So, what is the relationship here? Go ahead and calculate it, and try to explain to me everything you are doing as you go. Just think out loud.
  C: Visual best fit line. Know \( y \)-intercept is 0,0. Put ruler on so looks like same number of points are on both sides. Find two points on the line that line up will with the actual lines on the graph and plug those into the equation of the line. I tried to determine the numbers on the small vertical lines but too difficult, used 0,0 instead. The slope of the equation is \( \frac{y_2-y_1}{x_2-x_1} \). I solved for the slope because hideous number so doesn’t help visualize anything. I put the slope into \( y = mx + b \) but b equals zero. Could round to 1 but going to leave it. \( Y = 0.9167x \). For every HgO we have almost one mole of Hg.

### 4.3.4 Participant reflections.

Results showed that when asked about the names of the mathematical tools that participants used to quantify the relationship shown in the chemistry graph, 12 participants recognized that slope, \( y \)-intercept, and line of best fit were names of mathematical tools. One student focused on a ruler and calculator as mathematical tools. Participants who mentioned slope, etc. also referred to rulers and calculators, one also stated paper and pencil.

When participants were asked if anything in the course helped them to use such mathematical tools, five responded nothing, although one amended later, like two others, that practice helped. One of the participants who mentioned practice also mentioned lab, along with four others. One participant said feedback on exams was helpful and three said a combination of homework, workshop, and lecture helped. The combination helped them understand chemical phenomena. Georgia (medium) gave a representative response:

  R: Was there anything in this class that helped you be able to use these tools?
  G: Not necessarily this class, I already know this stuff.
  R: Please explain.
  G: I already had three years of chemistry and took 141 (a general chemistry course offered at the University of Montana) before.

### 4.4 Qualitative Discussion

Three following tables summarize the qualitative findings based on the category of interview questions asked. See Table 73, Table 74, and Table 75. Percentages of participants that responded are also listed in decreasing order where applicable. Table 73 summarizes the graphing conceptions, Table 74 shows the percent comparisons for the tables and graphs in both math and chemistry context, and Table 75 displays the participant quantification and reflections.
When asked generally about graphing participants understood that graphs were useful, especially to visualize data. They understood they worked with graphs during lab and that graphs were also useful to quantify relationships between variables. This information suggests that students recognized the amount of time they worked with, constructed, and interpreted graphs during this chemistry course.

Also, 100% knew that they needed to calculate a slope to quantify a relationship displayed with a graph, and over 50% also mentioned the y-intercept as necessary, suggesting the participants had a general understanding of the different parts of a graph: Line of best fit, slope, and y-intercept. Several participants said they knew how to quantify the pattern because they were taught (38%), indicating a lack of conceptual understanding of the process. Instead, those participants were more focused on surface features and memorization of steps. As discussed in Section 2.5.4 Schema construction, focus on surface features is not conducive to effective transfer. General understanding of these aspects had to be established before determining if the participants could then transfer that understanding from a math to chemistry context.

Table 73

Summary of Graphing Conceptions and the No Context Graph

<table>
<thead>
<tr>
<th>Category</th>
<th>Qualitative Finding</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphing Conceptions</td>
<td>Purpose of graphs is to visualize data</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td>Graphs are useful</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>*Graphs are especially useful in science</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>Recognize worked with related variables in lab</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>*Variables are related based on data collection process</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>*Variables are related based on chemistry involved</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>Graph to quantify the relationship found</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>*Using a graph is automatic</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>*Using a graph needs to be prompted</td>
<td>46</td>
</tr>
<tr>
<td>No Context Graph</td>
<td>Need to find slope to quantify the pattern</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Some level of understanding about y-intercept calculation</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>Need to find the y-intercept</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>Knew to solve for slope because line is linear</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>Knew to solve for slope because taught</td>
<td>38</td>
</tr>
</tbody>
</table>

Participants were shown tables in both math and chemistry contexts to determine (a) if participants could recognize that a pattern was being expressed in the data of the table and from that, (b) if they realized a graph would help them quantify the pattern. Then, since general understanding of graphical concepts was understood, both a math and chemistry graph were shown to participants. The purpose of both was to determine (a) if participants could see that a relationship was expressed in the graph and (b) how they would quantify the relationship.

Comparing how participants responded to the math and the chemistry context questions could provide insight into their ability to transfer the math skills required to determine a graphical relationship in the math context to a chemistry context. Table 74 shows these percent comparisons to look at transfer based on student understanding.

It appears that participants were unable to fully transfer their math knowledge to the chemistry context. Overall, it seems participants got lost in the context of chemistry as soon as the tables and graphs were not unit less math.
When looking at the chemistry table participants seemed to be distracted by the context of chemistry—variables and values—and appeared, to a large extent, unable to realize the need to construct a graph to see the relationship. When participants looked at the chemistry tables they were much more focused on the surface features than the underlying meaning of those features, such as when participants focused only on the values expressed whether they were small numbers or a lot of data, which is more about surface features than potential meaning. This indicates a lack of transfer already at a data only level.

Once participants were looking at the math graphs all but a couple realized there was a pattern between variables and accurately explained how to quantify that pattern using the line of best fit and calculating the slope. However, when shown the chemistry graph, participants students exhibited an inability to transfer that underlying understanding. For all findings with the graphs the percent of students showing understanding with the chemistry graph was less than that of the math graph, except needing a line of best fit to quantify the pattern. More participants recognized a need for a line of best fit with the chemistry graph likely due to the data not falling in a perfect line already. Overall, with regards to the chemistry graph, even though students collected imperfect data all semester, and all participants realized that there were relationships between variables with that imperfect data, they still showed trouble transferring that knowledge to a similar chemistry graph shown to them.

Table 74

Summary and Comparison of the Math and Chemistry Tables and Graphs – Transfer

<table>
<thead>
<tr>
<th>Category</th>
<th>Qualitative Finding</th>
<th>Math %</th>
<th>Chemistry %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tables</td>
<td>Recognition of a pattern in the data</td>
<td>100</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>Recognition of a graph to quantify the pattern</td>
<td>100</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td>Variables stood out</td>
<td></td>
<td>69</td>
</tr>
<tr>
<td></td>
<td>Values stood out</td>
<td></td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>Chemical relationship could be found</td>
<td></td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>Proportion could be found</td>
<td></td>
<td>23</td>
</tr>
<tr>
<td>Graphs</td>
<td>Linear as rationale for a relationship</td>
<td>100</td>
<td>92</td>
</tr>
<tr>
<td></td>
<td>Recognized a relationship</td>
<td>92</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>Need for slope to quantify the pattern</td>
<td>77</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>Need for line of best fit to quantify the pattern</td>
<td>46</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>Recognized a directly proportional relationship</td>
<td>38</td>
<td>15</td>
</tr>
</tbody>
</table>

Some participants became convinced that a graph of the chemistry data would show a general trend of an unrelated chemical equation. They recognized a trend could be present but linked it to a chemical scenario that stuck with them to the end of the interview. This speaks to the quantitative data that shows chemical misconceptions hinder ability to transfer. This is another example of being context bound. The chemistry graph was meant to display a 1-to-1 molar ratio between mercury(II) oxide and elemental mercury. Erik (low) provides an example of maintaining a misconception throughout the interview:

R: (Showing the chemistry table). What stands out to you on this table?
E: Small values, harder to graph/more time consuming. There’s not as clear a relationship. There aren’t whole numbers so it’s harder to visualize.
R: What sort of calculations might you be asked to do?
E: Could find how much oxygen is lost. Could find grams of each substance.
R: What sort of relationships might exist between the variables?
E: Mass relationship. How much, percent lost oxygen, could find percent composition.
R: Would a graph be useful to use with this data?
E: ‘Spose it’d be nice to see.
R: Why is that?
E: Small (referring to the values) so nice to see a visual representation.
R: What would a graph show you about this data?
E: Could see a general trend, how much percent oxygen was lost, the amount of substance that remains. A general direction of trend.

R: (Jumping ahead to showing the chemistry graph). Is there a relationship between these variables?
E: Yeah, probably.
R: Can you guide me through your thought process on how you decided that?
E: If you have an amount of HgO you’re probably applying heat. Graphically HgO increases and Hg increases.
R: How would you determine the relationship that exists here?
E: Find percent oxygen lost and then the percent would be approximately constant. That’d show the relationship.
R: Can you guide me through your thought process on how you decided on that?
E: From the percent composition problems we did.
R: So, what is the relationship here? Go ahead and calculate it, and try to explain to me everything you’re doing as you go. Just think out loud.
E: (He did not use the graph to calculate). List points to find the data table. (Saying with one less zero than listed but writing correctly). Looks like the first four are in line and the 5th may be an outlier. For finding slope I’d use the 1st and 4th points. (He used y2-y1/x2-x1). Approximately the slope is about 1.29x. I would do the percent composition to find the percent oxygen lost per sample.

Even after a semester of focused graphical construction and interpretation and feedback, 15% were unable to correctly solve for the line of best fit, 31% were unable to solve for the y-intercept correctly, and 38% of participants were still unable to transfer meaning into the mathematical formula of a slope for the chemistry graph. This indicates that participants are more focused on surface features than on underlying structure of quantifying and interpreting a graphical relationship. This could indicate they are more likely memorizing the steps they think they should be doing rather than understanding those steps.

Yet, when asked if any aspects of the course were helpful to them in being able to use these tools of graphing, only five participants stated that the labs, homework, and lecture helped them understand relationships and molecules, and that the labs were “all about figuring out relationships,” most of which were direct proportions. One of those participants did, however, state that graphing tools were not discussed in lab or class much, only that his or her workshop leader went over the material. Five different participants stated that nothing in the class helped them with graphing. They “had to know what to do before” coming to class or they learned it in high school, and only 8% thought feedback on exams was helpful.

This type of feedback also points to the strength of conceptions students come into the course with; very few participants could gain more knowledge from this course over what had already been taught to them. Additionally, it suggests students do not have full knowledge of their own minds. All participants, 100%, previously in the interview had stated that they recognized the usefulness of graphs, that they had worked with graphs in lab consistently, and that they used
graphs to quantify the relationships between the variables in lab. It appears that students do not easily take in feedback, but rather, work through the process of their task without utilizing metacognition – thinking about their thinking.

Table 75

Summary of the Quantification of the Chemistry Graph and Help from the Course

<table>
<thead>
<tr>
<th>Category</th>
<th>Qualitative Finding</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantification of Chemistry Graph</td>
<td>Solved for the equation correctly using the slope</td>
<td>92</td>
</tr>
<tr>
<td></td>
<td>Solved for the equation correctly using the line of best fit</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>Solved for the y-intercept correctly</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td>Recognized the physical representation of a 1-to-1 molar ratio</td>
<td>62</td>
</tr>
<tr>
<td>Tools Used</td>
<td>Slope, line of best fit, y-intercept, etc.</td>
<td>92</td>
</tr>
<tr>
<td>What helped from this course?</td>
<td>Nothing</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>Lab</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>Practice</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>Homework/Lecture/Workshop</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>Feedback on exams</td>
<td>8</td>
</tr>
</tbody>
</table>

While students recognized the amount of time they worked with graphs and could quantify the relationships expressed there, there appears to be a lack of ability to transfer that knowledge once it is placed into a chemistry context. Students seemed to be more focused on the surface features of the data—variables, values, placement of data points—than the underlying structure or concepts the data was displaying. Conceptions, whether accurate or not, stuck with the participants throughout their interview and there seemed to be little effect of feedback on altering those conceptions, indicating a lack of conscious thought about their own thought processes.
Chapter 5: Conclusions

5.1 Summary of Research Problem and Method

This study set out to investigate the issue of students’ high fail rates in general chemistry (Chambers & Blake, 2008; Freeman et al., 2014; Gafney, 2001; Gellene & Bentley, 2005). General chemistry is a gatekeeper course; it is one of the first science courses college students need to take, and if students do not pass, they cannot move on to upper level chemistry, higher levels of biology, or pursue the study of health sciences professions (Tai et al., 2005). Historically, it was hypothesized that the issue was that students lacked arithmetic and algebra skills, but our investigation showed no specific area of weakness in arithmetic, algebra, graphical understanding, or other basic mathematical skills (Busby, unpublished data, 2016). Students must also exhibit competency in intermediate algebra to place into general chemistry. These factors validate that students’ foundation in mathematics is not what hinders student success at the University of Montana (UM), the setting for this study. UM is similar to many other public universities in the United States, which gives this study significant external validity.

However, we observed that students still demonstrated an inability to utilize math skills in chemistry. This inability to apply math skills to a chemistry context was seen in the literature as well (Andrews & Andrews, 1979; Armstrong et al., 2014; Leopold & Edgar, 2008; Nicoll & Francisco, 2001). In the literature, this issue of application is known as transfer, which became the focus of this study. Transfer is the ability to apply skills that were learned in one area of study into another area of study (Chi & VanLehn, 2012; Dori & Sasson, 2013; Roberts, Sharma, Britton, & New, 2007; Sasson & Dori, 2015). Near transfer (Dori & Sasson, 2013; Ngu & Yeung, 2012), where problems have the same underlying structure but the surface features are different, was the specific area of transfer studied; students would need to use the same skills to solve problems of interest in both math and chemistry contexts. For further details on definitions of transfer and the problem of transfer, refer to Section 2.5 Transfer.

Since graphs used in chemistry are a mathematical representation of a chemical concept or chemical relationship, they were a logical tool to investigate this issue of transfer, especially from a math to a chemistry context. Graphical representations are used extensively in science courses to provide conceptual information in a visual manner (Leinhardt & Steele, 2005; Mitnik et al., 2009; Roth & Bowen, 1999, 2001; Roth et al., 2002). A graph provides a mathematical representation of a function by showing the construction of the relationship between the independent and dependent variables (Leinhardt et al., 1990). No research on transfer had been previously done with math graphing to chemistry context in general chemistry.

The method used to measure transfer was based on a literature review of other studies that have measured transfer (Ngu & Yeung, 2012; Ngu et al., 2015; Stern et al., 2003). Figure 68 below shows the method used in this study, including the specific tools used for each step. For further details on the method used to investigate transfer in this study, Refer to Section 3.5.2 Research design.
While researching transfer, several variables were discovered to influence math knowledge acquisition and transfer. These variables include general intelligence (Marek & Cavallo, 1997; McGrew & Wendling, 2010), scientific reasoning (Adje & Shayer, 1997; Cracolice, 2012; Cracolice & Busby, 2015; McGrew & Wendling, 2010; Primi et al., 2010), prior knowledge in the source domain (McGrew & Wendling, 2010; Shah & Freedman, 2009; Shah & Hoeffner, 2002) (which is math graphing in this study), and the target domain—chemistry content and misconceptions (Leinhardt et al., 1990; McGrew & Wendling, 2010; Pushkin, 1998). Since these variables were shown to be predictive of transfer in other contexts, assessments were administered to explore if they were predictive of students’ ability to transfer math graphing to chemistry context. For more information on each of the assessments, refer to Section: 3.5.3 Research instruments.

Students were also asked, using a demographic questionnaire, what percentage of time they felt they received story problems and inquiry labs in their high school math, chemistry, and physics courses. Inquiry means students collected data, and could develop concepts from that data, before they talked about the concepts in lecture. Both story problems and inquiry labs require logical reasoning so these variables were also investigated as potential predictive variables of transfer ability (Dori & Sasson, 2008; Kapur, 2014; Nicoll & Francisco, 2001; Sasson & Dori, 2012, 2015).

In addition to the predictor variables tested, students were given a pretest measure of transfer ability. The assessment administered required students to answer a series of graphing questions in three domains: math, economics, and physics (Planinic et al., 2013). All questions had the same underlying structure but differed in their surface features and context; therefore, they measured near transfer ability. For more details on the instrumentation used in this study, refer to Section 3.5.3 Research instruments.

Literature-based instructional treatments were created using components previously shown to help students transfer (Ngu & Yeung, 2012; Ngu et al., 2015; Stern et al., 2003). In these studies, students were given an instructional treatment and tested for their ability to transfer, either immediately or after a delay. The instructional treatments correlated to an improvement in students’ transfer ability, even after a delay. Therefore, a similar instructional treatment setup was implemented to help facilitate transfer for students in this area of study, math graphing to a chemistry context. For further details on instructional treatments, refer to Section 3.5.2 Research design. Detailed descriptions of the treatments are in Appendix L – Instructional Treatments.

Each of the three instructional treatments (a) provided definitions for graphing, (b) presented a mathematical scenario of a direct proportion, and (c) provided an opportunity to apply those skills to a chemistry context. It has been demonstrated that giving students an opportunity to actively construct graphs themselves is beneficial in drawing attention to underlying structure and facilitating transfer (Ng & Yeung, 2012; Ngu et al., 2015; Stern et al., 2004; Terwel et al.,
2009), so one of the treatments involved active construction of the mathematical scenario, part b. Additional studies have shown that presenting students with the graph and asking them to interpret it is more beneficial in drawing their attention to underlying structure (Stern et al., 2004), so one of the treatments involved interpretation of the mathematical scenario, part b, already provided. The third treatment is called a worked example, which has been shown to not help facilitate transfer (Ngu & Yeung, 2012; Ngu, Yeung, & Phan, 2015; Stern et al., 2004); the worked example was used as a control.

In addition to the instructional treatments, students participated in a chemistry measurement laboratory exercise in the first week of class. The measurement lab had students explore a direct proportion and an inverse proportion. Students were asked to collect data for both scenarios and then explain the pattern found. Some students were only asked to explain what pattern they found, and some students were given explicit instructions to graph the data, find the algebraic equation, and then explain the meaning of that equation. The answers given by students who did not receive the explicit prompt were meant to measure if students could spontaneously realize they should graph to quantify a chemical relationship.

Other instruments were administered throughout the semester to measure students’ ability to transfer into a chemistry context. These instruments included students’ graphs constructed and interpreted during lab and those they constructed and interpreted on three of the four midterm exams. Students had repeated opportunities to graph directly proportional relationships of their collected data in seven of their twelve chemistry labs. For each lab requesting a graph, they were told in the instructions to describe the pattern found. Following the general instruction, a hint, already written into the directions of the lab, to graph the data and write an algebraic expression. This acted as a measure of transfer of math graphing skills to a chemistry context. In three of the four midterm exams, students were given a question much like those they had seen and worked with in lab. The exam questions asked them to graph the data provided and interpret the physical representation shown by the graph. Each exam question is in Section 3.5.3 Research Instruments, and a description of these methods are in Section 3.5.2 Research design.

At the end of the semester, 13 students were interviewed. The purpose was to better understand the quantitative results. The interviews investigated how students viewed graphing. The qualitative research questions were: (a) What do students perceive when they look at a table showing numbers with only x and y as variables, which is a math context that contains no units? (b) What do students perceive when they look at a table of chemistry data with units and variables of masses of elements or compounds? (c) Did students know how to quantify a relationship if they were just shown a graph with no numbers to reference? (d) Did students understand the need for a line of best fit, a slope calculation, or a y-intercept calculation? (e) What did students perceive when they were shown a graph in math context with no units that consisted of data that were in a straight line? (f) What did students perceive if they saw a similar graph with the same structure but in a chemistry context with units and linear but imperfect data? Gaining a qualitative understanding of the phenomenon of transfer added a richness to the study so that we could postulate why the quantitative results were found. For a description of this process, refer to Section 3.6 Qualitative Research. The interview question protocol is in Appendix O – Interview Questions.

5.2 Analysis of Results with Implications for STEM

Three major overarching results with implications for STEM education research and STEM instruction were found: (a) transfer does not happen, (b) of all the predictor variables investigated,
only scientific reasoning and lack of chemical misconceptions influenced transfer, and (c) the type of instruction conducted in this study is inadequate. This section will be comprised of an introduction to each of these findings, a synthesis of integrated quantitative and qualitative data, and conclusions based on the findings.

5.2.1 Transfer does not happen.

One purpose of this study was to determine if transfer was the problem underlying students’ difficulty with success in general chemistry. This issue was investigated by studying students’ ability to transfer their math graphing skills into a chemistry context. The results indicated that transfer does not happen.

5.2.1.1 The issue of transfer.

Transfer is the ability to apply skills learned in one area of study to an area of study in another context (Chi & VanLehn, 2012; Dori & Sasson, 2013; Roberts, Sharma, Britton, & New, 2007; Sasson & Dori, 2015). For example, if students learn to control variables in a scenario with different weights at the ends of different length strings, and they want to determine if length of string is the determining factor for time it takes to swing back and forth, they would have to assess which variable to control and which to observe. Transfer would be the students’ ability to apply the same logical principles to a scenario with different length rods, made of different types of metals, that are also different lengths, and determine which variable has an effect on bend of the rod. For transfer to occur, students must have an overarching, generalized, mental representation of the underlying structure of a type of problem (Ngu & Yeung, 2012; Ngu et al., 2014; Terwel et al., 2009). Transfer has been shown to be an issue in several areas of study; math-to-math contexts, math-to-chemistry or other science contexts, and analogical transfer, which utilizes analogies, or comparable stories, where the underlying structure of the stories is similar. Students have demonstrated an inability to transfer at the high school level and at the college level. For a full review, refer to Section 2.5.2 The problem. There are also several categories of transfer, depending on three main attributes: “(a) task distance [TD], which refers to the similarity or difference from the previous task; (b) interdisciplinarity [I], which refers to contexts, domains, or disciplines; and (c) skill set [S], which accounts for the various thinking skills that the task requires” (Dori & Sasson, 2013, p. 366). Dori and Sasson (2013) wrote a review of the nuances of transfer. Refer to Section 2.5.1 Definitions of transfer.

A focus of this study was the near transfer of math graphing skills to the chemistry context in general chemistry. Near transfer refers to the new learning situation being only slightly different from the learning situation where the original skills were developed, i.e., the underlying structure of the problem is the same but the surface features differ (Dori & Sasson, 2013; Ngu & Yeung, 2012). Graphing skills learned in a math context and applied to a chemistry context were chosen as the context to investigate this near transfer. It is an area of study that has not been explored before.

5.2.1.2 Integrated data from this study.

The evidence collected in this study conclusively shows that transfer does not happen in general chemistry. This is new knowledge. Transfer has already been shown to not happen in several other contexts, with few exceptions. Refer to Section 2.5.2 The problem.
Students were given a graphing-transfer instrument that contained questions on graphing in three domains: math, economics, and physics (Planinic et al., 2015). Results showed that students could answer questions about graphing correctly in the math context, but when asked the same structural question with a different surface feature context, they were not able to answer those questions. This was the case for both economics context and physics context. Transfer did not occur. Differences between average scores out of 16 for each of the three areas of graphing skills: math, economics, and physics, were compared ($F = 176.558, p < 0.001$, partial eta squared $= 0.495$), indicating that about 50% of the variance in transfer was due to context. Pairwise comparisons showed that the means of math context differed from economics context ($p < 0.001$) and physics context ($p < 0.001$). There was also a difference between economics context and physics context ($p = 0.009$). Comparison of transfer index scores between the math-to-economics and math-to-physics categories also showed a difference ($t_{159} = -2.644, p = 0.009$).

Students demonstrated a lack of transfer to chemistry context as well. Scientific accuracy, a measure of transfer into chemistry context, had a scale of 0–11 and the average score, for students across all exams, was under six out of eleven. Scientific accuracy was measured by assessing several details of graphing, two of which are: (a) Did students draw a straight line through 0,0 for a directly proportional relationship? (b) Could students calculate slope and interpret its meaning? The rubric for scientific accuracy is discussed in Section 3.5.3 Research instruments. Students had seen graphing situations like their midterm exam questions previously during lab but were still unable to accurately respond on an exam. Students scored lower than 50% in scientific accuracy. Maximized scores were measured on the second exam, with an average scientific accuracy of less than 50%. Scientific accuracy was shown to be a function of transfer ($F = 6.311, p = 0.013$) with a small effect on the first exam ($R^2 = 0.041$, adjusted $R^2 = 0.028$) and a function of time ($F = 14.885, p < 0.001$) accounting for 10.1% variance in scientific accuracy explained by time (partial eta squared = 0.101).

When students were interviewed they also demonstrated a lack of transfer, both when they were looking at tables of data for math to chemistry and looking at graphs of math and chemistry. For details, see Section 4.3 Qualitative Results. The math and chemistry context tables and graphs are shown in Figure 64, Figure 66, and Figure 67. In the math contexts for both the table and graph, participants universally recognized that the data showed a relationship, and they were generally able to spontaneously decide to express the relationship quantitatively. About 40% of the participants even realized it was a directly proportional relationship, just like those they had seen continuously throughout the course.

Students also knew, when shown the table of math data, that they could construct a graph to quantify the data. They understood that they would need to draw a line of best fit and calculate a slope, which are aspects they had received feedback on during labs and on exams. However, when they were shown a table of chemistry data, with units of moles of substances related by a chemical change as the $x$ and $y$ variables, 85% of the students realized it showed a relationship, and 15% expressed an understanding that it was a directly proportional relationship.

When shown the math-context graph, 77% of students could explain the need for a slope calculation. However, with the chemistry-context graph, 38% students saw the need. Sixty two percent did not understand what quantifying the relationship on the chemistry graph would tell them. For detailed examples, refer to Section 4.3 Qualitative Results.
5.2.1.3 Conclusions drawn from integrated data.

Lack of transfer is occurring largely due to students thinking in context, not focusing on the underlying structure of the relationship. The interviews brought to light that students became more focused on the variables presented in the chemistry-context table and graph. They knew what to expect from a variable $x$ and $y$ in the math context, and they had been taught that seeing those meant to graph. Chemistry context variables confused them. They struggled more with understanding the intention of the data or what to do with it. They had questions such as: (a) Do I need to graph the data or perform a calculation from the data? (b) Is the purpose to determine a chemistry relationship? (c) Do I need to determine the percent composition of a substance? Refer to Section 4.4 Qualitative Discussion.

Additionally, the units of the chemistry-context data were in moles rather than grams. Some students wanted to change the units to grams, which, while both grams and moles are measures of amount, grams are a macroscopic-level measurement and thus a less abstract unit than moles. For more detail about the need for formal reasoning to conceptualize abstract concepts, such as the mole, refer to Section 2.2 Constructivism.

Students also focused on the small numeric values of the data points themselves (e.g., 0.0035 mole). The math values were expressed as whole numbers and the chemistry values were decimal fractions. This confused students. They were no longer sure if a graph would be helpful and stated repeatedly that the values were very small and possibly close together. Some students stated this would be a good reason to construct a graph and others used the same reasoning to not need a graph to visualize the pattern. It was more difficult for students to recognize the underlying structure of the chemistry table because the context distracted them. For specific examples, refer to Section 4.3 Qualitative Results.

In a standard U.S. general chemistry course, there is much to learn and focus on, relative to most other college courses. Students get hindered in thinking about underlying structure by context, such as the units, what the units mean, and what the variables are. They get confused by imperfect data, even though they have experienced personally-collected imperfect data in multiple laboratory exercises. There are too many layers for students to sort through before they hit the underlying structure. In general, research clearly illustrates that when there is context, people think in context. They are not able to remove the context and independently process the underlying structural logic. See Section 4.4 Qualitative Discussion.

5.2.2 Scientific reasoning and lack of chemical misconceptions influence transfer.

Transfer was an issue for students, and a related goal was to determine what mental abilities and types of content knowledge were predictive of the ability to transfer. Variables that had been shown to predict performance in chemistry may also be predictive of transfer. These variables included: scientific reasoning (Bird, 2010; Cantu & Herron, 1978; Cracolice & Busby, 2015; Cracolice et al., 2008; Lawson & Renner, 1975; Lewis & Lewis, 2010), prior content knowledge and alternate conceptions (Cracolice & Busby, 2015; Garnett, Garnett, & Hackling, 1995; Hale, 2000; Nakhleh, 1992), and intelligence (Neisser et al., 1996), as well as prior knowledge of math graphing skills (Bassok & Holyoak, 1989; Menis, 1987; Potgieter, Harding, & Engelbrecht, 2008; Scott, 2012). The instruments administered to quantify students’ abilities in each of these variables are discussed in more detail in Section 3.5.3 Research instruments. Instruments in the public domain are also available in the appendices: Appendix D – Classroom Test of Scientific Reasoning (CTSR) – Appendix G – Test of Graphing Skills (TOGS).
5.2.2.1 Predictor variables of transfer.

Several mental abilities and types of prior content knowledge were measured to determine what influenced student ability to transfer: scientific reasoning, prior chemistry content knowledge and alternate conceptions (misconceptions), intelligence, and high school graphing ability (prior math-graphing knowledge).

Scientific reasoning is the ability to use proportional reasoning, probabilistic reasoning, and combinatorial reasoning, among others (Adey & Shayer, 1997; Cracolice et al., 2008; Lawson, 2000). Scientific reasoning is used to measure level of formal reasoning ability, which is the ability to think abstractly (Adey & Shayer, 1997; Cracolice & Busby, 2015; Piaget, 1970, 1997). Chemistry concepts are almost exclusively abstract. The fundamental entity studied in chemistry is the electron. This entity exists at the particulate level, which means that students must be at an adequate formal reasoning level to be able to meaningfully understand chemistry concepts. Research has shown that 60-75% of students coming into college are still at a concrete reasoning level (Bird, 2010; Cracolice, 2012; McKinnon & Renner, 1971; Moore & Rubbo, 2012). They must work with macroscopic objects to create mental constructs of concepts (Cantu & Herron, 1978; Cracolice, 2012; Lawson & Renner, 1975; Lawson & Wollman, 1976). Refer to Section 1.1.3.1 Scientific Reasoning. and 2.2.1 Theory of equilibration.

Alternate conceptions are concepts students have that differ from scientifically acceptable concepts, and they are robust (Hale, 2000). They are repeatable and explicit incorrect features of student knowledge (Leinhardt et al., 1990). Student knowledge originates from acting on objects and the physical or mental transformations the objects go through. General structures of these actions, or schemes, of this constructed knowledge reside in the mind (Piaget, 1970). Links become created between concepts as the person learns and develops, acting like a mental concept map. If a student learns something incorrectly or comes to an alternate conclusion, that conclusion and conceptual understanding are linked into the mental schema. Once an alternate conception is linked, it never goes away; they are robust (Chi & VanLehn, 2012; Hadjidementriou & Williams, 2008; Moschkovich, 1998). To attempt to remove them, a person must reconstruct the schema in their mind (Hale, 2000). However, to reconstruct a mental schema, the student must realize that what is linked already in their mind does not fit; this is disequilibrium (Marek & Cavallo, 1997). Once the student realizes information is not matching he or she must choose to reconstruct the mental links already present (Marek & Cavallo, 1997). This is not a comfortable or easy process and often causes emotional backlash for the student, classmates, and the instructor. Refer to Sections 2.2.1 Theory of equilibration. and 2.4.2 Misconceptions.

Intelligence is the effectiveness of the cognitive executive function. It includes abilities of perception, attention (memory span), and working memory (McGrew & Wendling, 2010; Primi et al., 2010). Piaget (1997) and Holyoak (1985) describe human intelligence as adaptive, stating that current knowledge of a system can be modified based on environmental feedback. There is a large body of evidence, when considered independently, that intelligence links to students’ ability to do math, science, and to transfer (Kroeger et al., 2012; McGrew & Wendling, 2010).

Prior knowledge has been claimed to be the most important factor influencing someone’s learning, where prior knowledge can refer to declarative knowledge (Ausubel et al., 1978) and procedural knowledge (Lawson et al., 2000). It is also a foundational requirement for transfer to occur; a mental schema cannot be constructed without prior knowledge and experiences (Bassok & Holyoak, 1989; Becker & Towns, 2012; Shah & Freedman, 2009; Shah & Hoeffner, 2002). Students must be able to recall an example in the context they learned the skill to be able to apply
it to another context (Holyoak, 1985; Holyoak & Hoh, 1987; Ng & Yeung, 2012). Prior knowledge is discussed in greater detail in Section 2.5.3 Source knowledge: Prior knowledge and practice.

### 5.2.2.2 Integrated data from this study.

This study confirmed that scientific reasoning, prior chemistry content knowledge and alternate conceptions (misconceptions), intelligence, and high school graphing ability (prior math-graphing knowledge), when considered independently, influenced transfer. Individually, transfer, for both the math-to-physics and math-to-economics transfer indices, was a function of:

(a) *high school graphing ability* – the pretest measure of students’ prior graphing knowledge (MPTI: $F = 23.746$, $p < 0.001$, $R^2 = 0.133$, adjusted $R^2 = 0.127$; METI: $F = 32.258$, $p < 0.001$, $R^2 = 0.172$, adjusted $R^2 = 0.167$), even indicating a minimum score of 13 out of the 26 points possible (50%) in general graphing skills, is necessary to transfer graphing skills in either transfer category,

(b) *intelligence*, via pattern recognition (MPTI: $F = 28.041$, $p < 0.001$, $R^2 = 0.149$, adjusted $R^2 = 0.144$; METI: $F = 27.746$, $p < 0.001$, $R^2 = 0.148$, adjusted $R^2 = 0.142$),

(c) *scientific reasoning* (MPTI: $F = 51.266$, $p < 0.001$, $R^2 = 0.247$, adjusted $R^2 = 0.243$; METI: $F = 62.905$, $p < 0.001$, $R^2 = 0.287$, adjusted $R^2 = 0.283$), and

(d) *prior chemistry content knowledge and alternate conceptions*, or lack of misconceptions (MPTI: $F = 54.838$, $p < 0.001$, $R^2 = 0.260$, adjusted $R^2 = 0.255$; METI: $F = 39.276$, $p < 0.001$, $R^2 = 0.201$, adjusted $R^2 = 0.196$).

Refer to Section 4.1 Quantitative Results.

However, it is prudent to question studies that only include one predictive variable at a time. There is ample evidence to support each variable’s importance when they are examined in isolation of one other. However, when all the predictor variables were considered in concert (MPTI: $F = 20.151$, $p < 0.001$, $R^2 = 0.350$, adjusted $R^2 = 0.332$; METI: $F = 20.370$, $p < 0.001$, $R^2 = 0.352$, adjusted $R^2 = 0.335$), it was discovered that only scientific reasoning and a lack of chemical misconceptions predicted ability to transfer. For example, intelligence alone was correlated with ability to transfer at the $p < 0.001$ level, but in the multiple linear regression equation, $p = 0.074$ regarding math-to-physics transfer and $p = 0.145$ regarding math-to-economics transfer. Math-to-physics results showed coefficients of 0.695 ($t = 1.796$, $p = 0.034$) for intelligence, 0.649 ($t = 0.764$, $p = 0.074$) for prior math-graphing skills, 2.471 ($t = 3.778$, $p < 0.001$) for lack of alternate conceptions, and 2.140 ($t = 2.297$, $p = 0.023$) for scientific reasoning. Math-to-economics results showed coefficients of 0.500 ($t = 1.466$, $p = 0.145$) for intelligence, 1.011 ($t = 1.350$, $p = 0.179$) for prior math-graphing skills, 1.352 ($t = 2.343$, $p = 0.020$) for lack of alternate conceptions, and 2.692 ($t = 3.275$, $p = 0.001$) for scientific reasoning. Refer to Section 4.1.9 Question 8: Multiple linear regression.

The interviews supported a need for a lack of chemical misconceptions to assist with visualizing the underlying structure of a problem. When asked what relationship the chemistry-context table illustrated, about 60% participants got so caught up in the surface features that they would state a conclusion and that conclusion would stick with them for the remainder of the interview. Almost 50% of participants thought that what they were trying to find was a percent composition because the variables were amount in moles of two species in a chemical change; they thought the data must be meant to tell them the percentage of an element in a compound. For detailed examples, see Section 4.4 Qualitative Discussion.
5.2.2.3 Conclusions drawn from the integrated data.

The mental abilities and prior content knowledge data from this study indicate that students need help navigating the specific complexities of chemistry. The evidence suggests that students develop ideas about the purpose of a presented problem quickly after seeing it based on the surface features involved. It appears that, based on those surface features, students put together anything they can think of from what they learned throughout the semester, and it is difficult for them to see the underlying point. Having misconceptions about these concepts makes it even more difficult because students must work through disequilibrium (Hale, 2000; Marek & Cavallo, 1997; Paiget, 1997). Also, challenging misconceptions about abstract concepts requires sufficiently-developed formal thinking abilities (Adey & Shayer, 1997; Cracolice & Busby, 2015; Piaget, 1970, 1997). Unfortunately, about 60–75% of general chemistry students are not at a formal reasoning level yet, as demonstrated by this study, as well as others (Cantu & Herron, 1978; Cracolice, 2012; Lawson & Renner, 1975; Lawson & Wollman, 1976). It is likely that only reasoning ability and lack of misconceptions predict transfer ability, rather than intelligence, because general intelligence is a measure of overall mental capacity (McGrew & Wendling, 2010; Primi et al., 2010). Scientific reasoning ability and lack of misconceptions refer to an ability to utilize the knowledge held within the mental capacity (Primi et al., 2010).

5.2.3 The type of instruction conducted in this study is not sufficient.

When aspects of learning are revealed as areas of difficulty for students, changes in instruction are the most frequently prescribed cure. Transfer is a major educational goal; students need to be provided with an education that will last a lifetime, not just for one course (Educational Policies Commission, 1961; Georgiades, 2000; Sasson & Dori, 2012). Instruction is one of the most common aspects that researchers, instructors, and administration can alter with hopes to improve student outcomes.

5.2.3.1 Instruction for transfer.

The instructional treatments applied in this study, hypothesized to help students with transfer, were based on previous studies that had been shown to be effective in drawing student attention to underlying structure of problems (Ngu & Yeung, 2012; Ngu et al., 2015; Stern et al., 2004). For details of components shown to help students transfer, refer to Section 2.5.5 Instructional tools. The treatments in this study included aspects to point out the similarities in both the math context and the chemistry context, provide definitions to help students understand the parts of graphing they are working with, and offer hints in the chemistry context. The hints were to direct students’ attention back to the math context. This helped students notice that the previous problem had the same underlying structure, but with different surface features. The chemistry context graph gave students an opportunity to practice in the chemistry context right away. For more detailed information on the instructional treatments used in this study, refer to Section 3.5.2 Research design.

Students also had multiple opportunities to work on graphing in the chemistry context. There were seven labs that required, or strongly hinted at, students to graph the relationship between the variables they were working with based on the data they collected. The hint in their labs also suggested students construct an equation to quantify the relationship they found. The literature says that time is not an issue so much as context is, so the hints provided even a week or more
later should have still triggered students’ memories of what they did in previous graphing problems (Catrambone & Holyoak, 1989; Holyoak & Koh, 1987; Ngu & Yeung, 2012).

The first three exams also provided students with an instrument designed to measure their ability to express the equation relating two directly proportional variables in a chemistry scenario, which is something they had already seen and worked with in the laboratory portion of the course, with similar contexts but with numerically different data. The exam questions are shown in Section 3.5.3 Research instruments. As discussed earlier, scientific accuracy was used as a measure of students’ ability to transfer math-graphing into the chemistry context on exams. Specifically, we measured if students could: (a) Determine which variables to put on which axes, with an emphasis on their knowledge of the difference between independent and dependent variables and their demonstration of knowing how to include units. (b) Plot correctly the data points that were given to them. (c) Recognize the need to draw a line of best fit (d) Realize that the origin (0,0) made sense as a point on the graph. (e) Quantify the relationship and find the slope, (f) Interpret the quantified relationship and explain its meaning. The rubric for measurement of scientific accuracy is discussed in Section 3.5.3 Research instruments.

5.2.3.2 Integrated data of this study.

Students ceased to improve after the second exam, achieving a maximum of about 50% scientific accuracy, a measure of transfer into a chemistry context. The data also showed that there was no main effect of instructional treatments on scientific accuracy on exams ($F = 2.994$, $p = 0.054$) or interaction effect between instructional treatment and time ($F = 0.618$, $p = 0.636$). No main effect was found for instructional treatment on spontaneous graphing throughout the semester, another measure of transfer to a chemistry context ($F = 1.336$, $p = 0.266$), or an interaction effect of prompt and instructional treatment either ($F = 0.938$, $p = 0.393$). There was only an average mean difference in spontaneous graphing between Passive Interpretation treatment and Worked Example treatment ($mean\ difference = 14.023$, $p = 0.018$).

However, the explicit prompt that half the students got on their first week of lab, telling them to graph the data, quantify the relationship, and explain its meaning, did relate to students’ graphing ability during subsequent labs ($F = 16.723$, $p < 0.001$, $partial\ eta\ squared = 0.092$). Refer to Section 4.1 Quantitative Results. Students who did not receive the explicit prompt demonstrated that graphing to quantify a relationship between variables was not a spontaneous process. Most students with no explicit direction responded in a general form. For example, a typical response for a directly proportional relationship was that, as one variable increased so did the other. Examples of each version of the measurement labs are in Appendix K – Measurement Labs from the First Week.

When asked if anything from this course helped them utilize tools such as slope, line of best fit, or $y$-intercept, over a third of the interview participants (38%) said no. Refer to Section 4.3 Qualitative Results. This suggests that over one-third of students were not utilizing feedback of any kind from the course, which was also reflected in students’ performance on their chemistry graphing exam questions. In fact, only 8% of participants said feedback on exams was helpful.

5.2.3.3 Conclusions based on integrated data.

The results indicate that the instructional treatments were not sufficient. Repeated instruction of this type was also not sufficient. Repeated explicit instruction is needed. It appears that no real disequilibrium occurred throughout the semester in terms of graphing. The data suggest that
students did not take in feedback about graphing and realize that their current mental schema needed to be altered to incorporate the new information. Rather, students worked on memorizing steps, not reconstructing their mental schemas about the procedures and concepts involved.

There are very few curricula that can help students improve in their scientific reasoning, in their ability to transfer, or in their lack of misconceptions (Adey & Shayer, 1993, 2011; Lawson, 2000). There are also very few instructors who have the fortitude to deal with students who are going through disequilibrium. Disequilibrium is not a pleasant experience for either the student, classmates, instructors, or administration for that matter. If disequilibrium is great enough and the student complains, administrators are the ones who must deal with it, and administration does not like to deal with student complaints. Changes would need to be made that allow administration to understand what quality instruction is so they can recognize if a student is coming with a complaint based on having to work hard or if it is a real issue.

Because no disequilibrium occurred, it is probable that students were not employing metacognition. Metacognition is thinking about your thinking. Within each stage of development (Piaget, 1970, 1997), people need to think about their thinking. It is required for disequilibrium and further generalization of concepts to occur, otherwise mental schema cannot be reconstructed (Hale, 2000; Shah & Hoeffner, 2002). Students must be aware of the concepts that are already present in their minds and the links between those concepts (Ausubel et al., 1978; Driscoll, 2005). They must, in other words, be aware of their mental schema. Students must think about the new information coming in and where it fits into the scheme already present. If the information does not fit, they must think about why, how to make it fit, or if they can make it fit (Marek & Cavallo, 1997). Disequilibrium requires metacognition and, generally speaking, any person will do whatever is required to do the least amount of work, known as the principle of least effort. If students do not choose to control what and how they learn, they will not learn (Piaget, 1997). Students need explicit instruction in how to employ metacognition.

5.3 Limitations

There were several potential limitations to the validity of this study. The participants of the experiment may have been influenced from outside sources. This could have resulted in a change in their maturity apart from the experiment as the experiment occurred over an extended period. Attrition may also have skewed results since students may drop the course at any point during the semester. Final outcomes for those students are unknown and inconclusive. While we attempted to keep the control and treatment groups separate, students within the same course could interact outside of class and may have influenced the results within the groups. Treatments were not random, they were based on time of laboratory, which students select for themselves. This implies that results cannot be applied to a larger population, only suggested. However, since there is no difference in reasoning ability across laboratory times, we believe that the groups are equivalent. Each section of students also includes males and females in a proportion we believe to be representative of students in other college general chemistry courses. All information gained from assessments is limited by the reliability of the instruments themselves. The University of Montana (UM) is similar to many other public universities in the United States, which gives this study significant external validity.

The nature of qualitative research is to focus on each subjects’ own unique experience. Because of this, the findings of this qualitative study could not be generalized. However, the human experience and phenomenon of transfer of math-graphing skills to chemistry context was transferable. Potential lack of transferability could arise from selecting participants who may have
been unable to verbally articulate the phenomenon. Another limitation may have included the relationship between the participant and researcher. If a trusting relationship was not achieved between the researcher and participant, the researcher may not have fully gained the participant’s interpretation of his or her learning experience. Information gleaned from interviews was also indirect, as it was filtered through the views of the participants. In addition, the information was presented outside a natural setting, and the presence of the researcher may have biased responses. Each participant showed varying degrees of articulation and perception. The researcher could also have asked more pointed follow up questions that were variable based on participant responses.

5.4 Questions for Future Research and Implications for Instruction

Further research needs to be done, incorporating the research design from this study, but making instruction more explicit. Students need explicit instruction that draws their attention to underlying features of problems, that develops scientific reasoning skills, and that employs metacognition. During the laboratory portion of the course, students had repeated instruction in what to do, but students need to be asked to compare, in detail, the graphing processes they utilized between each of the labs, every lab. Each lab each gave students a hint to graph the data and find an equation to quantify the relationship, but it was not enough. Explicit instructions should ask: What did the previous lab have you do? What kind of relationship was it that you found? How did you know what to put on which axes? How was this lab different than the previous lab? Are the units different? Are you working with mass or amount or heat transferred? Are the compounds different? What relationship are you looking for this time? Students need to graph in multiple contexts with the same principle and repeatedly have the same questions, drawing attention to and helping them to construct the concept of the underlying structure.

A new experiment could be set up in a similar manner as this study, but instead of an instructional treatment at the beginning, provide repeated explicit instruction. It has been shown that scientific reasoning can be improved in one semester of college. Lawson (2000) published research with non-major biology students where are they had repeated explicit instruction in developing hypotheses and predicting the outcome before doing the experiment. This allowed them to employ metacognition about abstract concepts so that they could see and confirm what the results were. Lawson’s curriculum was very specifically designed to improve scientific reasoning, and he showed that it was possible. Adey and Shayer (1993) worked with students in middle school in England where they applied a very specific science curriculum once every two weeks over the course of two years. This was only a quarter of the time spent on scientific reasoning development, as opposed to content knowledge, but they found that not only did students show a marked improvement in their science scores at the end of two years, they also showed a higher score in their math and English studies as well, compared to those schools who did not implement this instructional treatment (Adey & Shayer, 2011). In both cases there was an explicit repeated instruction.

We may not get students to transfer as it has been shown repeatedly in multiple contexts that transfer does not happen, except in rare cases, but we can help students see underlying structure and help them slowly start to generalize concepts they learn in science. We can also help them develop their scientific reasoning ability at the college level, as Lawson et al. (2000) demonstrated. Further research could be done by implementing a research design similar to that developed by Lawson et al. (2000) within college general chemistry courses.

This work also needs to start sooner. Future research could be done by implementing a research design similar to that developed by Adey and Shayer (1993) in middle schools and high schools.
within the States. Students need to learn how to scientifically reason as they are undergoing puberty (Piaget 1970, 1997). When they get to college it is not necessarily too late, but mental flexibility is decreasing (Dementriou et al., 2013). Students need to have these skills already by the time they get to college so they can use them. Unfortunately, this will be a lost cause without major changes in high school. High school teachers would need high quality professional development; teaching to help students develop scientific reasoning and reconstruct misconceptions is not easy. There must be a curriculum shown to work, such as Adey and Shayer’s (1993) and Lawson’s (2000), with teachers who are willing to push through the difficulties, and administration that is there to support them. To develop high quality professional development there needs to be collaborations between psychologists, chemists, and mathematicians so that the teachers can understand the connection between the psychology of what’s going on and the content knowledge. Teachers would also need a support system to continue to help them, to cheer them on. Future research could also be done with professional development and working with teachers over time.
References


Gentner, D., Loewenstein, J., & Thompson, L. (2003). Learning and transfer: A general role for analogical encoding. *Journal of Educational Psychology, 95*(2), 393-408.


Appendix A – Institutional Review Board Consent

Date: August 9, 2016

To: Brittany Busby, Chemistry and Biochemistry
    Dr. Mark Cracolice, Chemistry and Biochemistry

From: Paula A. Baker, IRB Chair and Manager

RE: IRB #155-16: “Graphing skill transfer between math and chemistry”

Your IRB proposal cited above has been approved under the exempt category 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:

N (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.

The consent forms used for this project must bear the dated and signed IRB stamp. Use the PDF sent with this approval notice as a “master” from which to make copies for the subjects.

University of Montana IRB policy does not require you to file an annual Continuation Report for exempt studies as there is no expiration date on the approval. However, you are required to notify the IRB of the following:

Amendments: Any changes to the originally-approved protocol must be reviewed and approved by the IRB before being made (unless extremely minor). Requests must be submitted using Form RA-110.

Unanticipated or Adverse Events: You are required to timely notify the IRB if any unanticipated or adverse events occur during the study. If you experience an increased risk to the participants, or if you have participants withdraw from the study or register complaints about the study. Use Form RA-111.

Please contact the IRB office with any questions at (406) 243-6672 or email irb@umontana.edu.
Appendix B – Institutional Review Board Stamped Consent for Research

These documents were approved and stamped by the Institutional Review Board at the University of Montana–Missoula for consent of research and interviews, to be presented and signed by students.
PARTICIPANT INFORMATION AND INFORMED CONSENT FOR RESEARCH

Study Title: Graphing skill transfer between math and chemistry

Investigator(s):
  Name: Brittany Busby
  Title: Graduate student
  Faculty supervisor: Mark Cracolice
  Department: Department of Chemistry and Biochemistry
  University address: Room 101B, Department of Chemistry & Biochemistry, University of Montana – Missoula, 59812
  Telephone: 406-243-4823
  Email: mark.cracolice@umontana.edu

Purpose:
You have been invited to participate because you are currently enrolled in the first semester general chemistry course.
The purpose of this research study is to investigate the relationship between math and chemistry.
The results will be used for the researcher's dissertation and publications to inform the public on how to improve instruction and reduce the relationship between math and chemistry.
You must be 18 or older to participate in this research.

Procedures:
If you agree to take part in this research study, you will be given an instructional worksheet to read and highlight based on what you deem relevant to learning.
You will be asked to take several assessments that will be part of your course grade, but the researcher requires permission to collect the laboratory and exam grades.
Aside from the required assessments and reading through an instructional worksheet during laboratory time, this research will not require any additional time from you.

Risks/Discomforts:
There is no anticipated discomfort for those contributing to this study, so risk to participants is minimal.

Benefits:
Although you may not directly benefit from taking part in this study, your contribution will provide pertinent information for current and future research.

Confidentiality:
Your records will be kept confidential and will not be released without your consent except as required by law.
Your identity will be kept private and if the results of this study are written in a scientific journal or presented at a scientific meeting, your name will not be used.
The data will be stored in a locked file cabinet with your signed consent form in a cabinet separate from the data.
Voluntary Participation/Withdrawal:
Your decision to take part in this research study is entirely voluntary. If you refuse to take part in the study at any time you will not be penalized or experience a loss of benefits to which you are normally entitled. However, you will be required then to take part in another form of relevant instruction for the duration of time devoted to the research study.

Questions:
If you have any questions about the research now or during the study, please contact: Mark Cracolice at 406-243-4823. If you have any questions regarding your rights as a research subject, you may contact the UM Institutional Review Board (IRB) at (406) 243-6672.

Statement of Your Consent:
I have read the above description of this research study. I have been informed of the risks and benefits involved, and all my questions have been answered to my satisfaction. Furthermore, I have been assured that any future questions I may have will also be answered by a member of the research team. I voluntarily agree to take part in this study. I understand I will receive a copy of this consent form.

______________________________
Printed Name of Participant

______________________________
Participant's Signature Date
PARTICIPANT INFORMATION AND INFORMED CONSENT FOR INTERVIEWS

Study Title: Graphing skill transfer between math and chemistry

Investigator(s):
Name: Brittany Busby
Title: Graduate student
Faculty supervisor: Mark Cracolice
Department: Department of Chemistry and Biochemistry
University address: Room 101B, Department of Chemistry & Biochemistry, University of Montana – Missoula, 59812
Telephone: 406-243-4823
Email: mark.cracolice@umontana.edu

Purpose:
You have been invited to participate because you are currently enrolled in the first semester general chemistry course.
The purpose of this research study is to investigate the relationship between math and chemistry.
The results will be used for the researcher's dissertation and publications to inform the public on how to improve instruction and reduce the relationship between math and chemistry.
You must be 18 or older to participate in this research.

Procedures:
If you agree to be a participant in this study you will be asked to engage in a 10-20 minute face-to-face interview with Brittany Busby.
You will be asked a variety of questions exploring your thought processes when given different chemistry problems emphasizing a mathematical foundation. The interview will take place at a location and time convenient to both parties.

The interview will be audio recorded and transcribed by the researcher if necessary. The recording will be destroyed upon completion of the study. A detailed analysis will be done of the data provided through your interview. You may also present other documents or artifacts, which might offer significant insight into your experience. Your initials ________ indicate your permission to audio record the interview.

Risks/Discomforts:
There is no anticipated discomfort for those contributing to this study, so risk to participants is minimal.

Benefits:
Although you may not directly benefit from taking part in this study, your contribution will provide pertinent information for current and future research.

Confidentiality:
Your records will be kept confidential and will not be released without your consent except as required by law. Participant codes will be utilized to ensure that your name is not used throughout the study and therefore, it will not be attached to any data.
If the results of this study are written in a scientific journal or presented at a scientific meeting, your name will not be used.
The data will be stored in a locked file cabinet.
Your signed consent form will be stored in a cabinet separate from the data.
The audiotape will be transcribed without any information that could identify you. The tape will then be erased upon completion of the study.

Voluntary Participation/Withdrawal:
Your decision to take part in this research study is entirely voluntary.

Questions:
If you have any questions about the research now or during the study, please contact: Mark Cracolice at 406-243-4823.
If you have any questions regarding your rights as a research subject, you may contact the UM Institutional Review Board (IRB) at (406) 243-6672.

Statement of Your Consent:
I have read the above description of this research study. I have been informed of the risks and benefits involved, and all my questions have been answered to my satisfaction. Furthermore, I have been assured that any future questions I may have will also be answered by a member of the research team. I voluntarily agree to take part in this study. I understand I will receive a copy of this consent form.

Printed Name of Subject

__________________________________________

Subject's Signature                              Date

The University of Montana IRB
Expiration Date
Date Approved
Chair/Admin
Appendix C – Test Distribution Protocol

The test distribution protocol walks through the order of operations, assessments to distribute, and time frames for each, in addition to general information for students to be aware of.
Test Distribution Protocol

IRB consent will have to be obtained from students at the beginning of the first week of lab for permission to use their grades confidentially.

1. Explain some of the details of the research.
2. Read the IRB consent form to the students.
3. If students do not choose to participate in the research they will be given an alternate option – Read a provided research article and write a report on several questions that I provide.
4. Explain the alternate option.
5. Hand out IRB consent forms. **I will leave the room while they sign or do not sign. They need to sign the IRB consent form if they agree to participate. They will turn the consent forms in up front and one of the TAs will come get me when they are done.
6. We will conduct several assessments across the 1st three weeks.

There will be seven total assessments to administer, three the 1st week, three the 2nd week, and one the 3rd week. A post measure of the graph transfer instrument will also be administered the 15th week.

**Week 1 tests:** Scientific reasoning (CTSR), Basic graphing skills (TOGS), and Textbook reading (TRP)

**Week 2 tests:** Pattern recognition (SPM+), Chemistry content knowledge (CCI), and Demographics questionnaire

**Week 3 test:** Transfer (ToG)

**Week 15 test:** Post Transfer (ToG)

After IRB consent is obtained announce:

- These will be graded but you will not be given the tests back (do not say at some point). Effort is important.
- Each test will have a set time limit. If you finish early turn in the test and sit quietly until the time is up. Since there is a time it is recommended you use it. There is no advantage to finishing early.
- BE QUIET if you finish before others. Do NOT talk/whisper or otherwise engage with others or activities that may be distracting.
- There will be a folder up front for you to put the answer sheet when you finish. Place your test booklet, if you have one, next to the folder.
- Do NOT write on the test booklets if an answer sheet is provided as well. If you need to work out a problem do so on the answer sheet.
- The answer sheet has a portion at the top for the students’ information. They must be sure to fill that out on each test or they will not get credit.
- You will NOT need calculators for any of these tests.
- Pen or pencil is fine to use.
If there is a test booklet pass out the answer sheet first, then the test booklet. Do not let them start until you say. When the time is up have them turn in the answer sheets and test booklets separately.

Have the students take the FULL time before starting the next test (they may rush if they know you'll let them stop early). At the same time, be reasonable. If everyone is done by the time you say 10 min left maybe only have them sit 5 min of the 10.

If they require more time let them finish. If more time is longer than 5 minutes have the students, who did not finish in the set time, work on the assessments after class.

Go through all test booklets after they are turned in. If any have markings on them they cannot be used again. If markings are in pencil please erase them. If in pen or the pencil cannot be erased fully set aside to be recycled later.

Make note of how many more test booklets or answer sheets need to be made for each test. Please, make those copies or let me know so I can make them before the next lab period. It is very frustrating when you don’t have enough and have to run down to get more so plan ahead.

1st Week:

Test 1: Classroom Test of Scientific Reasoning (CTSR) (booklet + answer sheet) 35 minutes. (They usually take between 15-30 minutes)

Test 2: Test of Graphing Skills (TOGS) (booklet + answer sheet) 40 minutes.

Test 3: Textbook Reading from Pilot (TRP) (answer sheet) 10 minutes.

2nd Week:

Test 4: Chemical Concepts Inventory (booklet + answer sheet) 25 minutes once started (They usually take about 10-20 minutes)

Test 5: Demographics Questionnaire (DQ) (answer sheet) 20 minutes. It's ok to answer any questions with this if students ask.

Test 6: Pattern Recognition (booklet + answer sheet) 60 minutes.

3rd Week:

Test 7: Test on Graphs (ToG) (answer sheet) 60 minutes.

15th Week:

Test 8: Test on Graphs (ToG) (answer sheet) 60 minutes. Post measure
Appendix D – Classroom Test of Scientific Reasoning (CTSR)
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

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.

\[
\begin{array}{cccc}
R & R & R & R \\
Y & Y & Y & Y \\
B & B & B & B \\
\end{array}
\quad \quad \quad 
\begin{array}{cccc}
R & R & R & R \\
Y & Y & Y & Y \\
B & B & B & B \\
\end{array}
\]

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).

![Diagram of glass and candle](image)

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). 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](image)

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 – Chemistry Concepts Inventory (CCI)

The CCI was utilized to measure alternative conceptions that students enter general chemistry with as described in section 3.5.3 Research instruments. This instrument is copyrighted so must be retrieved from the publisher.
Appendix F – Raven Standard Progressive Matrices–Plus Version (SPM+)

The SPM+ instrument was utilized to measure intelligence as discussed in section 3.5.3 Research instruments. This instrument is copyrighted so must be retrieved from the publisher.
Appendix G – Test of Graphing Skills (TOGS)

Permission from Dr. Michael Padilla was obtained via email on August 17, 2015 to use the TOGS as needed.
An Examination of Line Graphing Ability of Students in Grades Seven Through Twelve

Michael J. Padilla
Department of Science Education
The University of Georgia
Athens, Georgia

Danny L. McKenzie
Department of Instruction and Teacher Education
University of South Carolina
Columbia, South Carolina

Edward L. Shaw, Jr.
Department of Education
Southeastern Louisiana University
Hammond, Louisiana
Test of Graphing in Science
(TOGS)

Version 3

Directions
This is a test of how well you understand graphs. Read each question carefully. Choose the one best response to each question. Mark the space on the answer sheet with your answer.

Danny McKenzie
Michael Padilla
Department of Science Education
University of Georgia
Athens, Georgia 30602
1. Tom wanted to know how much fertilizer he should give his tomato plants. He gave different amounts of fertilizer to his plants. He then counted the number of tomatoes grown on each plant. His results are in the data table below.

<table>
<thead>
<tr>
<th>Amount of Fertilizer (grams)</th>
<th>Number of Tomatoes Produced</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>100</td>
<td>4</td>
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<tr>
<td>150</td>
<td>6</td>
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<tr>
<td>250</td>
<td>8</td>
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<tr>
<td>450</td>
<td>8</td>
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</table>

Which set of axes below is the best to use for graphing his results?
Use the information below to answer questions 2-5.

Rose owns a flower shop. She gave different amounts of water to several plants each day. She measured the height of the plants after three weeks. The graph below shows the results.

2. One plant was given 140 ml of water daily for three weeks. What would be the expected height of this plant at that time?
   A. 11 cm
   B. 16 cm
   C. 20 cm
   D. 23 cm

3. How much water was given each day to the plant that grew 10 cm tall?
   A. 120 ml
   B. 140 ml
   C. 160 ml
   D. 180 ml

4. The following statements describe the relationship between the amount of water given and the height of the plant. Which is the best description?
   A. As the amount of water increased to 120 ml, the height of the plants decreased. With amounts greater than 120 ml the height of the plants increased.
   B. Both the amount of water and the height of the plants increased up to 120 ml. Then they both decreased.
   C. As the amount of water increased to 120 ml the plant growth quickly increased. After 120 ml of water the plant growth increased more slowly.
   D. As the amount of water increased to 120 ml the height of the plants increased. With amounts greater than 120 ml the height of the plants decreased.

5. How tall would you expect plants to grow if given 205 ml of water each day?
   A. less than 5 cm
   B. 8 cm
   C. 10 cm
   D. more than 20 cm
Use the graph below to answer questions 6 & 7.

6. What are the proper coordinates for point a?
   A. (9,12)
   B. (20,12)
   C. (20,8)
   D. (12,20)

7. Which point is identified by the coordinates (15,8)?
   A. a
   B. b
   C. c
   D. d

8. Danny measured the time needed to heat various amounts of water to boiling. Which of the following is correctly labeled for showing the results?
9. A best fit line describes the trend in a set of data points. Which of the following is the most appropriate best fit line.

- A
- B
- C
- D

10. Mike wanted to know if the weight of chickens affected the number of eggs they laid each day. Which of the following is correctly labeled for showing his results?

- A
- B
- C
- D
11. Lisa measured the height a ball bounced when it was dropped. When dropped 50 cm the ball bounced 40 cm. A 10 cm drop bounced 8 cm. A 30 cm drop bounced 24 cm. A 100 cm drop bounced 80 cm. A 70 cm drop bounced 56 cm. Which of the following graphs best describes these results?
Questions 12-15 refer to the following investigation.

Lynn measured the amount of gas needed to drive one km at different speeds. Her results are plotted below.

12. How much gas (liters) was used to drive one km at 60 km per hour?
   A. .05  
   B. .06  
   C. .07  
   D. .08

13. Which of the following is the best description of the relationship shown on the graph?
   A. As the speed of the car increases, the amount of gas used also increases.
   B. As the speed of the car decreases, the amount of gas used increases.
   C. The amount of gas used increases as the speed of the car decreases.
   D. The amount of gas used decreases as the speed of the car increases.

14. At 55 km per hour, how much gas (liters) would the car use?
   A. .04  
   B. .05  
   C. .06  
   D. .07

15. At 80 km per hour, how much gas (liters) would the car use?
   A. .07  
   B. .08  
   C. .09  
   D. .10
Use the following information to answer questions 16 and 17.

Dick plans to study how well sunflowers grow in different size pots. The graphs below show four possible outcomes of his experiment.

Which graph is best described by the following statements.

16. As the pot size increases, the plant height decreases.

17. As the pot size increases, the plant height increases up to a certain pot size. With larger pots, plant height remains the same.

18. Liz jogs 2 miles everyday. One day after running, she measures her pulse every two minutes. These are the results. Her pulse rate was 140 beats per minute 2 minutes after running. It was 115 beats per minute after 4 minutes. It was 105 beats per minute after 6 minutes. It was 90 beats per minute after 8 minutes. It was 75 beats per minute after 10 minutes.

Which of these graphs best shows her results?
19. A scientist was interested in the number of foxes and rabbits living in a valley. She counted their numbers many times over twenty years. A copy of her graphed results is below.

Which of these statements is supported by the two graphs?

A. The number of rabbits and foxes increases at the same time.
B. During the 6th year there are more foxes in the area than rabbits.
C. There were the greatest number of foxes and the fewest rabbits at the six year point.
D. An increase in the number of rabbits is followed within a few years by an increase in the number of foxes.
20. Which axis below would be the best to use in graphing the following data?

<table>
<thead>
<tr>
<th>Time (day)</th>
<th>Plant height (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.03</td>
</tr>
<tr>
<td>3</td>
<td>1.00</td>
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<tr>
<td>6</td>
<td>3.40</td>
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<tr>
<td>10</td>
<td>4.80</td>
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<tr>
<td>13</td>
<td>4.80</td>
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</table>
21. John let his flashlight burn for 14 straight hours. He measured the amount of light given off (in lumens) at various times. He collected this data.

<table>
<thead>
<tr>
<th>Time (hours)</th>
<th>Light Given off (lumens)</th>
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<tbody>
<tr>
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<td>9.5</td>
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<tr>
<td>2</td>
<td>8.5</td>
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<td>8</td>
<td>4.2</td>
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<td>14</td>
<td>0.6</td>
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</table>

Which graph best shows his results?
22. Eddie grew pumpkins. He found the average weight of ten pumpkins at different times after planting. His results are listed below.

<table>
<thead>
<tr>
<th>Time After Planting (weeks)</th>
<th>Average Weight of Pumpkins (Kg)</th>
</tr>
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<tbody>
<tr>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
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<tr>
<td>12</td>
<td>9</td>
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<td>18</td>
<td>22</td>
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Which of these graphs best describes his results?
23. Anne studied fruit flies for one month. She measured the amount of waste produced by the fruit flies. She concluded that as the number of flies increased, the amount of waste increases. Which pair of graphs best support her conclusion?

24. A best fit line describes the trend in a set of data points. Which of these graphs shows the most appropriate best fit line?
25. Jim studied the effect that clearing land has on the number of deer. Every year for 10 years he measured the amount of cleared land and the number of deer in an area. He found that the amount of cleared land increased and the number of deer decreased.

Which pair of graphs best support his conclusion?

A.  

<table>
<thead>
<tr>
<th>A</th>
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<th>B</th>
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<tbody>
<tr>
<td><img src="image" alt="Graph A" /></td>
<td><img src="image" alt="Graph B" /></td>
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26. Tom wanted to know how the amount of heating oil needed to heat a large school was affected by the outside temperature. He measured the amount of heating oil used each hour for 24 hours. The school was kept at 20°C. He also took the outside temperature each hour. His results are graphed below.

![Graph C](image)

Which of these statements is supported by the graph?

A. As the outside temperature rises, the amount of heating oil used increases.
B. As the outside temperature falls, the amount of heating oil used decreases.
C. When the outside temperature stays the same, the amount of heating oil used decreases slightly.
D. As the outside temperature rises, the amount of heating oil used decreases.
Test of Graphing Skills in Science

Sex: M F Name __________________________
Date of Birth __________________________ Grade __________________________

Blacken the space between the parentheses corresponding to your choice.

1. (A) (B) (C) (D) 19. (A) (B) (C) (D)
2. (A) (B) (C) (D) 20. (A) (B) (C) (D)
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8. (A) (B) (C) (D) 26. (A) (B) (C) (D)
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Appendix H – Test of Graphs (ToG)

Permission to use and adapt this instrument for use with the general chemistry students was obtained from Dr. Maja Planinic on July 13, 2016. Confidence intervals were added but otherwise the instrument is the same as utilized by Planinic. Coding and grading the assessment was done using the same criteria presented in Planinic’s work.
TEST ON GRAPHS

Name: Last ____________________________________ First ____________________________________
Student ID # ____________________________________________________________
Lab TA ________________________________________________________________
Section # __________________________
Date test was taken: Month __________ Day __________ Year __2016________

Please read carefully the text of each question and consider the attached graph. Choose the correct answer in the multiple choice questions or write your answer on the provided line in the open-ended questions. Please provide procedure and/or explanation for all your answers. Explanations do not have to be long, yet they should clearly show your reasoning.

Thank you for your cooperation!

1. a. Find the slope of the straight line from the graph.

PROCEDURE / EXPLANATION:

ANSWER: _____________

b. How confident are you in the answer you just chose?
   a) very confident
   b) somewhat confident
   c) neither confident nor unconfident
   d) somewhat unconfident
   e) very unconfident
2. a. In which interval is the slope of the line negative?

[Diagram showing intervals A to E with a line graph]

a) A – B  
b) A – C  
c) C – D  
d) D – E 

b. How confident are you in the answer you just chose?
   a) very confident  
   b) somewhat confident  
   c) neither confident nor unconfident  
   d) somewhat unconfident  
   e) very unconfident

3. a. Calculate the area under the given function graph from $x = 0$ to $x = 5$.

[Graph with axes and a line segment]

ANSWER: _____________

b. How confident are you in the answer you just chose?
   a) very confident  
   b) somewhat confident  
   c) neither confident nor unconfident  
   d) somewhat unconfident  
   e) very unconfident
4. a. Straight lines $p$ and $q$ are shown on the graph. Compare their slopes at $x = 1$.

![Graph showing lines $p$ and $q$.]

**a)** The slope of $p$ is less than the slope of $q$.
**b)** The slopes of $p$ and $q$ are equal.
**c)** The slope of $p$ is greater than the slope of $q$.

b. How confident are you in the answer you just chose?
- a) very confident
- b) somewhat confident
- c) neither confident nor unconfident
- d) somewhat unconfident
- e) very unconfident

5. a. Calculate the area under the given function graph from $x = 0$ to $x = 4$.

**ANSWER:**

![Graph showing the area under the curve from $x = 0$ to $x = 4$.]

**PROCEDURE / EXPLANATION:**

**b.** How confident are you in the answer you just chose?
- a) very confident
- b) somewhat confident
- c) neither confident nor unconfident
- d) somewhat unconfident
- e) very unconfident
6. a. A straight line is shown in the coordinate system. Which of the following statements is correct?

**PROCEDURE / EXPLANATION:**

![Graph of a straight line](image)

a) The slope of the line is constant and positive.
b) The slope of the line is constant and negative.
c) The slope of the line is constantly decreasing and it is negative.
d) The slope of the line is constantly decreasing and it is positive.

b. How confident are you in the answer you just chose?
   a) very confident
   b) somewhat confident
   c) neither confident nor unconfident
   d) somewhat unconfident
   e) very unconfident

7. a. Calculate the area under the given function graph from $x = 0$ to $x = 8$.

**PROCEDURE / EXPLANATION:**

![Graph of the function](image)

**ANSWER:**

b. How confident are you in the answer you just chose?
   a) very confident
   b) somewhat confident
   c) neither confident nor unconfident
   d) somewhat unconfident
   e) very unconfident
8. a. Find the value of $x$ for which the slopes of the tangents to the functions $f(x)$ and $g(x)$ are equal.

PROCEDURE / EXPLANATION:

- $x = -4$
- $x = -3$
- $x = 0$
- $x = 3$

b. How confident are you in the answer you just chose?
   a) very confident
   b) somewhat confident
   c) neither confident nor unconfident
   d) somewhat unconfident
   e) very unconfident

9. a. The graph shows how the total cost of a phone call changes with the call duration. Find the call cost per minute.

PROCEDURE / EXPLANATION:

ANSWER: _____________

b. How confident are you in the answer you just chose?
   a) very confident
   b) somewhat confident
   c) neither confident nor unconfident
   d) somewhat unconfident
   e) very unconfident
10. a. Variation of prices of stocks ING and EXP with time are shown on the graph. Compare the growth rates of prices at $t = 3$ months. 

![Graph showing stock prices over time]

**PROCEDURE / EXPLANATION:**

a) The growth rate of the price of stock ING is less than the growth rate of the price of stock EXP.
b) The growth rates of the prices of stocks ING and EXP are equal.
c) The growth rate of the price of stock ING is larger than the growth rate of the price of stock EXP.

b. How confident are you in the answer you just chose?
   a) very confident  
   b) somewhat confident  
   c) neither confident nor unconfident  
   d) somewhat unconfident  
   e) very unconfident

11. a. The graph shows how the population of a country changes over time. Which of the following statements is correct?

![Graph showing population over time]

**PROCEDURE / EXPLANATION:**

a) The rate of change of the population is constant and positive. 
b) The rate of change of the population is constant and negative. 
c) The rate of change of the population is constantly increasing. 
d) The rate of change of the population is constantly decreasing.

b. How confident are you in the answer you just chose?
   a) very confident  
   b) somewhat confident  
   c) neither confident nor unconfident  
   d) somewhat unconfident  
   e) very unconfident
12. a. The graph shows the rate of change of water level of a certain river during one day. What is the total change in water level of the river during the first 20 hours?

PROCEDURE / EXPLANATION:

![Graph of water level rate of change (cm/h).]

ANSWER: _______________

b. How confident are you in the answer you just chose?
   a) very confident
   b) somewhat confident
   c) neither confident nor unconfident
   d) somewhat unconfident
   e) very unconfident

13. a. The graph shows how the GDP (gross domestic product) expressed in billions of dollars changed over the years. GDP is calculated with the base year of 2000, so it can be either positive or negative, depending on whether it was higher or lower than GDP in 2000. In which time interval was the growth rate of the GDP negative?

PROCEDURE / EXPLANATION:

![Graph of GDP (billion $) over years.]

a) 2000 – 2004
b) 2004 – 2008
c) 2006 – 2010
d) 2008 – 2010

b. How confident are you in the answer you just chose?
   a) very confident
   b) somewhat confident
   c) neither confident nor unconfident
   d) somewhat unconfident
   e) very unconfident
14. a. The graph shows how the consumption of fuel per kilometer changed for a certain vehicle with the covered distance. How many liters of fuel were spent for the first 400 km of the trip?

**PROCEDURE / EXPLANATION:**

![Graph showing fuel consumption per kilometer](image)

**ANSWER:** 

b. How confident are you in the answer you just chose?
   
   a) very confident
   b) somewhat confident
   c) neither confident nor unconfident
   d) somewhat unconfident
   e) very unconfident

15. a. The graph shows how the bus rental cost per kilometer changes with the covered distance. The initial bus rental price is 200 EUR. What is the total bus rental price for a 200 km journey?

**PROCEDURE / EXPLANATION:**

![Graph showing bus rental cost per kilometer](image)

**ANSWER:** 

b. How confident are you in the answer you just chose?

   a) very confident
   b) somewhat confident
   c) neither confident nor unconfident
   d) somewhat unconfident
   e) very unconfident
16. a. The graph shows how the height of two plants P and R changes over time. When do the plants grow equally fast?

**PROCEDURE / EXPLANATION:**

![Graph showing the height of two plants P and R over time.](image)

a) At \( t = 0 \) months
b) At \( t = 4 \) months
c) At \( t = 8 \) months
d) At \( t = 12 \) months

b. How confident are you in the answer you just chose?
   a) very confident
   b) somewhat confident
   c) neither confident nor unconfident
   d) somewhat unconfident
   e) very unconfident

17. a. Motion of a car along a straight horizontal road is represented by a \( v \) vs. \( t \) graph. Find the acceleration of the car at \( t = 8 \) s.

**PROCEDURE / EXPLANATION:**

![Graph showing the velocity of a car over time.](image)

**ANSWER:** __________

b. How confident are you in the answer you just chose?
   a) very confident
   b) somewhat confident
   c) neither confident nor unconfident
   d) somewhat unconfident
   e) very unconfident
18. a. Motions of objects A and B are represented by a \( v \) vs. \( t \) graph. Compare accelerations of the objects at \( t = 2 \) s.

\[\text{PROCEDURE / EXPLANATION:}\]

\[\begin{array}{c}
\text{\( t \) (s)} \\
1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\
\hline
\text{\( v \) (m/s)} \\
0 & 2 & 4 & 6 & 8 & 10 & 12 & 14 & 16 \\
\end{array}\]

a) Acceleration of A is less than the acceleration of B.
b) Accelerations of A and B are equal.
c) Acceleration of B is less than the acceleration of A.

b. How confident are you in the answer you just chose?
   a) very confident
   b) somewhat confident
   c) neither confident nor unconfident
   d) somewhat unconfident
   e) very unconfident

19. a. Motion of a train is represented by an \( a \) vs. \( t \) graph. What is the change in the train’s speed between \( t = 0 \) s and \( t = 4 \) s?

\[\text{PROCEDURE / EXPLANATION:}\]

\[\begin{array}{c}
\text{\( t \) (s)} \\
1 & 2 & 3 & 4 & 5 \\
\hline
\text{\( a \) (m/s^2)} \\
-2 & -1 & 0 & 1 & 2 \\
\end{array}\]

\[\text{ANSWER: \underline{\text{\( \theta \)}}}\]

b. How confident are you in the answer you just chose?
   a) very confident
   b) somewhat confident
   c) neither confident nor unconfident
   d) somewhat unconfident
   e) very unconfident
20. a. In which time interval is the acceleration of the motion represented by the following \( v \) vs. \( t \) graph negative?

\[
\begin{align*}
\text{PROCEDURE / EXPLANATION:} \\
\end{align*}
\]

\[
\begin{align*}
\text{a) } t_1 \rightarrow t_2 \\
\text{b) } t_3 \rightarrow t_4 \\
\text{c) } t_4 \rightarrow t_5 \\
\end{align*}
\]

b. How confident are you in the answer you just chose?

a) very confident
b) somewhat confident
c) neither confident nor unconfident
d) somewhat unconfident
e) very unconfident

21. a. Motion of an object is represented by the following \( v \) vs. \( t \) graph. Which statement best describes this motion?

\[
\begin{align*}
\text{PROCEDURE / EXPLANATION:} \\
\end{align*}
\]

\[
\begin{align*}
\text{a) The object moves with a constantly increasing acceleration.} \\
\text{b) The object moves with a constantly decreasing acceleration.} \\
\text{c) The object moves with a constant positive acceleration.} \\
\text{d) The object moves with a constant negative acceleration.} \\
\end{align*}
\]

b. How confident are you in the answer you just chose?

a) very confident
b) somewhat confident
c) neither confident nor unconfident
d) somewhat unconfident
e) very unconfident
22. a. An elevator is moving from the basement to the top of a building. The motion of the elevator is represented by the following $v$ vs. $t$ graph. What is the distance traveled by the elevator during the first two seconds of the motion?

\[ v \text{ (ms)} \]

\[ t \text{ (s)} \]

\[ 1 \quad 2 \]

\[ 5 \]

\[ 4 \]

\[ 3 \]

\[ 2 \]

\[ 1 \]

\[ 0 \]

\[ -1 \]

\[ -2 \]

\[ -3 \]

\[ -4 \]

\[ -5 \]

\[ 100 \]

\[ 200 \]

\[ 300 \]

\[ 400 \]

\[ x \text{(in)} \]

\[ 10 \]

\[ 12 \]

\[ 14 \]

\[ 16 \]

\[ 2 \]

\[ 4 \]

\[ 6 \]

\[ 8 \]

\[ 10 \]

\[ t \text{(min)} \]

\[ 2 \]

\[ 4 \]

\[ 6 \]

\[ 8 \]

\[ 10 \]

\[ 12 \]

\[ 14 \]

\[ 16 \]

\[ A \]

\[ B \]

\[ \text{PROCEDURE / EXPLANATION:} \]

\[ \text{ANSWER: _____________} \]

b. How confident are you in the answer you just chose?
   a) very confident
   b) somewhat confident
   c) neither confident nor unconfident
   d) somewhat unconfident
   e) very unconfident

23. a. Motion of objects A and B is represented by a $x$ vs. $t$ graph, where $x$ is the distance from the starting position. When do the objects A and B have the same speed?

\[ x \text{(in)} \]

\[ t \text{(min)} \]

\[ 10 \]

\[ 12 \]

\[ 14 \]

\[ 16 \]

\[ 2 \]

\[ 4 \]

\[ 6 \]

\[ 8 \]

\[ 10 \]

\[ A \]

\[ B \]

\[ \text{PROCEDURE / EXPLANATION:} \]

\[ a) t = 0 \text{ min} \]
\[ b) t = 3 \text{ min} \]
\[ c) t = 6 \text{ min} \]
\[ d) t = 11 \text{ min} \]

b. How confident are you in the answer you just chose?
   a) very confident
   b) somewhat confident
   c) neither confident nor unconfident
   d) somewhat unconfident
   e) very unconfident
24. a. Motion of a car along a straight horizontal road is represented by an $a$ vs. $t$ graph. The speed of the car at $t = 0$ s was 30 m/s. Find the speed of the car at $t = 7$ s.

PROCEDURE / EXPLANATION:

![Graph showing acceleration vs. time]

ANSWER: ____________

b. How confident are you in the answer you just chose?
   a) very confident
   b) somewhat confident
   c) neither confident nor unconfident
   d) somewhat unconfident
   e) very unconfident

Answer Key (not including coding):
0.33, d, 15, c, 10, b, 58, c, 0.6 Eur/min, c, b, 180 cm, b, 36 L, 395 Eur, b, 0.625 m/s$^2$, a, 14 m/s, d, d, 4 m, d, 43 m/s

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Appendix I – Textbook Reading Pilot (TRP)

This pilot was meant to gain understanding on what students look at and focus on when they are trying to learn via reading a textbook.

3.0 Volume Relationships

Volume relationships are important. In cooking, volumes of various liquids must be measured so that food turns out well. In medicine proper volumes of solutions must be determined so as not to harm patients. In scientific experiments volumes must be measured accurately so accurate conclusions can be drawn from the observations.

On a fictitious world much like ours, a relationship of 3.0 fips in one jim exists between two measures of volume. In order to investigate the relationship between the two, volumetric containers for both were acquired. They found that when they transferred liquid from the fip containers into the jim containers a pattern emerged. They collected the data in Table 3.0▼, and plotted it in Figure 3.0▼.

<table>
<thead>
<tr>
<th>Table 3.0 Fips vs. Jims</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fip (Fp)</td>
</tr>
<tr>
<td>0.3</td>
</tr>
<tr>
<td>0.9</td>
</tr>
<tr>
<td>1.4</td>
</tr>
<tr>
<td>2.1</td>
</tr>
</tbody>
</table>

Figure 3.0 Fips vs. Jims. The number of fips is proportional to the number of jims.
A learning objective is a statement of what you, the student, will be able to do after studying a textbook passage.

1. Pretend you are a textbook author and write the learning objective that corresponds to the textbook passage that you just studied.

   a) In words:

   

   b) Mathematically:

   

2. How did you determine that learning objective?

3. If you were tested on this material in two weeks what would you focus on to study?

   a) Using the highlighter provided, *highlight* the areas of focus for you.

   b) Briefly explain *why* next to the highlighted areas.
Appendix J – Demographic Questionnaire (DQ)
Student Demographics Survey     UM Chemistry 141 Fall 2016

Name: Last ___________________ First ____________________________
Student ID # ________________________________________________
Today's date: Month ___________ Day _______ Year _______________
Lab TA (Lab section instructor) __________________________________
Section # ____________________
Date of birth: Month ___________ Day _______ Year _______________
Gender: Female _____ Male _____ Other _____, please specify ____________
Are you a transfer student: Y _____ N ______
Number of college credits completed: ____________________________
Major: __________________________________________________________________
2nd Major (if any): __________________________________________________________________
Minor (if any): __________________________________________________________________
Are you a pre-health sciences student: Y ______ N ______
Course load this semester: Number of credits _________________
Current GPA (from high school if you do not have college credits yet.)
    High school ____________________
    College ____________________
Paternal parent or guardian's highest level of education: _________________
Maternal parent or guardian's highest level of education: _________________

Math:
What was your highest level of math completed with a passing grade before taking this course
(Check the closest match)?
    ______ Algebra I
    ______ Intermediate algebra
    ______ Trigonometry
    ______ College algebra
    ______ Probability & linear math
    ______ Calculus I
    ______ Calculus II
    ______ Calculus III
    ______ Higher level than Calculus III
In your high school math courses, when working on math problems were they more often "solve for x" problems or story problems?

- 20% story problems
- 40% story problems
- 60% story problems
- 80% story problems
- 100% story problems

**Physics:**

Have you taken high school physics? Y ______ N _______
If Yes, how many semesters? _______

Have you taken college physics? Y _________ N __________
If Yes, how many semesters? _______

In your high school physics courses did you perform laboratory exercises that involved measuring data that were later used as the basis of developing conceptual understanding? Y _______ N _______
If yes, how often?
- 10 – 30%
- 30 – 60%
- 60 – 90%
- 100%

In general, was your high school physics course designed for you to:
- learn about a concept in lecture first and then collect data,
- learn about a concept in lecture after data was collected, or
- neither?

In your high school physics courses, when working on math problems were they more often "solve for x" problems or story problems?

- 20% story problems
- 40% story problems
- 60% story problems
- 80% story problems
- 100% story problems
### Chemistry:

From which school did you take high school chemistry? ____________________________
In which state? _____________________ City? _________________________________
Who was your high school chemistry teacher? _________________________________
High school chemistry letter grade: __________________________

In your *high school* chemistry courses did you perform laboratory exercises that involved measuring data that were later used as the basis of developing conceptual understanding? *Mark yes or no for the years applicable.*

<table>
<thead>
<tr>
<th>Year</th>
<th>Y</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>First year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Second year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Third year</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

If yes, how often?

<table>
<thead>
<tr>
<th>Range</th>
<th>10 – 30%</th>
<th>30 – 60%</th>
<th>60 – 90%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>First year</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Third year</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In general, was your high school chemistry course designed for you to:

- ______ learn about a concept in lecture first and then collect data,
- ______ learn about a concept in lecture after data was collected, or
- ______ neither?

In your *high school* chemistry courses, when working on math problems were they more often "solve for x" problems or story problems? Indicate the percent frequency *story problems* were used in the chemistry years applicable below
<table>
<thead>
<tr>
<th>First year:</th>
<th>Second year:</th>
<th>Third year:</th>
</tr>
</thead>
<tbody>
<tr>
<td>20%</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>40%</td>
<td>40%</td>
<td>40%</td>
</tr>
<tr>
<td>60%</td>
<td>60%</td>
<td>60%</td>
</tr>
<tr>
<td>80%</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Have you taken college general chemistry before:
A preparatory general chemistry course (CHMY 104 in Montana)? Y ______ N _______
Semester _______________________________
Institution _______________________________________________________
Completed Y N
Final grade _____________

First-semester general chemistry (CHMY 141 in Montana)? Y ______ N _______
Semester _______________________________
Institution _______________________________________________________
Completed Y N
Final grade _____________

Please rank the following (1-10) from your least (10) to most (1) important factors necessary to succeed in this chemistry course:

1. Actively participating in breakout sessions at every lecture meeting
2. Understanding the concepts in the lab portion of the course
3. My intelligence
4. The quality of the textbook
5. Total time committed to study outside of class and efficiency of study
6. Teaching ability and content knowledge of the course instructors
7. Attending all class, lab, and workshop meetings, and going to Study Jam
8. Having good luck
9. Doing the assigned homework questions
10. My background in chemistry, physics, and math from high school
Appendix K – Measurement Labs from the First Week

The key versions of these measurement labs are presented below. For each lab there are two versions, one with a more open-ended instructions and one with explicit graphing instructions.
Are You a Little Wrist?

No prompt Key: 5 points total

1. Imagine living long ago in a medieval kingdom. The standard measurement units were often based on anatomical parts of the ruler of the time, hence the origin of the foot.

You are the King or Queen of your kingdom and the new unit of measure will be based on the circumference of your royal wrist. Construct a standard length unit based on the circumference of your wrist by wrapping a string around the wrist, over the wrist bones. Carefully cut the string so that it matches the distance around your royal wrist. Name your unit after your royal highness, such as 1 Caseywrist.

Using your personal measurement unit, determine the lengths of the objects provided by your teacher. For example, how many Caseywrists is a paperclip, sheet of paper, lab bench, or a pen? Record your measurements in the table below.

<table>
<thead>
<tr>
<th>Object Description</th>
<th>Length (Personal Measuring Unit)</th>
<th>Length (Centimeters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) long edge of a paperclip</td>
<td>0.2</td>
<td>3.1</td>
</tr>
<tr>
<td>b) long edge of this sheet of paper</td>
<td>1.82</td>
<td>27.85</td>
</tr>
<tr>
<td>c) short edge of your lab bench or table</td>
<td>4.85</td>
<td>73.5</td>
</tr>
<tr>
<td>d) length of a pen or pencil (the one you are using is fine)</td>
<td>0.91</td>
<td>14.0</td>
</tr>
</tbody>
</table>

1 point for completely filled in data. They will not have gone over significant figures yet and may be able to measure to different significant figures depending on the object.

3. Things are going along well in your little kingdom until the evil French invader, Marquis de’ Centimeter arrives and forces your kingdom to adopt their standard units, called the metric system. The Marquis is ordering you to re-measure objects A-D using a meter stick and record the measurements, in centimeters, in the data table.

4. What are the patterns shown?

4 points total
If they give some explanation for the relationship, that makes sense, i.e. as one increases the other increases, give them at least 2 points.

If they give an explanation and use proportional or explain in some more detail how the two variables are related give them 3 points.

If they do a graph or calculate ratios give them 4 points.
Are You a Little Wrist?

*With prompt Key: 5 points total*

1. Imagine living long ago in a medieval kingdom. The standard measurement units were often based on anatomical parts of the ruler of the time, hence the origin of the foot.

You are the King or Queen of your kingdom and the new unit of measure will be based on the circumference of your royal wrist. Construct a standard length unit based on the circumference of your wrist by wrapping a string around the wrist, over the wrist bones. Carefully cut the string so that it matches the distance around your royal wrist. Name your unit after your royal highness, such as 1 Caseywrist.

Using your personal measurement unit, determine the lengths of the objects provided by your teacher. For example, how many Caseywrists is a paperclip, sheet of paper, lab bench, or a pen? Record your measurements in the table below.

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</tr>
<tr>
<td>d) length of a pen or pencil (the one you are using is fine)</td>
<td>0.91</td>
<td>14.0</td>
</tr>
</tbody>
</table>

1 point for completely filled in data. They will not have gone over significant figures yet and may be able to measure to different significant figures depending on the object.

3. Things are going along well in your little kingdom until the evil French invader, Marquis de’ Centimeter, arrives and forces your kingdom to adopt their standard units, called the metric system. The Marquis is ordering you to re-measure objects A-D using a meter stick and record the measurements, in centimeters, in the data table.

4. On the grid(s) below, construct a plot of your data in length in centimeters versus unit of measurement with your wrist device. The metric unit will go on the y-axis and your unit on the x-axis.
5. Determine the equation of the line.

1 point
They should have something resembling $y = mx + b$.

6. Use words to describe the meaning of your algebraic equation.

This is a linear relationship that shows how one unit of length increases proportionally with another unit of length. The y-intercept is zero because if you have zero of one unit of length you would still have zero of the other unit of length. Since the wrist unit is so much larger than a cm it shows that to determine the number of cm from a wrist unit it would be 15 times greater.

2 points:
Give them points for having some explanation about the equation, anything that describes both increasing, proportional, etc. Basically, these are points for trying as long as it makes sense for their equation.
Gas Pressure and Volume Relationship

No prompt Key

1. Obtain a pressure-measuring device, a Labquest and Vernier Pressure Sensor, and Vernier Sensor adaptor depending on which type of Vernier Pressure Sensor you choose.

2. Attach the Vernier Pressure Sensor to one of the "channels" on the edge of the Labquest, using the adaptor if necessary.

3. On the Labquest, select the corresponding "channel." One of the headings will read "Sensor." Click that and scroll down to the "Gas Pressure" sensor option.

4. Change your units to mm Hg by tapping the units that show up and selecting mm Hg.

5. Obtain a 20-mL syringe. Move the plunger to a volume reading of about 10 mL.

6. Before you attach the syringe to the sensor, turn the blue lever so that it points toward the sensor box, Figure 1 A. This connects the vent port and the syringe port, which are perpendicular to each other.

7. With the innermost black plastic sealing disk even with the 10 cc mark, attach the syringe to the sensor by turning the syringe in a clockwise direction so its threaded end screws onto the short syringe port, parallel to the injection tube, as illustrated in Figure 1B.
8. Now turn the blue plastic lever so it points to the vent port, Figure 1C (measure position). Do not move the vent port lever. Keep it in the measure position. You may use the 10 mL volume as your first measurement.

9. Observe and record the volume and pressure of trapped air in the Syringe at five different volumes between 3 and 19 mL. Move and hold the syringe plunger until the pressure reading stabilizes.

10. Record your data in the table below.

<table>
<thead>
<tr>
<th>Pressure (mmHg)</th>
<th>Volume (mL)</th>
<th>1/Volume (1/mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1323.5</td>
<td>5.8</td>
<td>0.172</td>
</tr>
<tr>
<td>692.8</td>
<td>10.8</td>
<td>0.093</td>
</tr>
<tr>
<td>548.0</td>
<td>13.3</td>
<td>0.075</td>
</tr>
<tr>
<td>455.0</td>
<td>15.8</td>
<td>0.063</td>
</tr>
<tr>
<td>398.1</td>
<td>18.3</td>
<td>0.055</td>
</tr>
</tbody>
</table>

1 point for completely filled in data. They will not have gone over significant figures yet and may be able to measure to different significant figures depending on the object. (You can use the numbers you collected to have a better idea of data points).

11. What are the patterns shown?

4 points total

If they give some explanation for the relationship, that makes sense, i.e. as one increases the other decreases, give them at least 2 points.

If they give an explanation and use inverse relationship or explain in some more detail how the two variables are related give them 3 points.

If they do a graph or calculate ratios give them 4 points.
Gas Pressure and Volume Relationship

*With prompt Key*

1. Obtain a pressure-measuring device, a Labquest and Vernier Pressure Sensor, and Vernier Sensor adaptor depending on which type of Vernier Pressure Sensor you choose.

2. Attach the Vernier Pressure Sensor to one of the "channels" on the edge of the Labquest, using the adaptor if necessary.

3. On the Labquest, select the corresponding "channel." One of the headings will read "Sensor." Click that and scroll down to the "Gas Pressure" sensor option.

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5. Obtain a 20-mL syringe. Move the plunger to a volume reading of about 10 mL.

6. Before you attach the syringe to the sensor, turn the blue lever so that it points toward the sensor box, Figure 1 A. This connects the vent port and the syringe port, which are perpendicular to each other.

7. With the innermost black plastic sealing disk even with the 10 cc mark, attach the syringe to the sensor by turning the syringe in a clockwise direction so its threaded end screws onto the short syringe port, parallel to the injection tube, as illustrated in Figure 1B.
8. Now turn the blue plastic lever so it points to the vent port, Figure 1C (measure position). Do not move the vent port lever. Keep it in the measure position. You may use the 10 mL volume as your first measurement.

9. Observe and record the volume and pressure of trapped air in the Syringe at five different volumes between 3 and 19 mL. Move and hold the syringe plunger until the pressure reading stabilizes.

10. Record your data in the table below.

<table>
<thead>
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<td>18.3</td>
<td>0.055</td>
</tr>
</tbody>
</table>

1 point for completely filled in data. They will not have gone over significant figures yet and may be able to measure to different significant figures depending on the object. (You can use the numbers you collected to have a better idea of data points).

11. On the grid below, construct a plot of pressure versus volume. Pressure will go on the y-axis and volume on the x-axis.

1 point
They need to have points on the graph with labels on the correct axes based on the direction given in #11.

12. On the grid below, construct a plot of pressure versus 1/volume. Pressure will go on the y-axis and 1/volume on the x-axis. **Add these calculations to the table above.**
They need to have points on the graph with labels on the correct axes based on the direction given in #12.

13. Determine the equation of the line for the pressure versus 1/volume plot.

They should have something resembling $y = mx + b$.

14. Use words to describe the meaning of your algebraic equation.

This is a linear relationship that shows how pressure increases proportionally with the inverse of volume. The $y$-intercept is zero because if you have zero volume you will have zero pressure. Pressure is proportional to the inverse of volume. Multiplying pressure and volume will give a constant of 7500.

1 points:
Give them points for having some explanation about the equation, anything that describes both increasing, proportional, etc. Basically, these are points for trying as long as it makes sense for their equation.
Appendix L – Instructional Treatments

Active Construction; Passive Interpretation; Worked Example

All three instructional treatments are presented below.
**AE**

Name: ___________________________ First ___________________________

Today's date: ___________________________ Section # ____________

Lab TA ________________________________________________

**Instruction:**

The purpose of this lesson is to support your ability to work with graphs. Please read the following information carefully and follow the instructions.

**Graph terms:**

*Ordered pair:* lists the domain and range of data, \((x, y)\).

*Axes:* the number lines that denote the coordinate plane in which your data occurs.

*Scatter plot:* graph that relates two sets of data by plotting as ordered pairs; used to determine a relationship between the two sets of data if one set of data depends on the another set.

*Independent variable:* The variable representing a set of data that may be the reason for variation in the dependent variable. This is usually a parameter the researcher has control over. It is placed on the x-axis.

*Dependent variable:* The variable representing a set of data that is dependent on the other set of data. This represents the outcome of the variation being studied. It is placed on the y-axis.

*Line of best fit:* A straight line drawn through a set of data points on a scatter plot. It is meant to average all the data points and shows how the two variables are related. It is used to identify trends.

*Slope:* The average rate of change between two points on the line of best fit; \(m\) in \(y = mx + b\); \(m = \frac{\Delta y}{\Delta x} = \frac{(y_2 - y_1)}{(x_2 - x_1)}\)

*y-intercept:* the y-coordinate where the line of best fit crosses the y-axis; \(b\) in \(y = mx + b\)

**Graph problem 1:**

Students turned a large cog to see its affect on a small cog. They collected data for the number of turns on each cog, seen in the table below. Determine the relationship between the number of small cog turns versus large cog turns.

![cogs.png](http://1.bp.blogspot.com/-PKNsZj7NINs/Ta1x1EVkxjI/AAAAAAAACiU/7KY_y1c/i600cours.png)
The term "relationship" indicates that this problem can be solved with a graph.

Graph the data:
1. Determine which variable belongs on the x and y-axes—the independent and dependent variables. Label the axes with the names and units of the variables.

2. Scale both axes based on the data—start at 0 for both axes and maintain equal intervals. Use as much of the graph grid as possible.

3. Plot the ordered pairs.

From this you can express the linear relationship with \( y = mx + b \).

4. Determine if the ordered pair of \((0, 0)\) makes sense as a point for the graph. If you have zero of one would you have zero of the other?
5. Add a line of best fit, averaging all of the data points. If (0,0) does make sense as a point make the line go through that point and use zero as your y-intercept (b). Hold the end of the ruler, or straight edge, at that point and adjust the other end of the ruler to have close to an equal number of data points on both sides of the line.

6. Calculate the slope (m) of the line using two points directly on the line, not original data points unless they fall on the line.

\[ m = \frac{\Delta y}{\Delta x} = \]

7. Write a complete expression to describe the relationship between cogs. Use the axes' names rather than the variables x or y, of the algebraic equation \( y = mx + b \) you found. Fill in numbers for (m) and (b) appropriately.

Graph problem 2:

Students wanted to investigate the effect of pressure on temperature of a fixed quantity of gas at a constant volume. Determine the relationship of pressure versus temperature given the data collected below.

The term "relationship" indicates that this problem can be solved using a graph.

*Hint:* you may refer to the previous example of problem representation

<table>
<thead>
<tr>
<th>Pressure (torr)</th>
<th>Temperature (K)</th>
<th>Pressure (torr)</th>
<th>Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>20</td>
<td>700</td>
<td>220</td>
</tr>
<tr>
<td>250</td>
<td>80</td>
<td>200</td>
<td>60</td>
</tr>
<tr>
<td>500</td>
<td>160</td>
<td>450</td>
<td>140</td>
</tr>
</tbody>
</table>
**PE**

Name: ______________________________ First ______________________________

Today's date: ______________________ Section # ______________

Lab TA __________________________________________________

**Instruction:**

The purpose of this lesson is to support your ability to work with graphs. Please read the following information carefully and follow the instructions.

**Graph terms:**

*Ordered pair:* lists the domain and range of data, (x, y).

*Axes:* the number lines that denote the coordinate plane in which your data occurs.

*Scatter plot:* graph that relates two sets of data by plotting as ordered pairs; used to determine a relationship between the two sets of data if one set of data depends on the another set.

*Independent variable:* The variable representing a set of data that may be the reason for variation in the dependent variable. This is usually a parameter the researcher has control over. It is placed on the x-axis.

*Dependent variable:* The variable representing a set of data that is dependent on the other set of data. This represents the outcome of the variation being studied. It is placed on the y-axis.

*Line of best fit:* A straight line drawn through a set of data points on a scatter plot. It is meant to average all the data points and shows how the two variables are related. It is used to identify trends.

*Slope:* The average rate of change between two points on the line of best fit; m in 

\[ y = mx + b; \quad m = \frac{\Delta y}{\Delta x} = \frac{(y_2 - y_1)}{(x_2 - x_1)} \]

*y-intercept:* the y-coordinate where the line of best fit crosses the y-axis; b in 

\[ y = mx + b \]

**Graph problem 1:**

Students turned a large cog to see its affect on a small cog. They collected data for the number of turns on each cog. To determine the relationship between the number of small cog turns versus large cog turns they graphed the data seen below. They found that # of turns for small cog = 5 x # of turns for large cog (y = mx + b).
The term "relationship" indicates that this problem can be solved using a graph.

How did they know which variable to put on the x-axis?

How did they know which variable to put on the y-axis?

How did they determine the slope (m) of the line? Show a possible calculation below.

Why is there no y-intercept (b) in the equation they determined to express the relationship between cogs?
Graph problem 2:

Students wanted to investigate the effect of pressure on temperature of a fixed quantity of gas at a constant volume. Determine the relationship of pressure versus temperature given the data collected below.

The term "relationship" indicates that this problem can be solved using a graph.

*Hint:* you may refer to the previous example of problem representation

<table>
<thead>
<tr>
<th>Pressure (torr)</th>
<th>Temperature (K)</th>
<th>Pressure (torr)</th>
<th>Temperature (K)</th>
</tr>
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<td>250</td>
<td>80</td>
<td>200</td>
<td>60</td>
</tr>
<tr>
<td>500</td>
<td>160</td>
<td>450</td>
<td>140</td>
</tr>
</tbody>
</table>
Instruction:

The purpose of this lesson is to support your ability to work with graphs. Please read the following information carefully and follow the instructions.

Graph terms:

Ordered pair: lists the domain and range of data, (x, y).

Axes: the number lines that denote the coordinate plane in which your data occurs.

Scatter plot: graph that relates two sets of data by plotting as ordered pairs; used to determine a relationship between the two sets of data if one set of data depends on the other set.

Independent variable: The variable representing a set of data that may be the reason for variation in the dependent variable. This is usually a parameter the researcher has control over. It is placed on the x-axis.

Dependent variable: The variable representing a set of data that is dependent on the other set of data. This represents the outcome of the variation being studied. It is placed on the y-axis.

Line of best fit: A straight line drawn through a set of data points on a scatter plot. It is meant to average all the data points and shows how the two variables are related. It is used to identify trends.

Slope: The average rate of change between two points on the line of best fit; m in \( y = mx + b \); \( m = \frac{\Delta y}{\Delta x} = \frac{(y_2 - y_1)}{(x_2 - x_1)} \)

y-intercept: the y-coordinate where the line of best fit crosses the y-axis; b in \( y = mx + b \)

Graph problem 1:

The following worked example shows how a relationship between variables can be determined.

Question:
Students turned a large cog to see its affect on a small cog. They collected data for the number of turns on each cog, seen in the table below. Determine the relationship between the number of small cog turns versus large cog turns.

http://1.bp.blogspot.com/-PKNz77NISv/TzrvLoEVRtI/AAAAAAAAAAC/Ziw7r1K76fU/s1600/cogs.png
Solution:
To determine the relationship the data was graphed as seen below.

\[
\begin{array}{cccc}
\text{Large cog} & \text{Small cog} & \text{Large cog} & \text{Small cog} \\
8 & 40 & 5 & 25 \\
3 & 15 & 7 & 35 \\
6 & 30 & 1 & 5 \\
2 & 10 & 4 & 20 \\
\end{array}
\]

The ordered pair \((0,0)\) was decided to be an appropriate additional point, a line of best fit was added, and the slope \((m)\) calculated.

\[
m = \frac{\Delta y}{\Delta x} = \frac{40 - 0}{8 - 0} = 5
\]

Answer: # of turns for small cog = \(5 \times \) # of turns for large cog
Graph problem 2:

Students wanted to investigate the effect of pressure on temperature of a fixed quantity of gas at a constant volume. Determine the relationship of pressure versus temperature given the data collected below.

Hint: you may refer to the previous example of problem representation

<table>
<thead>
<tr>
<th>Pressure (torr)</th>
<th>Temperature (K)</th>
<th>Pressure (torr)</th>
<th>Temperature (K)</th>
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</tr>
<tr>
<td>500</td>
<td>160</td>
<td>450</td>
<td>140</td>
</tr>
</tbody>
</table>
Appendix M – Teacher Assistant Training

For the research over the course of the semester to run as smoothly as possible all the teacher assistants (TA’s) had to be trained to be aware of the research and how to assist in the research and work with the students.
TA Training

Introductions

I am a graduate student in Chemical Education. My research is to investigate students' ability to transfer their math graphing skills into a chemistry context. To achieve this I will be administering several assessments during the first three weeks of lab – scientific reasoning (CTSR), basic graphing skills (TOGS), prior chemistry content knowledge (CCI), intelligence (SPM+), ability to extract learning objectives from a textbook example (TRP), demographic information including prior high school experiences, and a test of transfer (ToG) (pre- and post-).

In addition, I will be using portions of student lab reports that deal with graphs and a purposefully composed lab question that will go on each exam.

This is all mapped out, with expected times as well, in Table 2 below.

Your roles as teaching assistants in each of these portions will also be explained in detail below.

Data collection will only take one semester.

In order to do any human research the research plan must be presented to the Institutional Review Board (IRB). They review the research objectives and methods to make sure everything is ethical and that the benefits of the research outweigh any risks. For this research there are no anticipated benefits or risks to the students although potentially great benefits for the field of Chemical Education. The purpose of this research is to investigate the phenomenon of transfer so future students could potentially benefit.

IRB consent will have to be obtained from students at the beginning of the first week of lab for permission to use their grades confidentially. This means that I will use their grades on the data collection methods to conduct comparisons and determine relationships, but names will never be used in publications or my dissertation.

Course layout

Week 1

7. The lab coordinator (Dr. Adams) will discuss the lab in general and materials needed.

   He will also announce that:
   • Students must use pens during lab.
   • If they need to graph anything, they are to use the graph paper provided that will be placed on both sides of the lab.
   • All labs will be conducted individually.

   He will introduce me and explain that I will be conducting research this semester.

8. I will explain some of the details of the research and read the IRB consent form to the students. If students do not choose to participate in the research they will be given an alternate option – Read a provided research article and write a report on several questions that I provide.
After I explain the alternate option the IRB consent forms will be handed out and I will leave
the room while they sign or do not sign. They need to sign the IRB consent form if they agree
to participate. They will turn the consent forms in up front and one of you will have to come
get me when they are done.

9. We will conduct several assessments: scientific reasoning, basic graphing skills, and
extracting the learning objective from a textbook passage. These should take 35 minutes, 35
minutes, and 10 minutes.

I will have all the materials for the assessments and will oversee their administration. You
will be expected to help pass out the materials and enforce quiet among your students.
Students need to remain seated and study quietly if they finish any of the instruments with
time remaining. They have a tendency to whisper but whispers carry easily and are disruptive
so please enforce quiet.

10. After completion of the assessments the students will conduct two mini-labs.

The first component will ask students to develop a personal unit of measure, based on each
student's wrist size, and investigate how that unit of measure relates to centimeter units of
measure. They will be asked to describe the relationship pattern observed.

The second component is the relationship of pressure and volume of a fixed amount of air at
constant temperature.

**We want to make sure we do not cue the students on anything related to graphing
construction or interpretation. Please do not use the terms directly proportional or inversely
proportional.

Half of the students will start with the personal unit of measure lab and half the pressure vs.
volume lab to ensure enough materials are available. Students may need help setting up the
Labquest used for the pressure vs. volume lab but otherwise should not require much
direction beyond the lab worksheets.

The labs will not be part of the regularly-used lab material. I created these for the purpose of
my research.

I will provide copies of both parts of the measurement lab to you at the beginning of the lab.

Materials for the personal unit of measure component and stacks of graph paper will also be
provided.

Laboratory sections will be given worksheets that ask one of the two questions below. The
questions will be the same for both lab components depending on which section you TA.

1. What are the patterns shown?

2. On the grid(s) below, construct a plot of your data. Determine the equation of the line.
   Use words to describe the meaning of your algebraic equation.
For question 2 graphing grids will be provided on the laboratory worksheets and will be used as a control to determine how students' will construct the algebraic expression and explain the physical relationships observed.

For the broader question 1 we are investigating:

1. Whether or not students construct a graph.
2. If students construct a graph, are the scales appropriate? Are axes appropriate? Is a line of best fit drawn to show the algebraic expression? Is 0,0 used as the y-intercept?
3. If students have constructed the algebraic expression, do they interpret that expression to describe the physical relationship being represented?

Due to the nature of this research, two aspects that you, the teaching assistants, will need to be diligent about:

1. Students will need to work individually on labs.
2. In regard to graphing questions, you must not provide specific help.

These are explained in more detail below.

1. Students will work individually on all labs. This means data collection and answering questions. This needs to be enforced so that the resulting lab report is a measure of individual’s thought processes rather than that of a group.

You will need to state this expectation to the students at the beginning of the first lab where they will be collecting data. Just remind them to work individually because the lab coordinator will have already told them once.

Data Collection

While students are collecting data they must set up their own station and collect their own data. You cannot control everything and do not need to. You are one TA for a section of 24 students. For example, if students look at neighbors instrument setups to see how to connect pieces or ask their neighbor for setup help while you are helping someone else that is ok. That said you are expected to walk around your lab area and initiate questions to students to inquire if they need help with anything. You are there to assist and support students in such a way that they feel comfortable asking for your help. This does not mean you have to give them all the answers, but you need to be approachable.

For example, if a student asks where certain equipment is in the lab, tell them and point it out. If they ask specifics, such as, "Are we supposed to use the lid on the crucible while we heat the hydrates?" tell them the answer. Answers to questions like that can also be addressed to the entire group if you feel that it will be a common question. That will also help reduce the amount of collaboration between neighbors.

If students are unsure how to set up their ring stand, or other equipment, you can guide them while they work to set it up themselves. Do not do the work for them but absolutely assist them. If students cannot seem to get something to work and you have seen them try, step in to trouble shoot. Sometimes the flames on the Bunsen burners are hard to adjust or they do not understand how to set up the Labquest devices so you may have to show the students.
Examples for situations where answers should not be directly given are typically in regards to the data they are collecting rather than the mechanics of how to do the collecting. Often students will be making qualitative observations before they collect quantitative data and may want you to tell them what they are observing. They could say "Am I supposed to be seeing anything? Nothing's happening" and you can guide them to look more closely or wait longer: "Really? You don't see anything? Look again, tell me if there is anything different from when you started." This could be a tiny amount of bubbles forming at the bottom of a beaker with clear solution in it, for example. Often, questions arise when students expect a dramatic or obvious change, when in reality the observations are often subtle. We will discuss in more detail what students should be observing prior to each lab during our TA meetings. That way you will be prepared for specific potential questions.

Sometimes, students really are not observing what should be happening. This occurs usually when they mixed the wrong solutions, wrong concentration of solutions, or set up the experiment wrong. In those cases you will need to ask questions about what they did exactly to try to help them determine where the mistake occurred. Keep in mind mistakes are ok. That is how we learn. If a student is not seeing something you can acknowledge it, acknowledge them, and help them trouble shoot. For example, "Huh, you are correct. I don't see anything happening either. Let's look at the directions and make sure no steps were missed." From there you can either ask them about the steps they were supposed to take or have them read through the directions while you are present and see if they can determine what was missed.

Data Analysis

While students are working on the questions from the lab they need to do this individually as well. Have them remain at their lab station after they finish collecting their data and clean it. If they want to go to the shared space in the center of the lab make sure they are only one or two to a table and are not collaborating. If they have questions tell them to raise their hands and you will come over as soon as you can.

2. Do not provide students with the answers to their lab report questions. You may guide them and ask leading questions for the most part. However, if students have questions about the graphing portions do not lead them. You will need to be noncommittal.

For example, students may ask questions about the qualitative observation questions like, "Is this ok? Is this what the question is looking for?" You can read what they have written and if it is on track let them know. If they are missing something you can point out the portion of the question they still need to address. Do not tell them explicitly what they should put down. The same will be true for questions about their quantitative data. They will often have questions about the data analysis and conclusion portions. If they ask something about "What am I supposed to be relating?" or "What variable am I supposed to put where?" reread the prompt in the lab book to them or ask them to read it and tell you what they think it means. It typically says "What are the patterns shown?" so you can read that and encourage them to do their best to answer based on what they observed in both their qualitative and quantitative data collection. If students ask "I think I should plot the data and determine the line of best fit, what do you think?" you can respond noncommittally. Students will often be watching your non-verbal cues as well with a question like this. For example, a small smile or shrug can cue them that they are on the right track, so try to maintain neutral features. You can say something like "Do your best and go with whatever you think will answer the question."
Another common question is about the "mental model" question. Students do not often understand what is expected of them for this question. If they ask "What do you want here?" explain that they are supposed to draw some picture that describes what they observed but at the particulate level. Students may struggle with that explanation even but again, encourage them to do their best. They need to learn to think about what they observe in lab and what it means. If you give them answers they are no longer required to think; you need to guide them in such a way to encourage their own thinking while providing some emotional support so they do not get so frustrated they shut down.

Week 2

1. Three assessments will be given at the beginning of lab: intelligence, prior content knowledge, and demographics. These will take 60 minutes, 25 minutes, and 20 minutes. If students finish early they must stay seated and work quietly by themselves.

2. Students will be given an instructional treatment. This will be a worksheet either: (a) describing how to work through graphing construction mathematically, or (b) describing a chemistry analogy of data collection that works through the construction of a graph, or (c) describing a chemistry analogy with no mention of graphs. While reading the worksheet, students will be asked to highlight what they focus on and explain why. This is expected to take about 40 minutes.

These treatments will be given to lab sections as described in Table 1 below.

<table>
<thead>
<tr>
<th>Laboratory Section</th>
<th>Laboratory Time</th>
<th>Version 1 Active</th>
<th>Version 2 Passive</th>
<th>Version 3 Worked</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wednesday 8 am – 11 am</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Wednesday 8 am – 11 am</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Wednesday 11 am – 2 pm</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Wednesday 3 pm – 6 pm</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>5</td>
<td>Thursday 8 am – 11 am</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Thursday 8 am – 11 am</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>7</td>
<td>Thursday 1 pm – 4 pm</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Thursday 1 pm – 4 pm</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>9</td>
<td>Friday 8 am – 11 am</td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

Table 1. Breakdown of instructional treatment across laboratory time and teaching assistant.

3. The lab coordinator will finish the time in lab with safety instructions. The students will sign a lab safety awareness document.

Week 3

1. Students will be given a graphing transfer instrument. Students will take 60 minutes.

2. Students will check into their lab drawers, which will take about 30 minutes.

3. They will then begin the Hydrates lab. This will be modified so each student will collect only one quantitative data point. Each student will pick a mass from a hat or other container before beginning the lab. I will provide the masses on slips of paper and have them in containers for you.

After the quantitative portion of the lab the students will all write their data points on the board so students can write down four or five more points from the class.
For subsequent labs I will be collecting the data analysis questions from student lab reports. One question on each of the four midterm exams will also be used for this research. A post measure of the transfer instrument, Test on Graphs, will also be given the last week of class.

**Grading**

You will not be required to do any grading on the assessments. I will do that.

*Lab Reports*

For lab reports please bring them to my office, CHEM 101A, and turn them all in to me after you collect them from your students. If I am not in my office when you come to drop them off I will have a box on my desk where you can place them. In either case please have all of your students' lab reports in a clearly marked folder so they stay organized.

I will need to photocopy the data analysis section for those students who signed the IRB consent form. I will return them to you in person within 24 hours so you may still have a week to grade them.

For the reports in general, you will be provided a grading key from the lab coordinator. On the data analysis questions you will grade leniently, in such a way as to provide equal point opportunity to students despite what instructional treatment they had. This will be explained further on the grading keys for each lab.

*Exams*

The exam question created for this research, one per exam, will also need to be photocopied. Exams take place on Thursday evenings and must be graded by Sunday afternoon. I will photocopy the exams Thursday night and they will be available by Friday morning, 12 am, to grade.

On exams the course instructor will provide you grading keys.

**Today: Thursday, August 25th**

Today we are going to role-play. I will be the TA and you will pretend you are students taking this course. You will each do the labs that the students will be conducting their first week.

I will then have you read through the instructional treatment.

Afterwards you will grade your peer's lab reports who were role playing as freshmen entering general chemistry. I will provide you with a grading rubric. Afterwards we will discuss any questions you have. This will allow you to really understand what the students will be going through, understand the grading expectations, and prepare you to face the first week confidently.

**Course overview**

Below is an outline of each week of lab throughout the semester. It includes what experiment will be conducted along with a brief description of that experiment. The assessments we will be administering and/or collecting each week are also listed along with expected times for each. All data analysis questions and exam questions listed in the assessments column are part of the
regular laboratory or lecture portions of the course and will not take extra time from you or the students.

<table>
<thead>
<tr>
<th>Week</th>
<th>Experiment</th>
<th>Description</th>
<th>Order of the Week + Assessments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Measurement Lab</td>
<td>Two-parts: 1) Direct relationship between two units of measure – 40 min 2) Inverse relationship between pressure and volume of a fixed amount of air at constant temperature – 40 min</td>
<td>Logistics – 10 min IRB explanation &amp; consent – 15 min CTSR – 35 min TOGS – 35 min TRP – 10 min</td>
</tr>
<tr>
<td>2</td>
<td>Instructional Treatments</td>
<td>Worksheets that provide instruction either for math graphing, graphing with a chemistry example, or a chemistry example with no graphing – 40 min</td>
<td>SPM+ – 60 min CCI – 25 min Demographics questionnaire – 20 min Instructional Treatment Safety</td>
</tr>
<tr>
<td>3</td>
<td>Hydrates lab</td>
<td>Heat hydrated copper(II) sulfate to obtain the anhydrous compound and explore the mass relationships found</td>
<td>Test on Graphs – 60 min Data analysis questions</td>
</tr>
<tr>
<td>4</td>
<td>Precipitates lab</td>
<td>Explore double displacement reactions, determine identity of the precipitate, and gain conceptual understanding of particulate-level interactions</td>
<td>Exam 1 question</td>
</tr>
<tr>
<td>5</td>
<td>Zinc &amp; Hydrochloric Acid lab</td>
<td>Investigate the reaction between zinc and hydrochloric acid, what products are created, learn how to do a titration, and from the data, determine the relationships that exist between zinc and hydrochloric acid</td>
<td>Data analysis questions</td>
</tr>
<tr>
<td>6</td>
<td>Dissolution Reactions</td>
<td>Study the relationship of amount of heat transferred given different chemical reactions and quantify with magnesium sulfate reaction</td>
<td>Data analysis questions</td>
</tr>
<tr>
<td>7 – 8</td>
<td>Open Inquiry: Mass Relationships</td>
<td>Investigate a system of choice. Students develop the entire experiment, collect the data, and analyze their results</td>
<td>Data analysis results, Exam 2 question</td>
</tr>
<tr>
<td>9</td>
<td>Chemical Properties</td>
<td>Explore chemical properties of various metals with acids and bases</td>
<td>None</td>
</tr>
<tr>
<td>10</td>
<td>Poster Presentation</td>
<td>Students present their Open Inquiry: Mass Relationships results via a poster presentation to the class</td>
<td>Exam 3 question</td>
</tr>
<tr>
<td>11</td>
<td>Molecular Structure</td>
<td>Study the configurations of chemical compounds using molecular modeling kits</td>
<td>None</td>
</tr>
<tr>
<td>12</td>
<td>Open Inquiry: Heat Laws</td>
<td>Investigate a system of choice. Students develop the entire experiment, collect the data, and analyze their results</td>
<td>Data analysis results</td>
</tr>
<tr>
<td>13</td>
<td><strong>Thanksgiving</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Open Inquiry: Heat Laws</td>
<td>Continuation of system exploration</td>
<td>Exam 4 question</td>
</tr>
<tr>
<td>15</td>
<td>Poster Presentation</td>
<td>Students present their Open Inquiry: Heat Laws results via a poster presentation to the class</td>
<td>Post: Test on Graphs – 60 min Check out – 30 min</td>
</tr>
</tbody>
</table>

Table 2. Overview of the course. Note: The Friday of week 11, November 11th, there are no classes due to Veteran’s Day. Finals occur the 17th week with class only on Monday, December 12th the 16th week.
Appendix N – Interview Protocol

Graphing Skill Transfer between Math and Chemistry
Dissertation

Date: ___________, 2016    Start Time: _____ (am / pm) End Time: _____ (am / pm)
Male: ___    Female: ___
Participant Code: ________________________    Interview #: ______
College Standing: ________________________
Setting: _____________________________________

Opening Statements:

Thank you for agreeing to take time from your busy schedule to participate in this research study. There are a few things that I would like to make sure you understand before we get started.

• I will be asking you some general questions, recording audio of the interview, and writing notes as we proceed.
• All information from this interview will be confidential. Your name, location, or college standing in this study, or in any report from this study, will not identify you.
• You will only be identified as "________" in these notes. A confidential subject code will be used to identify you for any follow up questions.
• No direct quotes from you will be used in the study without your prior permission. When quoted, your identity, location, and college standing will remain confidential.
• Your name will only be known by me. All other reviewers and researchers in this study will only have access to your Participant Code that cannot be traced to your identity.
• The confidentiality of your name and college standing is protected under the purview of the Institutional Review Board at The University of Montana.
• You may stop this interview at anytime without any negative consequences.
• Before I ask you the interview questions we will go over the Institutional Review Board consent form, which requires your signature.

Please be assured that there are no incorrect answers to the questions that I will be asking. What is important to us are your thought processes. The intent of this interview is to understand your thought processes and not to make judgments on your responses.
Appendix O – Interview Questions

Graphing Skill Transfer between Math and Chemistry
Dissertation

Show math table
What do you think when you see this table?

How about calculations? What sort of calculations might you imagine being done with these?

How about relationships between the values? Why might you look for any?

How would you look for them?

How might a graph look with this data?

What would make you think a table of data should be graphed?

Show chemistry table
What stands out to you on this table?

What sort of calculations might you be asked to do?

What sort of relationships might exist between the variables?

Would a graph be useful to use with this data? Why or why not?

*What would a graph show you about this data? (ask if need to)
What aspects of a table do you look for that clues you in that something should be graphed versus just getting the principle from the table?

What do you see as the purpose of a graph? Why?

Do you personally find graphs useful?

When you were in lab how often did you find you were working with variables that were related to one another?

What made you realize the values were related?

*How did you decide to show those relationships? (ask if need to)

Have you had an experiment where you envisioned solving it with a graph right away or did you need to be prompted? Why?

Show graph w non-zero intercept
How would you go about solving the equation of this line?

Can you guide me through your thought process on how you decided on that?

What about the y-intercept?
Show math graph
Is there a relationship between these variables?
Can you guide me through your thought process on how you decided on that?
How would you go about determining a relationship on a graph like this?

Show chemistry graph
Is there a relationship between these variables?
Can you guide me through your thought process on how you decided on that?
How would you determine the relationship that exists here?

*Can you guide me through your thought process on how you decided on that? (ask if need to)
What are the names of the mathematical tools you are using to do that?
So what is the relationship here? Go ahead and calculate it, and try to explain to me everything you are doing as you go. Just think out loud.

Was there anything in this class that helped you be able to use these tools? Please explain.
Tables and Figures Used During the Interview

Table O1

Math Table Used in the Interview

<table>
<thead>
<tr>
<th>x</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>2.35</td>
</tr>
<tr>
<td>2.00</td>
<td>4.70</td>
</tr>
<tr>
<td>3.00</td>
<td>7.05</td>
</tr>
<tr>
<td>4.00</td>
<td>9.40</td>
</tr>
<tr>
<td>5.00</td>
<td>11.75</td>
</tr>
</tbody>
</table>

Table O2

Chemistry Table Used in the Interview

<table>
<thead>
<tr>
<th>Amount HgO (mol)</th>
<th>Amount Hg (mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0042</td>
<td>0.0035</td>
</tr>
<tr>
<td>0.0060</td>
<td>0.0050</td>
</tr>
<tr>
<td>0.0074</td>
<td>0.0070</td>
</tr>
<tr>
<td>0.0115</td>
<td>0.0130</td>
</tr>
<tr>
<td>0.0143</td>
<td>0.0140</td>
</tr>
</tbody>
</table>

Figure O1. Graph with a non-zero intercept, used in the interview.
Figure O2. Math graph used in the interview.

Figure O3. Chemistry graph used in the interview.
Appendix P – Alternative Instruction Option

For those students who did not want to participate in the research an alternative instructional option was required that would offer them another way to learn the material that the instructional treatment would allow.

CHMY 141
Autumn 2016

Alternative Instructional Option to Replace Research Participation
Due September 14th, 15th, or 16th 2016

Dependent on which day your laboratory class takes place. You will have one week to complete this assignment.

Read the article Functions, Graphs, and Graphing: Tasks, Learning, and Teaching by Leinhardt, Zaslavsky, and Stein (1990) and answer the following questions:

a) Explain how graphs and functions are related: Compare and contrast both and describe why each is necessary for the other.

b) Describe each perspective – tasks, learning, and teaching – in regards to graphing, that Leinhardt et al. (1990) discusses. Outline the aspects for each, explain each aspect, and discuss how they relate across perspectives.

c) Discuss the difference between mathematical and scientific presentations of graphs. Explain experiences you have had with both presentations along with difficulties you have had with either and successes with both.

d) Discuss methods of teaching graphing that have helped you or hindered you. Relate them to aspects of learning and teaching from the article.

Submit your responses typed, double-spaced, and approximately 5-10 pages.
Appendix Q – Data from R

The following data is not included in the body of the text but matches the data from SPSS that is. Some of the code used in R is also included here. Any graphs from R that are already in the body of the text will not be included here, unless accompanied by code. The portions of data that are highlighted show some of the important data that matches that in SPSS. When data falls under a heading of “Quick R data” it means that code and direction were gleaned from Quick–R online rather than a textbook.

Q1: Is there a difference between Transfer Index based on Transfer Category (MP vs. ME)?

Q1data
tcategory N mean sd se
1 ME 160 42.7000 21.52833 1.701964
2 MP 160 39.5625 24.32166 1.922796

Quick R data:
Paired t-test
#data: Q1redo$MP.TI and Q1redo$ME.TI
#t = -2.6592, df = 159, p-value = 0.008635
#alternative hypothesis: true difference in means is not equal to 0
#95 percent confidence interval:
# -5.4677428 -0.8072572
#sample estimates:
#mean of the differences
# -3.1375

Q2: Is Scientific Accuracy on exam 1 a function of Transfer Index Score and Transfer Category?

> SAxC : Scientific Accuracy for Exam 1
#Tcategory N mean sd se
#1 ME 149 3.805369 2.015742 0.165136
#2 MP 149 3.805369 2.015742 0.165136

TISxC<-ddply(Q2, c("Tcategory"), summarise,
N = length(TIScore),
mean = mean(TIScore),
sd = sd(TIScore),
se = sd/sqrt(N))

#> TISxC : Transfer Index Score
#Tcategory N mean sd se
#1 ME 149 42.90604 21.56365 1.766563
#2 MP 149 39.82550 24.47192 2.004818
Quick R data:

```r
corr(as.matrix(Q2data))
```

```
#             SciAcc Math.Physics Math.Econ
#SciAcc         1.00         0.20      0.15
#Math.Physics   0.20         1.00      0.78
#Math.Econ      0.15         0.78      1.00

#n= 149

P

```

```
#             SciAcc Math.Physics Math.Econ
#SciAcc               0.0137       0.0666
#Math.Physics 0.0137               0.0000
#Math.Econ    0.0666  0.0000
```

Quick R data:

```r
anova(fit)
```

```
#Analysis of Variance Table
#Response: SciAcc
#              Df Sum Sq Mean Sq F value Pr(>F)
#Math.Physics  1  24.44  24.4446  6.1871 0.01399 *
#Math.Econ    1   0.09   0.0856  0.0217 0.88320
#Residuals   146 576.83  3.9509
```

`---

# Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

```r
fit<-lm(SciAcc ~ Math.Physics + Math.Econ)
```

```r
summary(fit)
```

```
#Call:
#  lm(formula = SciAcc ~ Math.Physics + Math.Econ)
#Residuals:
#    Min      1Q  Median      3Q     Max
#-4.6913 -1.3803 -0.3588  1.4271  5.8279

#Coefficients:
#              Estimate Std. Error t value Pr(>|t|)
#(Intercept)   3.171637   0.364029   8.713 5.94e-15 ***
#Math.Physics  0.017848   0.010756   1.659   0.0992 .
#Math.Econ    -0.001796   0.012207  -0.147   0.8832
```

`---

# Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

#Residual standard error: 1.988 on 146 degrees of freedom
#Multiple R-squared:  0.04079, Adjusted R-squared:  0.02765
#F-statistic: 3.104 on 2 and 146 DF,  p-value: 0.04782

283
R data:

ggplot(Q2, aes(x=TIScore, y=SA1, group=Tcategory, color=Tcategory)) +
  geom_point(shape=1, position = position_jitter(width = .5, height = .5)) +
  geom_smooth(method = lm, se=FALSE, size=.4) +
  xlab("Transfer Index Score") +
  ylab("Scientific Accuracy") +
  ggtitle("Scientific Accuracy on Exam 1 based on Transfer Index Score and Transfer Category") +
  scale_y_continuous(breaks = seq(0, 11, 1))

Q3: Is Scientific Accuracy a function of Time (Exams 1-3)?

Quick R data:

Q3fit<-aov(Q3$SAScore ~ Q3$Exam+Error(Q3$Name/Q3$Exam), data = Q3)
summary(Q3fit)

# Error: Q3$Name
# Df  Sum Sq Mean Sq  F value   Pr(>F)
# Residuals 132   1013   7.676

# Error: Q3$Name:Q3$Exam
# Df  Sum Sq Mean Sq  F value Pr(>F)
# Q3$Exam     2  107.6   53.78 14.88   7.49e-07 ***
# Residuals 264  953.8    3.61

---
# Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R data:

E3data<-ddply(Q3, c("Exam"), summarise,
  N = length(SAScore),
  mean = mean(SAScore),
  sd = sd(SAScore),
  se = sd/sqrt(N))

E3data

# Exam    N  mean    sd   se
# 1  E1  133 3.977444 2.028084 0.1758572
# 2  E2  133 5.240602 2.243342 0.1945224
# 3  E3  133 4.736842 2.399163 0.2080338

R graph:

?barplot2
barplot2(heights, plot.ci=TRUE, ci.l=lower, ci.u=upper,
  ylim=c(0,11), xpd=FALSE,
  main="Scientific Accuracy by Exam",
  names.arg=c("Exam 1", "Exam 2", "Exam 3"),
  ylab = "Scientific Accuracy Score")
This 2nd graph displays error bars of +/- 1 SE, rather than the 2 from SPSS or the R graph using heights. The following SPSS graph was also adjusted to show +/- 1 SE.

library(ggplot2)
ggplot(E3data, aes(x=Exam, y=mean, colour=Exam)) +
  geom_col(position = "dodge", aes(fill=Exam)) +
  geom_errorbar(aes(ymin=mean-se, ymax=mean+se), colour="black", width=.2, position="dodge") +
  xlab("Exam") +
  ylab("Scientific Accuracy Score")+
  ylim(0,11) +
ggtitle("Scientific Accuracy Score based on Time across Three Exams")

###Heights give same results as means from the ddply summary.
Q4: Is Transfer Index Score a function of high school graphing skills (TOGS) and Transfer Category?

Quick R data:

```r
#> anova(MPmodel)
#Analysis of Variance Table

#Response: Tgroup$MP$Q4.TIScore
#  Df    Sum Sq Mean Sq F value    Pr(>F)
#Tgroup$MP$Q4.TOGS 1   12411 12411.2  23.806 2.622e-06 ***
#Residuals       155   80809   521.4

---
# Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

R data:

```r
MPmodel<-lm(Tgroup$MP$Q4.TIScore ~ Tgroup$MP$Q4.TOGS)
summary(MPmodel)
#Call:
#  lm(formula = Tgroup$MP$Q4.TIScore ~ Tgroup$MP$Q4.TOGS)

#Residuals:
#  Min       1Q  Median       3Q      Max
# -37.084   -17.806    -4.527   13.194   57.194

#Coefficients:
#             Estimate Std. Error t value Pr(>|t|)
# (Intercept)   -44.534    17.332   -2.570  0.0111 *
# Tgroup$MP$Q4.TOGS  3.639     0.746    4.879 2.62e-06 ***
# ---
# Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

#Residual standard error: 22.83 on 155 degrees of freedom
#Multiple R-squared:  0.1331,  Adjusted R-squared:  0.1275
#F-statistic: 23.81 on 1 and 155 DF,  p-value: 2.622e-06
```

Quick R data:

```r
#> anova(MEmodel)
#Analysis of Variance Table

#Response: Tgroup$ME$Q4.TIScore
#  Df    Sum Sq Mean Sq F value    Pr(>F)
#Tgroup$ME$Q4.TOGS 1   12679 12679.0  32.567 5.69e-08 ***
#Residuals       155   60345   389.3

---
# Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```
R data:

MEmodel<-lm(Tgroup$ME$Q4.TIScore ~ Tgroup$ME$Q4.TOGS) # These give the exact same results as how I previously split the Tcategory into groups

summary(MEmodel)
# Call:
#  lm(formula = Tgroup$ME$Q4.TIScore ~ Tgroup$ME$Q4.TOGS)
# # Residuals:
#   Min 1Q Median 3Q Max
# -45.923 -13.567 -1.923 10.468 61.433
# # Coefficients:
#                    Estimate Std. Error t value Pr(>|t|)
#  (Intercept)       -42.3537   14.9772  -2.828  0.0053 **
#  Tgroup$ME$Q4.TOGS  3.6782    0.6445   5.707  5.69e-08 ***
# ---
# Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
# Residual standard error: 19.73 on 155 degrees of freedom
# Multiple R-squared:  0.1736,  Adjusted R-squared:  0.1683
# F-statistic: 32.57 on 1 and 155 DF,  p-value: 5.69e-08

R data:

TI<-ddply(Q4, c("Tcategory"), summarise,
  N = length(TIScore),
  mean = mean(TIScore),
  sd = sd(TIScore),
  se = sd / sqrt(N))

#> TI
# Tcategory  N     mean       sd       se
# 1 ME      157 42.64331 21.63568 1.726715
# 2 MP      157 39.56051 24.44521 1.950940

Togs<-ddply(Q4, c("Tcategory"), summarise,
  N = length(TOGS),
  mean = mean(TOGS),
  sd = sd(TOGS),
  se = sd / sqrt(N))

#> Togs
# Tcategory  N     mean       sd       se
# 1 ME      157 23.10828 2.451006 0.1956116
# 2 MP      157 23.10828 2.451006 0.1956116
```r
ggplot(Q4, aes(x=TOGS, y=TIScore, shape=Tcategory, colour=Tcategory)) +
  geom_point() +
  geom_smooth(method = lm, aes(fill=Tcategory)) +
  xlab("Test of Graphing Skills Score") +
  xlim(0,26) +
  ylab("Transfer Index Score (%)") +
  ylim(0,100) +
  ggtitle("Transfer Index based on High School Level Graphing Skills
and Transfer Category") +
  scale_size_manual(values = c(2,2.5)) +
  scale_x_continuous(breaks = round(seq(min(0), max(Q4$TOGS), by = 2)))
```

![Graph showing transfer index based on high school level graphing skills and transfer category](image)

```r
ggplot(Q4, aes(x=TOGS, y=TIScore, group=Tcategory, colour=Tcategory)) +
  geom_point(shape=1, position = position_jitter(width = .5, height = .5)) +
  geom_smooth(method = lm, se=FALSE, size = .4) +
  xlab("Test of Graphing Skills (TOGS) Score") +
  ylab("Transfer Index Score") +
  ggtitle("Transfer Index based on High School Level Graphing Skills
and Transfer Category") +
  scale_size_manual(values = c(2,2.5)) +
  scale_x_continuous(breaks = round(seq(min(0), max(Q4$TOGS), by = 2)))
```
Q5: Is Transfer Index Score a function of scientific reasoning (CTSR) and Transfer Category?

R data:

MPmodel5<-lm(Tgroup5$MP$Q5.TIScore ~ Tgroup5$MP$Q5.CTSR)
summary(MPmodel5)

# Call:
# lm(formula = Tgroup5$MP$Q5.TIScore ~ Tgroup5$MP$Q5.CTSR)
# Residuals:
#     Min      1Q  Median      3Q     Max
# -41.207 -14.862  -2.954   9.015  57.701
# Coefficients:
#                     Estimate Std. Error t value Pr(>|t|)
# (Intercept)       1.6089     5.5536   0.290    0.772
# Tgroup5$MP$Q5.CTSR 4.7816     0.6682   7.156 3.05e-11 ***
# Residual standard error: 21.23 on 156 degrees of freedom
# Multiple R-squared:  0.2471, Adjusted R-squared:  0.2423
# F-statistic: 51.21 on 1 and 156 DF,  p-value: 3.047e-11

Quick R data: Same results as original R data it seems.

#> Q5<-read.csv("Q5 R setup.csv")
#> dfmQ5<-data.frame(Q5$CTSR, Q5$TIScore)
#> Tgroup5<-split(dfmQ5, Q5$Tcategory)
MPmodel5<-lm(Tgroup5$MP$Q5.TIScore ~ Tgroup5$MP$Q5.CTSR)
summary(MPmodel5)

#Call:
#  lm(formula = Tgroup5$MP$Q5.TIScore ~ Tgroup5$MP$Q5.CTSR)

#Residuals:
#  Min      1Q  Median      3Q     Max
#-41.207 -14.862  -2.954  9.015  57.701

#Coefficients:
#     Estimate Std. Error t value Pr(>|t|)
#(Intercept)  1.6089     5.5536   0.290    0.772
#Tgroup5$MP$Q5.CTSR  4.7816     0.6682   7.156 3.05e-11 ***
#   ---
#  Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

#Residual standard error: 21.23 on 156 degrees of freedom
#Multiple R-squared:  0.2471,  Adjusted R-squared:  0.2423
#F-statistic: 51.21 on 1 and 156 DF,  p-value: 3.047e-11

anova(MPmodel5)

#Analysis of Variance Table
#Response: Tgroup5$MP$Q5.TIScore
#           Df Sum Sq Mean Sq F value Pr(>F)
#Tgroup5$MP$Q5.CTSR   1 23091 23090.8 51.21 3.047e-11 ***
#Residuals        156  70341   450.9
#---
#Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R data:

MEmodel5<-lm(Tgroup5$ME$Q5.TIScore ~ Tgroup5$ME$Q5.CTSR)
summary(MEmodel5)

#Call:
#  lm(formula = Tgroup5$ME$Q5.TIScore ~ Tgroup5$ME$Q5.CTSR)

#Residuals:
#  Min      1Q  Median      3Q     Max
#-39.043 -12.610  -2.759 10.957  54.228

#Coefficients:
#     Estimate Std. Error t value Pr(>|t|)
#(Intercept)   6.367      4.787   1.330  0.185
#Tgroup5$ME$Q5.CTSR  4.568      0.576   7.933 3.94e-13 ***
#   ---
#  Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

#Residual standard error: 18.3 on 156 degrees of freedom
#Multiple R-squared:  0.2873,  Adjusted R-squared:  0.2827
#F-statistic: 62.89 on 1 and 156 DF,  p-value: 3.935e-13

Quick R data: Same results as original R data it seems.

#> MEmodel5<-lm(Tgroup5$ME$Q5.TIScore ~ Tgroup5$ME$Q5.CTSR)
#> summary(MEmodel5)
# Call:
#  lm(formula = Tgroup5$ME$Q5.TIScore ~ Tgroup5$ME$Q5.CTSR)
# Residuals:
#    Min      1Q  Median      3Q     Max
#    -39.043 -12.610  -2.759  10.957  54.228
# Coefficients:
#                   Estimate Std. Error t value Pr(>|t|)
# (Intercept)           6.367      4.787    1.33    0.185
# Tgroup5$ME$Q5.CTSR    4.568      0.576    7.93 3.94e-13 ***
#  Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
# Residual standard error: 18.3 on 156 degrees of freedom
# Multiple R-squared:  0.2873,  Adjusted R-squared:  0.2827
# F-statistic: 62.89 on 1 and 156 DF,  p-value: 3.935e-13
#anova(MEmodel5)

# Analysis of Variance Table
# Response: Tgroup5$ME$Q5.TIScore
#          Df Sum Sq Mean Sq  F value    Pr(>F)
# Tgroup5$ME$Q5.CTSR   1 21070 21070.0 62.8903 3.935e-13 ***
# Residuals          156 52264   335.8
#---
# Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R data:
TI5<-ddply(Q5, c("Tcategory"), summarise,
  N = length(TIScore),
  mean = mean(TIScore),
  sd = sd(TIScore),
  se = sd / sqrt(N))

CTSR<-ddply(Q5, c("Tcategory"), summarise,
  N = length(CTSR),
  mean = mean(CTSR),
  sd = sd(CTSR),
  se = sd / sqrt(N))

#> TI5 : Transfer Index Score
#Tcategory     N  mean     sd   se
#1        ME 158 42.53165 21.61230 1.719382
#2        MP 158 39.46835 24.39476 1.940743
42.53165 + 1.719382 # = 44.25103
42.53165 - 1.719382 # = 40.81227

39.46835 + 1.940743 # = 41.40909
39.46835 - 1.940743 # = 37.52761

#> CTSR
#Tcategory     N  mean     sd   se
#1        ME 158  7.917722 2.536272 0.201775
#2        MP 158  7.917722 2.536272 0.201775
ggplot(Q5, aes(x=CTSR, y=TIScore, shape=Tcategory, colour=Tcategory)) +
  geom_point() +
  geom_smooth(method = lm, aes(fill=Tcategory)) +
  xlab("Classroom Test of Scientific Reasoning Score") +
  ylab("Transfer Index Score (%)") +
  ylim(0,100) +
  ggtitle("Transfer Index based on Scientific Reasoning Skills and Transfer Category") +
  scale_size_manual(values = c(2,2.5)) +
  scale_x_continuous(breaks = round(seq(min(0), max(Q5$CTSR), by = 2)))

Transfer Index based on Scientific Reasoning Skills and Transfer Category

------

ggplot(Q5, aes(x=CTSR, y=TIScore, group=Tcategory, colour=Tcategory)) +
  geom_point(shape=1, position = position_jitter(width = .5, height = .5)) +
  geom_smooth(method = lm, se=FALSE, size = .4) +
  xlab("Classroom Test of Scientific Reasoning (CTSR) Score") +
  ylab("Transfer Index Score") +
  ggtitle("Transfer Index based on Scientific Reasoning Skills and Transfer Category") +
  scale_x_continuous(breaks = round(seq(min(0), max(Q5$CTSR), by = 2)))
Q6: Is Transfer Index Score a function of chemistry misconceptions (CCI) and Transfer Category?

R data:

```R
MPmodel6 <- lm(Tgroup6$MP$Q6.TIScore ~ Tgroup6$MP$Q6.CCI)
summary(MPmodel6)
```

#Call:
# lm(formula = Tgroup6$MP$Q6.TIScore ~ Tgroup6$MP$Q6.CCI)

#Residuals:
#    Min      1Q  Median      3Q     Max
#-44.086 -11.992  -2.613   9.589  63.454

#Coefficients:
#                  Estimate Std. Error t value Pr(>|t|)
#(Intercept)        12.1402     4.0649   2.987  0.00328 **
#Tgroup6$MP$Q6.CCI  4.0676     0.5502   7.393 8.21e-12 ***
#---
# Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

#Residual standard error: 21.12 on 156 degrees of freedom
#Multiple R-squared:  0.2595, Adjusted R-squared:  0.2547
#F-statistic: 54.66 on 1 and 156 DF,  p-value: 8.206e-12

Quick R data: Same results as original R it seems.

```R
MPmodel6 <- lm(Tgroup6$MP$Q6.TIScore ~ Tgroup6$MP$Q6.CCI)
summary(MPmodel6)
```
# Call:
# `lm(formula = Tgroup6$MP$Q6.TIScore ~ Tgroup6$MP$Q6.CCI)`

# Residuals:
# Min 1Q Median 3Q Max
# -44.086 -11.992 -2.613 9.589 63.454

# Coefficients:
# Estimate Std. Error t value Pr(>|t|)
# (Intercept) 12.1402 4.0649 2.987 0.00328 **
# Tgroup6$MP$Q6.CCI 4.0676 0.5502 7.393 8.21e-12 ***
# Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

# Residual standard error: 21.12 on 156 degrees of freedom
# Multiple R-squared: 0.2595, Adjusted R-squared: 0.2547
# F-statistic: 54.66 on 1 and 156 DF, p-value: 8.206e-12

anova(MPmodel6)

# Analysis of Variance Table

# Response: Tgroup6$MP$Q6.TIScore
# Df Sum Sq Mean Sq F value Pr(>F)
# Tgroup6$MP$Q6.CCI 1 24376 24376.1 54.662 8.206e-12 ***
# Residuals 156 69567 445.9
# Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R data:

MEmodel6<-lm(Tgroup6$ME$Q6.TIScore ~ Tgroup6$ME$Q6.CCI)
summary(MEmodel6)

# Call:
# `lm(formula = Tgroup6$ME$Q6.TIScore ~ Tgroup6$ME$Q6.CCI)`

# Residuals:
# Min 1Q Median 3Q Max
# -49.53 -12.46 0.12 11.91 62.78

# Coefficients:
# Estimate Std. Error t value Pr(>|t|)
# (Intercept) 21.3926 3.7390 5.721 5.25e-08 ***
# Tgroup6$ME$Q6.CCI 3.1646 0.5061 6.253 3.68e-09 ***
# Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

# Residual standard error: 19.42 on 156 degrees of freedom
# Multiple R-squared: 0.2004, Adjusted R-squared: 0.1953
# F-statistic: 39.1 on 1 and 156 DF, p-value: 3.684e-09

Quick R data: Same results as original R it seems.

> Q6<-read.csv("Q6 R setup.csv")
> dfmQ6<-data.frame(Q6$CCI, Q6$TIScore)
> Tgroup6<-split(dfmQ6, Q6$Tcategory)
> MEmodel6<-lm(Tgroup6$ME$Q6.TIScore ~ Tgroup6$ME$Q6.CCI)
```r
#> summary(MEmodel6)
#Call:
# lm(formula = Tgroup6$ME$Q6.TIScore ~ Tgroup6$ME$Q6.CCI)

#Residuals:
#   Min     1Q    Median     3Q    Max
#-49.53  -12.46     0.12  11.91  62.78
#Coefficients:
#              Estimate Std. Error t value Pr(>|t|)
#(Intercept)   21.3926     3.7390   5.721 5.25e-08 ***
#Tgroup6$ME$Q6.CCI  3.1646     0.5061   6.253 3.68e-09 ***
# Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

# Residual standard error: 19.42 on 156 degrees of freedom
# Multiple R-squared:  0.2004,  Adjusted R-squared:  0.1953
# F-statistic: 39.1 on 1 and 156 DF,  p-value: 3.684e-09

anova(MEmodel6)

# Analysis of Variance Table
# Response: Tgroup6$ME$Q6.TIScore
#            Df  Sum Sq Mean Sq  F value    Pr(>F)
# Tgroup6$ME$Q6.CCI  1   14755 14754.6 39.10441 3.684e-09 ***
# Residuals      156 58862   377.3
# Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R data:

TI6 <- ddply(Q6, c("Tcategory"), summarise, 
              N = length(TIScore),
              mean = mean(TIScore),
              sd = sd(TIScore),
              se = sd / sqrt(N))

TI6
#> Tcategory  N  mean  sd  se
#1       ME 158 42.68 21.65 1.72
#2       MP 158 39.51 24.46 1.95

42.68 + 1.72 = 44.40
42.68 - 1.72 = 40.96
39.51 + 1.95 = 41.46
39.51 - 1.95 = 37.56

library(ggplot2)
```
ggplot(Q6, aes(x=CCI, y=TIScore, shape=Tcategory, colour=Tcategory)) +
  geom_point() +
  geom_smooth(method = lm, aes(fill=Tcategory)) +
  xlab("Chemical Concepts Inventory Score") +
  ylab("Transfer Index Score (\%)") +
  ylim(0,100) +
  ggtitle("Transfer Index based on Chemical Misconceptions and Transfer Category") +
  scale_size_manual(values = c(2,2.5)) +
  scale_x_continuous(breaks = round(seq(min(0), max(Q6$CCI), by = 2))) +
  theme_bw()

![Graph showing Transfer Index based on Chemical Misconceptions and Transfer Category](image)

ggplot(Q6, aes(x=CCI, y=TIScore, group=Tcategory, colour=Tcategory)) +
  geom_point(shape = 1, position = position_jitter(width = .5, height = .5)) +
  geom_smooth(method = lm, se=FALSE, size = .4) +
  xlab("Chemical Concepts Inventory (CCI) Score") +
  ylab("Transfer Index Score") +
  ggtitle("Transfer Index based on Chemical Misconceptions and Transfer Category") +
  scale_x_continuous(breaks = round(seq(min(0), max(Q6$CCI), by = 2))) +
  theme_bw()
Q7: Is Transfer Index Score a function of intelligence (SPM) and Transfer Category?

R data:
dfmQ7<-data.frame(Q7$SPM, Q7$TIScore)
Tgroup7<-split(dfmQ7, Q7$Tcategory)
MPmodel7<-lm(Tgroup7$MP$Q7.TIScore ~ Tgroup7$MP$Q7.SPM)
summary(MPmodel7)

#Call:
# lm(formula = Tgroup7$MP$Q7.TIScore ~ Tgroup7$MP$Q7.SPM)
#Residuals:
#   Min      1Q  Median      3Q     Max
#  -45.944  -15.252  -3.147    8.247  69.811

#Coefficients:
#                              Estimate Std. Error t value Pr(>|t|)
#(Intercept)                  -44.5744    15.8743  -2.808  0.0056 **
#Tgroup7$MP$Q7.SPM           1.9170     0.3614   5.305  3.7e-07 ***
#---
# Signif. codes:  *** 0.001 ** 0.01 * 0.05 . 0.1  1

#Residual standard error: 22.61 on 160 degrees of freedom
#Multiple R-squared:  0.1496,  Adjusted R-squared:  0.1443
#F-statistic: 28.14 on 1 and 160 DF,  p-value: 3.698e-07

Quick R data: Same results as original R it seems.

> Q7<-read.csv("Q7 R setup.csv")
> dfmQ7<-data.frame(Q7$SPM, Q7$TIScore)
> Tgroup7<-split(dfmQ7, Q7$Tcategory)
> MPmodel7<-lm(Tgroup7$MP$Q7.TIScore ~ Tgroup7$MP$Q7.SPM)
# Call:
#  lm(formula = Tgroup7$MP$Q7.TIScore ~ Tgroup7$MP$Q7.SPM)
# Residuals:
#    Min     1Q   Median     3Q    Max
# -45.944 -15.252  -3.147   8.247  69.811
#
# Coefficients:
#                      Estimate Std. Error t value Pr(>|t|)
# (Intercept)   -44.5744    15.8743  -2.808  0.00561 **
# Tgroup7$MP$Q7.SPM   1.9170     0.3614   5.305  3.7e-07 ***
# Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
#
# Residual standard error: 22.61 on 160 degrees of freedom
# Multiple R-squared:  0.1496, Adjusted R-squared:  0.1443
# F-statistic: 28.14 on 1 and 160 DF,  p-value: 3.698e-07

anova(MPmodel7)
# Analysis of Variance Table
#
# Response: Tgroup7$MP$Q7.TIScore
# Df Sum Sq Mean Sq F value Pr(>F)
# Tgroup7$MP$Q7.SPM   1 14393 14393.3  28.144 3.698e-07 ***
# Residuals         160  81827   511.4
# Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R data:

MEmodel7<-lm(Tgroup7$ME$Q7.TIScore ~ Tgroup7$ME$Q7.SPM)
summary(MEmodel7)
# Call:
#  lm(formula = Tgroup7$ME$Q7.TIScore ~ Tgroup7$ME$Q7.SPM)
# Residuals:
#    Min     1Q   Median     3Q    Max
# -46.830 -14.391  -2.079  11.844  65.484
#
# Coefficients:
#                      Estimate Std. Error t value Pr(>|t|)
# (Intercept)   -31.3008    14.0350  -2.230  0.0271 *
# Tgroup7$ME$Q7.SPM   1.6876     0.3195   5.282 4.11e-07 ***
# Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
#
# Residual standard error: 19.99 on 160 degrees of freedom
# Multiple R-squared:  0.1485, Adjusted R-squared:  0.1432
# F-statistic: 27.9 on 1 and 160 DF,  p-value: 4.112e-07

Quick R data: Same results as original R it seems.

> MEmodel7<-lm(Tgroup7$ME$Q7.TIScore ~ Tgroup7$ME$Q7.SPM)
summary(MEmodel7)
# Call:
#  lm(formula = Tgroup7$ME$Q7.TIScore ~ Tgroup7$ME$Q7.SPM)
# Residuals:
#    Min     1Q   Median     3Q    Max
# -46.830 -14.391  -2.079  11.844  65.484
#Coefficients:
#                  Estimate Std. Error t value Pr(>|t|)
#(Intercept)     -31.3008    14.0350  -2.230  0.0271 *
#Tgroup7$ME$Q7.SPM  1.6876     0.3195   5.282 4.11e-07 ***
# Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

#Residual standard error: 19.99 on 160 degrees of freedom
#Multiple R-squared:  0.1485,   Adjusted R-squared:  0.1432
#F-statistic:  27.9 on 1 and 160 DF,  p-value: 4.112e-07

anova(MEmodel7)
#Analysis of Variance Table
#Response: Tgroup7$ME$Q7.TIScore
#                   Df Sum Sq Mean Sq  F value    Pr(>F)
#Tgroup7$ME$Q7.SPM   1  11155 11154.6  27.903 4.112e-07 ***
#Residuals         160  63963   399.8
#Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R data:

TI7<-ddply(Q7, c("Tcategory"), summarise,
            N = length(TIScore),
            mean = mean(TIScore),
            sd = sd(TIScore),
            se = sd / sqrt(N))

#> TI7 : Transfer Index Score
#Tcategory  N  mean    sd    se
#1 ME   162 42.37037 21.60023 1.697075
#2 MP   162 39.11111 24.44667 1.920712

ggplot(Q7, aes(x=SPM, y=TIScore, shape=Tcategory, colour=Tcategory)) +
  geom_point() +
  geom_smooth(method = lm, aes(fill=Tcategory)) +
  xlab("Standard Matrices Plus Score") +
  ylab("Transfer Index Score (%)") +
  ylim(0,100) +
  ggtitle("Transfer Index based on Intelligence via Pattern Recognition 
           and Transfer Category") +
  scale_size_manual(values = c(2,2.5)) +
  scale_x_continuous(breaks = round(seq(min(Q7$SPM), by = 2))) +
  theme_bw()
ggplot(Q7, aes(x=SPM, y=TIScore, group=Tcategory, colour=Tcategory)) +
  geom_point(shape = 1, position = position_jitter(width = .5, height = .5)) +
  geom_smooth(method = lm, se=FALSE, size =.4) +
  xlab("Standard Matrices Plus (SPM+) Score") +
  ylab("Transfer Index Score") +
  ggtitle("Transfer Index based on Intelligence via Pattern Recognition and Transfer Category") +
  scale_x_continuous(breaks = round(seq(min(0), max(Q7$SPM), by = 2)))

Transfer Index based on Intelligence via Pattern Recognition and Transfer Category

Transfer Index based on Intelligence via Pattern Recognition and Transfer Category
Question 8: MLR: How much do each of the above four independent variables (TOGS, CTSR, CCI, SPM) correlate to Transfer Index Score?

Quick R data:

defMLR<-data.frame(MLR$SPM, MLR$TOGS, MLR$CCI, MLR$CTSR, MLR$TIScore)

TgroupMLR<-split(dfmMLR, MLR$Ticategory)

LMMLR<-	exttt{lm}(TgroupMLR$MP$MLR.TIScore ~ TgroupMLR$MP$MLR.SPM +
TgroupMLR$MP$MLR.TOGS +
TgroupMLR$MP$MLR.CCI +
TgroupMLR$MP$MLR.CTSR)

sum(LMMLR)

# Call:
# lm(formula = TgroupMLR$MP$MLR.TIScore ~ TgroupMLR$MP$MLR.SPM +
#     TgroupMLR$MP$MLR.TOGS + TgroupMLR$MP$MLR.CCI + TgroupMLR$MP$MLR.CTSR)

# Residuals:
#   Min     1Q    Median     3Q    Max
# -41.501  -12.556   -2.369    8.547  55.030

# Coefficients:
#             Estimate Std. Error t value Pr(>|t|)
# (Intercept) -39.7295    18.5869  -2.137  0.03418  *
# TgroupMLR$MP$MLR.SPM.  0.6994     0.3871   1.807  0.07277  .
# TgroupMLR$MP$MLR.TOGS  0.6539     0.8491   0.770  0.44244
# TgroupMLR$MP$MLR.CCI  2.4662     0.6544   3.768  0.00023  ***
# TgroupMLR$MP$MLR.CTSR 2.1337     0.9322   2.289  0.02349  *
# Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

# Residual standard error: 20.1 on 150 degrees of freedom
# Multiple R-squared:  0.3492,  Adjusted R-squared:  0.3318
# F-statistic: 20.12 on 4 and 150 DF,  p-value: 2.789e-13

# Response: TgroupMLR$MP$MLR.TIScore
# Df Sum Sq Mean Sq F value Pr(>F)
# TgroupMLR$MP$MLR.SPM. 1 14083 14082.6 34.8581 2.280e-08 ***
# TgroupMLR$MP$MLR.TOGS 1  4031 4030.6  9.9768  0.001917 **
# TgroupMLR$MP$MLR.CCI 1 12280 12279.5 30.3950 1.502e-07 ***
# TgroupMLR$MP$MLR.CTSR 1  2116 2116.3  5.2383  0.023491 *
# Residuals      150 60600  404.0
# Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Quick R data:

```r
MEmodelMLR<-.lm(TgroupMLR$ME$MLR.TIScore ~ TgroupMLR$ME$MLR.SPM. +
                   TgroupMLR$ME$MLR.TOGS +
                   TgroupMLR$ME$MLR.CCI +
                   TgroupMLR$ME$MLR.CTSR)
```

#> summary(MEmodelMLR)

```
# Call:
#  lm(formula = TgroupMLR$ME$MLR.TIScore ~ TgroupMLR$ME$MLR.SPM. +
#          TgroupMLR$ME$MLR.TOGS + TgroupMLR$ME$MLR.CCI + TgroupMLR$ME$MLR.CTSR)
# Residuals:
#  Min      1Q  Median      3Q     Max
#-42.675 -10.051 -1.285   8.250  57.675
# Coefficients:
#                      Estimate Std. Error t value Pr(>|t|)
# (Intercept)          -33.646  16.4163 -2.050  0.04215 *
# TgroupMLR$ME$MLR.SPM.   0.504    0.3419  1.474  0.14250
# TgroupMLR$ME$MLR.TOGS   1.033    0.7500  1.378  0.17038
# TgroupMLR$ME$MLR.CCI    1.345    0.5780  2.327  0.02128 *
# TgroupMLR$ME$MLR.CTSR   2.686    0.8234  3.262  0.00137 **
# Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ‘ 1
# Residual standard error: 17.75 on 150 degrees of freedom
# Multiple R-squared:  0.352, Adjusted R-squared:  0.3347
# F-statistic: 20.37 on 4 and 150 DF,  p-value: 2.028e-13
```

```r
#> anova(MEmodelMLR)
# Analysis of Variance Table
# Response: TgroupMLR$ME$MLR.TIScore
# Df  Sum Sq Mean Sq  F value    Pr(F)
# TgroupMLR$ME$MLR.SPM.  1  11005 11005.2  34.921 2.22e-08 ***
# TgroupMLR$ME$MLR.TOGS  1  5214  5214.0  16.545 7.65e-05 ***
# TgroupMLR$ME$MLR.CCI   1  6103  6103.3  19.366 2.04e-05 ***
# TgroupMLR$ME$MLR.CTSR  1  3354  3353.5  10.641  0.001369 **
# Residuals            150  47272   315.1
# Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ‘ 1
```

Q9: Is Transfer Index Score a function of % story problems in high school, story problem type, and Transfer Category?

R data:

```r
dataSP<-ddply(dfm9, c("Tcat9", "SPcat"), summarise,
               N=length(SP),
               mean=mean(SP),
               sd=sd(SP),
               se=sd/sqrt(t(N))
```

302
## dataSP

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<th>Tcat</th>
<th>SPcat</th>
<th>N</th>
<th>mean</th>
<th>sd</th>
<th>se</th>
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<td>ave%SP</td>
<td>159</td>
<td>39.33208</td>
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<td>1.388468</td>
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<tr>
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<td>C-ave</td>
<td>159</td>
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<td>23.42884</td>
<td>1.858028</td>
</tr>
<tr>
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</tr>
<tr>
<td>ME</td>
<td>P</td>
<td>159</td>
<td>30.72327</td>
<td>35.84494</td>
<td>2.842689</td>
</tr>
</tbody>
</table>

```r
ddply(melted, c("TIcat", "X.SPcat", "variable"), summarise,
    mean = mean(value),
    sd = sd(value),
    se = sd/sqrt(length(value)))
```

### Same data as above but necessary for graphing:

<table>
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<th>TICat</th>
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<th>variable</th>
<th>mean</th>
<th>sd</th>
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<td>C-ave</td>
<td>X.SP</td>
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<td>TIScore</td>
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<td>X.SP</td>
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</tr>
<tr>
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<td>P</td>
<td>X.SP</td>
<td>30.72327</td>
<td>35.84494</td>
<td>2.842689</td>
</tr>
</tbody>
</table>

### Quick R data:

```r
MPfit2 <- lm(MPTI ~ Mstoryprob + Pstoryprob + CAvestoryprob)
summary(MPfit2)
```

```
#Call:
# lm(formula = MPTI ~ Mstoryprob + Pstoryprob + CAvestoryprob)
#Residuals:
#   Min     1Q    Median     3Q    Max
# -46.62 -16.96     -3.25   12.18  68.87

#Coefficients:
#     Estimate Std. Error t value Pr(>|t|)
#(Intercept) 49.92919    5.72136   8.727  3.89e-15 ***
#Mstoryprob -0.20525    0.10413  -1.971     0.05049 .
#Pstoryprob  0.16941    0.05394   3.140     0.00202 **
#CAvestoryprob -0.15607    0.08227  -1.897     0.05968 .
#Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 1

#Residual standard error: 23.56 on 155 degrees of freedom
#Multiple R-squared: 0.08555, Adjusted R-squared: 0.06786
#F-statistic: 4.834 on 3 and 155 DF,  p-value: 0.003034
```
anova(MPfit2)
# Analysis of Variance Table

# Response: MPTI
# Df  Sum Sq Mean Sq  F value   Pr(>F)
# Mstoryprob  1  1735  1734.8  3.1265 0.078998 .
# Pstoryprob  1  4315  4314.9  7.7764 0.005957 **
# CAvestoryprob  1  1997  1996.9  3.5988 0.059680 .
# Residuals 155  86006   554.9
# Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

#> dataSP
# Tcat9 SPcat N  mean       sd       se
# 1    ME ave%SP 159 39.33208 17.50791 1.388468
# 2    ME C-ave 159 47.77358 23.42884 1.858028
# 3    ME M 159 39.49686 18.13447 1.438157
# 4    ME P 159 30.72327 35.84494 2.842689
# 5    MP ave%SP 159 39.33208 17.50791 1.388468
# 6    MP C-ave 159 47.77358 23.42884 1.858028
# 7    MP M 159 39.49686 18.13447 1.438157
# 8    MP P 159 30.72327 35.84494 2.842689

R data:
Tgroups<-split(dfm9, dfm9$Tcat9)
Tgroups
# $ME
# TI9 Tcat9 SP SPcat
# $MP
# TI9 Tcat9 SP SPcat
### Corrected plots: Jittered etc.

ggplot(Tgroups$ME, aes(x=SP, y=TI9, group=SPcat, color=SPcat)) +
  geom_point(shape = 1, position = position_jitter(width = 1.5, height = 1.5)) +
  geom_smooth(method = lm, se=FALSE, size = .5) +
  xlab("Story Problems (%)") +
  ylab("Math to Economics Transfer Index Score") +
  ggtitle("Math to Economics Transfer Index based on Percent Story Problems in High School") +
  scale_x_continuous(breaks = round(seq(min(0), max(100), by = 10))) +
  scale_y_continuous(breaks = round(seq(min(0), max(100), by = 10))) +
  theme_bw()

ggplot(Tgroups$MP, aes(x=SP, y=TI9, group=SPcat, color=SPcat)) +
  geom_point(shape = 1, position = position_jitter(width = 1.5, height = 1.5)) +
  geom_smooth(method = lm, se=FALSE, size = .5) +
  xlab("Story Problems (%)") +
  ylab("Math to Physics Transfer Index Score") +
  ggtitle("Math to Physics Transfer Index based on Percent Story Problems in High School") +
  scale_x_continuous(breaks = round(seq(min(0), max(100), by = 10))) +
  scale_y_continuous(breaks = round(seq(min(0), max(100), by = 10))) +
  theme_bw()
Q10: Is Transfer Index Score a function of % Inquiry Labs in high school, inquiry lab type, and Transfer category?

R data:
melted10<-melt(Q10, id.vars = c("Name", "TICat", "InqLabcat"))
head(melted10)
sample_n(melted10, 10)
ddply(melted10, c("TICat","InqLabcat", "variable"), summarise,
    N = length(value),
    mean = mean(value),
    sd = sd(value),
    se = sd/sqrt(N))
Quick R data:

MPfit10.2 <- lm(dfm10.2$MPTI ~ dfm10.2$PInqLab + dfm10.2$CInqLab)
summary(MPfit10.2)

#Coefficients:
#(Intercept) 38.71647 3.76393 10.286 <2e-16 ***
dfm10.2$PInqLab 0.17021 0.07507 2.267 0.0247 *
dfm10.2$CInqLab -0.05312 0.06858 -0.775 0.4398

#Residual standard error: 24.2 on 155 degrees of freedom

anova(MPfit10.2)

#Response: dfm10.2$MPTI
#Df Sum Sq Mean Sq  F value  Pr(>F)
dfm10.2$PInqLab 1 2712 2712.15 4.6310 0.03295 *
dfm10.2$CInqLab 1 351 351.35 0.5999 0.43978
Residuals 155 90776 585.65

R data:

MEfit10.2 <- lm(dfm10.2$METI ~ dfm10.2$PInqLab + dfm10.2$CInqLab)
summary(MEfit10.2)
```r
# Call:
# lm(formula = dfm10.2$METI ~ dfm10.2$PInqLab + dfm10.2$CInqLab)
# Residuals:
#     Min      1Q  Median      3Q     Max
#-45.945 -15.882  -0.958  10.738  58.167
#
# Coefficients:
#                      Estimate Std. Error t value Pr(>|t|)
# (Intercept)          44.09809   3.36206  13.116   <2e-16 ***
# dfm10.2$PInqLab      0.09234   0.06705   1.377    0.170
# dfm10.2$CInqLab     -0.06854   0.06126  -1.119    0.265
#
# Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
#
# Residual standard error: 21.62 on 155 degrees of freedom
# Multiple R-squared:  0.01657,  Adjusted R-squared:  0.003878
# F-statistic: 1.306 on 2 and 155 DF,  p-value: 0.274

anova(MEfit10.2)
# Analysis of Variance Table
# Response: dfm10.2$METI
# Df  Sum Sq Mean Sq F value Pr(>F)
# dfm10.2$PInqLab  1   635  635.16  1.3593 0.2454
# dfm10.2$CInqLab  1   585  584.99  1.2519 0.2649
# Residuals      155 72427   467.27

R data:
Tgroup10<-split(Q10, Q10$TIcat)
Tgroup10
# Name  TIScore TIcat InqLab InqLabcat
### Corrected graphs: Jittered etc.

ggplot(Tgroup10$ME, aes(x = InqLab, y = TIScore, group = InqLabcat, color = InqLabcat)) +
  geom_point(shape=1, position = position_jitter(width = 1, height = 1)) +
  geom_smooth(method =lm, se=FALSE, size =.5) +
  xlab("Inquiry Labs (%)") +
  ylab("Math to Economics Transfer Index Score") +
  ggtitle("Transfer Index based on Percent Inquiry Labs in High School") +
  scale_x_continuous(breaks = round(seq(min(0), max(100), by = 10))) +
  scale_y_continuous(breaks = round(seq(min(0), max(100), by = 10))) +
  theme_bw()

ggplot(Tgroup10$MP, aes(x = InqLab, y = TIScore, group = InqLabcat, color = InqLabcat)) +
  geom_point(shape=1, position = position_jitter(width = 1, height = 1)) +
  geom_smooth(method =lm, se=FALSE, size =.5) +
  xlab("Inquiry Labs (%)") +
  ylab("Math to Physics Transfer Index Score") +
  ggtitle("Transfer Index based on Percent Inquiry Labs in High School") +
  scale_x_continuous(breaks = round(seq(min(0), max(100), by = 10))) +
  scale_y_continuous(breaks = round(seq(min(0), max(100), by = 10))) +
  theme_bw()
```
Q11: Is % Spontaneous Graphing in lab a function of Instructional Treatment and having received a Prompt first week of lab?

Quick R data:

```
#  graph prompt                     Tx
#1  57.1    Yes Passive Interpretation
#2  14.3    Yes         Worked Example
#3 100.0    Yes         Worked Example
#4   0.0    Yes Passive Interpretation
#5   0.0    Yes         Worked Example
#6 100.0    Yes         Worked Example
```
```r
redofit11 <- lm(dfm11$graph ~ dfm11$prompt * dfm11$Tx)
summary(redofit11)
anova(redofit11)

#Call:
#  lm(formula = dfm11$graph ~ dfm11$prompt * dfm11$Tx)
#Residuals:
#    Min     1Q Median     3Q    Max
#-78.934 -17.174   6.766  18.793  47.393

#Coefficients:
#                                 Estimate Std. Error t value Pr(>|t|)
#(Intercept)                       54.6118     6.7301   8.115 1.06e-13 ***
#dfm11$promptNo                    19.6625     8.2033   2.397   0.0177 *
#dfm11$TxPassive Interpretation -0.8927     9.0532  -0.099   0.9216
#dfm11$TxWorked Example           -2.0044     8.0047  -0.250   0.8026
#dfm11$promptNo:dfm11$TxPassive Int 5.5526    11.1456   0.498   0.6190
#dfm11$promptNo:dfm11$TxWorked Ex -9.1172    11.2517  -0.810   0.4189
#Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

#Residual standard error: 27.75 on 165 degrees of freedom
#Multiple R-squared:  0.143, Adjusted R-squared:  0.117
#F-statistic: 5.505 on 5 and 165 DF,  p-value: 0.0001027

> anova(redofit11)
#Analysis of Variance Table

#Response: dfm11$graph
#            Df Sum Sq Mean Sq F value    Pr(>F)
#dfm11$prompt 1 17981 17980.5 23.3512 3.066e-06 ***
#dfm11$Tx      2  1768   884.1  1.1482    0.3197
#dfm11$prompt:dfm11$Tx 2  1447   723.4  0.9395    0.3929
#Residuals    165 127051   770.0
#Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Q12: Is Scientific Accuracy a function of Time and Instructional Treatment?

R data:
dfm12data<-ddply(dfm12, c("Time", "Treatment"), summarise,
N=length(sa),
mean=mean(sa),
sd=sd(sa),
se=sd/sqrt(N))
dfm12data
```

```
Quick R data:

```r
fit12redo<-aov(SA ~ (Time*Treatment) + Error(subject/Time) + Treatment, data=dfm12redo)
summary(fit12redo)

#Error: subject
#          Df Sum Sq Mean Sq F value Pr(>F)
#Treatment  2   41.2  20.585   2.994  0.054 .
#Residuals 116  797.5   6.875
#---
#Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

#Error: subject:Time
#          Df Sum Sq Mean Sq F value Pr(>F)
#Time      2  109.6  54.79   14.692 9.82e-07 ***
#Time:Treatment 4   9.2  2.30    0.618     0.65
#Residuals 232  865.2   3.73
#---
#Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R data:

```r
pd = position_dodge(.4)

```r
ggplot(dfm12data, aes(x = Treatment, y = mean, group = Time, color = Time)) +
  geom_errorbar(aes(ymin = mean - se, ymax = mean + se), width=.2, size = 0.7,
  position = pd) +
  geom_point(aes(shape=Time), size=4, position = pd) +
  ylab("Scientific Accuracy") +
  xlab("Instructional Treatment") +
  ggtitle("Scientific Accuracy based on Time and Instructional Treatment") +
  theme_bw()

```r
ggplot(dfm12data, aes(x = Time, y = mean, group = Treatment, color = Treatment)) +
  geom_errorbar(aes(ymin = mean - se, ymax = mean + se), width=.2, size = 0.7,
  position = pd) +
  geom_point(aes(shape=Treatment), size=4, position = pd) +
  ylab("Scientific Accuracy") +
  xlab("Time") +
  ggtitle("Scientific Accuracy based on Time and Instructional Treatment") +
  theme_bw()
```
Appendix R – Correlations Data

The following data are correlations and collinearity diagnostics for applicable research questions.

Question 1: Difference Between Math-to-Physics and Math-to-Economics Transfer Indices

Table R1

*Paired Samples Correlations*

<table>
<thead>
<tr>
<th>Pair 1</th>
<th>MP TI &amp; ME TI</th>
<th>N</th>
<th>Correlation</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MP TI &amp; ME TI</td>
<td>160</td>
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<td>.000</td>
</tr>
</tbody>
</table>

*Note.* MP stands for Math to Physics transfer category. ME stands for Math to Economics transfer category. TI stands for Transfer Index.

Question 2: Scientific Accuracy as a Function of Transfer Index Score

Table R2

*Multivariate Correlations*

<table>
<thead>
<tr>
<th></th>
<th>SA1</th>
<th>MPTI</th>
<th>METI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pearson Correlation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SA1</td>
<td>1.000</td>
<td>.203</td>
<td>.152</td>
</tr>
<tr>
<td>MPTI</td>
<td>.203</td>
<td>1.000</td>
<td>.783</td>
</tr>
<tr>
<td>METI</td>
<td>.152</td>
<td>.783</td>
<td>1.000</td>
</tr>
<tr>
<td><strong>Sig. (1-tailed)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SA1</td>
<td>.007</td>
<td></td>
<td>.032</td>
</tr>
<tr>
<td>MPTI</td>
<td>.000</td>
<td>.000</td>
<td></td>
</tr>
<tr>
<td>METI</td>
<td>.032</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>N</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SA1</td>
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<td>149</td>
<td>149</td>
</tr>
<tr>
<td>MPTI</td>
<td>149</td>
<td>149</td>
<td>149</td>
</tr>
<tr>
<td>METI</td>
<td>149</td>
<td>149</td>
<td>149</td>
</tr>
</tbody>
</table>

*Note.* SA1 stands for scientific accuracy on exam 1. MP stands for Math to Physics transfer category. ME stands for Math to Economics transfer category. TI stands for Transfer Index.

Table R3

*Univariate Correlations for Scientific Accuracy and Math-to-Physics Transfer Index*

<table>
<thead>
<tr>
<th></th>
<th>SA1</th>
<th>MPTI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pearson Correlation</strong></td>
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<td></td>
</tr>
<tr>
<td>SA1</td>
<td>1.000</td>
<td>.203</td>
</tr>
<tr>
<td>MPTI</td>
<td>.203</td>
<td>1.000</td>
</tr>
<tr>
<td><strong>Sig. (1-tailed)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SA1</td>
<td>.007</td>
<td></td>
</tr>
<tr>
<td>MPTI</td>
<td>.007</td>
<td></td>
</tr>
<tr>
<td><strong>N</strong></td>
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<td></td>
</tr>
<tr>
<td>SA1</td>
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<td>149</td>
</tr>
<tr>
<td>MPTI</td>
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</tr>
</tbody>
</table>

*Note.* SA1 stands for scientific accuracy on exam 1. MP stands for Math to Physics transfer category. TI stands for Transfer Index.
Table R4

<table>
<thead>
<tr>
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<th>SA1</th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Pearson Correlation</strong></td>
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<td></td>
</tr>
<tr>
<td>SA1</td>
<td>1.000</td>
<td>.152</td>
</tr>
<tr>
<td>METI</td>
<td>.152</td>
<td>1.000</td>
</tr>
<tr>
<td><strong>Sig. (1-tailed)</strong></td>
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<td></td>
</tr>
<tr>
<td>SA1</td>
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<td>.032</td>
</tr>
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Note. SA1 stands for scientific accuracy on exam 1. ME stands for Math to Economics transfer category. TI stands for Transfer Index.

**Question 4: Transfer as a function of high school graphing ability**

Table R5

<table>
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<tr>
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<th>MP TIScore</th>
<th>TOGS</th>
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</thead>
<tbody>
<tr>
<td><strong>Pearson Correlation</strong></td>
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<td></td>
</tr>
<tr>
<td>MP TIScore</td>
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</tr>
<tr>
<td>TOGS</td>
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<td><strong>Sig. (1-tailed)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MP TIScore</td>
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</tr>
<tr>
<td>TOGS</td>
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</tr>
<tr>
<td><strong>N</strong></td>
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</table>

Note. TOGS stands for Test of Graphing Skills. MP stands for Math to Physics transfer category. TI stands for Transfer Index.

Table R6

<table>
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<th>ME TIScore</th>
<th>TOGS</th>
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<tr>
<td>TOGS</td>
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<tr>
<td><strong>Sig. (1-tailed)</strong></td>
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</tr>
<tr>
<td>ME TIScore</td>
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</tr>
<tr>
<td>TOGS</td>
<td>.000</td>
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</tr>
<tr>
<td><strong>N</strong></td>
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Note. TOGS stands for Test of Graphing Skills. ME stands for Math to Economics transfer category. TI stands for Transfer Index.
Question 5: Transfer as a function of scientific reasoning ability

Table R7

*Multivariate Correlations*

<table>
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<th>CTSR</th>
<th>MP TIScore</th>
<th>ME TIScore</th>
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<td>ME TIScore</td>
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<td>.796</td>
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<tr>
<td><strong>Sig. (1-tailed)</strong></td>
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<tr>
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*Note.* CTSR stands for Classroom Test of Scientific Reasoning. MP stands for Math to Physics transfer category. ME stands for Math to Economics transfer category. TI stands for Transfer Index.

Question 6: Transfer as a function of lack of chemistry misconceptions

Table R8

*Multivariate Correlations*

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<th>CCI</th>
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<th>ME TIScore</th>
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<td>.794</td>
</tr>
<tr>
<td>ME TIScore</td>
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<td>.794</td>
<td>1.000</td>
</tr>
<tr>
<td><strong>Sig. (1-tailed)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCI</td>
<td>.</td>
<td>.000</td>
<td>.000</td>
</tr>
<tr>
<td>MP TIScore</td>
<td>.000</td>
<td>.</td>
<td>.000</td>
</tr>
<tr>
<td>ME TIScore</td>
<td>.000</td>
<td>.000</td>
<td>.</td>
</tr>
<tr>
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</tr>
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<tr>
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*Note.* CCI stands for Chemical Concepts Inventory. MP stands for Math to Physics transfer category. ME stands for Math to Economics transfer category. TI stands for Transfer Index.
**Question 7: Transfer as a function of intelligence**

**Table R9**

*Multivariate Correlations*

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*Note. SPM stands for Standard Progressive Matrices Plus. MP stands for Math to Physics transfer category. ME stands for Math to Economics transfer category. TI stands for Transfer Index.*
**Question 8: Multiple Linear Regression**

**Table R10**

*Multivariate Correlations*

<table>
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<tr>
<th></th>
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<th>CCI</th>
<th>CTSR</th>
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*Note.* MP stands for Math to Physics transfer category. TI stands for Transfer Index. SPM+ stands for Standard Progressive Matrices Plus, TOGS stands for Test of Graphing Skills, CCI stands for Chemistry Concepts Inventory, and CTSR stands for Classroom Test of Scientific Reasoning.
Table R11

*Multivariate Correlations*

<table>
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<tr>
<th></th>
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</table>

*Note.* ME stands for Math to Economics transfer category. TI stands for Transfer Index. SPM+ stands for Standard Progressive Matrices Plus, TOGS stands for Test of Graphing Skills, CCI stands for Chemistry Concepts Inventory, and CTSR stands for Classroom Test of Scientific Reasoning.
**Question 9: Transfer as a function of percent story problems in high school**

**Table R12**

*Multivariate Correlations*

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<th>M % story problems</th>
<th>P % story problems</th>
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| **N**            |       |        |                    |                    |            |
| MP TI            | 159   | 159    | 159                | 159                | 159        |
| ave%SP           | 159   | 159    | 159                | 159                | 159        |
| M % story problems | 159   | 159    | 159                | 159                | 159        |
| P % story problems | 159   | 159    | 159                | 159                | 159        |
| C % SP ave       | 159   | 159    | 159                | 159                | 159        |

*Note.* MP stands for Math to Physics transfer category. TI stands for Transfer Index. Ave%SP stands for average percent story problems across math, physics, and chemistry in high school. M % story problems stands for percent math story problems, P % story problems stands for percent physics story problems, and C % SP ave stands for average percent chemistry story problems across three years of high school.
### Table R13

*Multivariate Correlations*

<table>
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<tr>
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<th>P % story problems</th>
<th>C % SP ave</th>
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</table>

*Note.* ME stands for Math to Economics transfer category. TI stands for Transfer Index. Ave%SP stands for average percent story problems across math, physics, and chemistry in high school. M % story problems stands for percent math story problems, P % story problems stands for percent physics story problems, and C % SP ave stands for average percent chemistry story problems across three years of high school.
**Question 10: Transfer as a function of percent inquiry labs in high school**

**Table R14**

*Multivariate Correlations*

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*Note.* MP stands for Math to Physics transfer category. TI stands for Transfer Index. C Inq Lab Ave % stands for the average percent of inquiry-style laboratories students had in all their years of high school chemistry. P Inq Lab Ave % stands for the average percent of inquiry-style laboratories students had in all their years of high school physics.

**Table R15**

*Multivariate Correlations*

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<tr>
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<th>P Inq Lab Ave %</th>
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*Note.* ME stands for Math to Economics transfer category. TI stands for Transfer Index. C Inq Lab Ave % stands for the average percent of inquiry-style laboratories students had in all their years of high school chemistry. P Inq Lab Ave % stands for the average percent of inquiry-style laboratories students had in all their years of high school physics.
Appendix S – Extra Data Tables

These data tables are for the research questions where the null could not be rejected and there was no evidence for the predictor variable having an effect on the dependent variable.

4.1.10 Question 9: Transfer as a function of percent story problems in high school.

Effect size is given by $R^2$, shown in Table S1. It indicates the predictor variable of percent math story problems account for 1.2% variance in math-to-physics transfer index ($R^2 = 0.018$, adjusted $R^2 = 0.012$), chemistry percent story problems account for 1.1% variance in math-to-physics transfer index ($R^2 = 0.011$, adjusted $R^2 = 0.005$), and overall average percent story problems account for 0.2% variance in math-to-physics transfer index ($R^2 = 0.002$, adjusted $R^2 = -0.005$). For math-to-economics, the predictor variable of physics percent story problems account for 1.3% variance ($R^2 = 0.013$, adjusted $R^2 = 0.006$), chemistry percent story problems account for 1.2% variance ($R^2 = 0.012$, adjusted $R^2 = 0.006$), and overall average percent story problems account for 0.2% ($R^2 = 0.002$, adjusted $R^2 = -0.005$).

Table S1

Math to Physics Transfer Index (Dependent Variable) Univariate Model Summary

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<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
<th>R Square Change</th>
<th>F Change</th>
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<th>df2</th>
<th>Sig. F Change</th>
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b. Predictors: (Constant), Math percent story problems

Math to Economics Transfer Index (Dependent Variable) Univariate Model Summary

<table>
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<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
<th>R Square Change</th>
<th>F Change</th>
<th>df1</th>
<th>df2</th>
<th>Sig. F Change</th>
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</thead>
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<td>.013</td>
<td>1.998</td>
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<td>157</td>
<td>.160</td>
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</tbody>
</table>

b. Predictors: (Constant), Physics percent story problems
Table S2 shows that, for every one-point increase in math percent story problems, we can expect, on average, a 0.182-point decrease in math-to-physics transfer index (coefficient \( M\% = -0.182, t = -1.715, p = 0.088 \)). For every one-point increase in chemistry average percent story problems, we can expect, on average, a 0.110-point decrease in math-to-physics transfer index (coefficient \( C\% = -0.110, t = -1.326, p = 0.187 \)). For every one-point increase in overall average percent story problems we can expect 0.058-point increase in math-to-physics transfer index (coefficient \( Overall\% = 0.058, t = 0.524, p = 0.601 \)).

For every one-point increase in physics percent story problems, we can expect, on average, a 0.067-point increase in math-to-economics transfer index (coefficient \( P\% = 0.067, t = 1.413, p = 0.160 \)). For every one-point increase in chemistry average percent story problems, we can expect, on average, a 0.102-point decrease in math-to-economics transfer index (coefficient \( C\% = -0.102, t = -1.397, p = 0.164 \)). For every one-point increase in overall average percent story problems we can expect 0.045-point decrease in math-to-economics transfer index (coefficient \( Overall\% = -0.045, t = -0.455, p = 0.649 \)).

Table S2

Math to Physics (Dependent Variable) Univariate Coefficients

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
<th>t</th>
<th>Sig.</th>
<th>95.0% Confidence Interval for B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>Std. Error</td>
<td>Beta</td>
<td></td>
<td>Lower Bound</td>
</tr>
<tr>
<td>1 (Constant)</td>
<td>46.588</td>
<td>4.619</td>
<td></td>
<td></td>
<td>37.465</td>
</tr>
<tr>
<td>M % story problems</td>
<td>-0.182</td>
<td>.106</td>
<td>-0.136</td>
<td>-1.715</td>
<td>.088</td>
</tr>
</tbody>
</table>

b. Predictors: (Constant), Math percent story problems

c. Predictors: (Constant), Chemistry average percent story problems
4.1.10 Question 10: Transfer as a function of percent inquiry labs in high school

Effect size is given by \( R^2 \), shown in Table S3 for the univariate model. It indicates the predictor variable of average percent chemistry inquiry labs account for 0.1% variance in math-to-physics transfer index \( (R^2 = 0.001, \text{adjusted } R^2 = -0.006) \). For math-to-economics, the predictor variable of average percent physics inquiry labs account for 0.9% variance \( (R^2 = 0.009, \text{adjusted } R^2 = 0.003) \), average percent chemistry inquiry labs account for 0.4% variance \( (R^2 = 0.004, \text{adjusted } R^2 = -0.002) \).
Table S3

**Math to Physics Transfer Index (Dependent Variable) Univariate Model Summary**

<table>
<thead>
<tr>
<th>Model</th>
<th>R</th>
<th>R Square</th>
<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
<th>R Square Change</th>
<th>Change Statistics</th>
<th>F</th>
<th>df1</th>
<th>df2</th>
<th>Sig. F Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.024&lt;sup&gt;a&lt;/sup&gt;</td>
<td>.001</td>
<td>-.006</td>
<td>24.509</td>
<td>.001</td>
<td>.086</td>
<td>1</td>
<td>156</td>
<td></td>
<td>.769</td>
</tr>
</tbody>
</table>

b. Predictors: (Constant), **Average percent chemistry inquiry labs**

**Math to Economics Transfer Index (Dependent Variable) Univariate Model Summary**

<table>
<thead>
<tr>
<th>Model</th>
<th>R</th>
<th>R Square</th>
<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
<th>R Square Change</th>
<th>Change Statistics</th>
<th>F</th>
<th>df1</th>
<th>df2</th>
<th>Sig. F Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.095&lt;sup&gt;a&lt;/sup&gt;</td>
<td>.009</td>
<td>.003</td>
<td>21.600</td>
<td>.009</td>
<td>1.431</td>
<td>1</td>
<td>156</td>
<td></td>
<td>.233</td>
</tr>
</tbody>
</table>

c. Predictors: (Constant), **Average percent physics inquiry labs**

<table>
<thead>
<tr>
<th>Model</th>
<th>R</th>
<th>R Square</th>
<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
<th>R Square Change</th>
<th>Change Statistics</th>
<th>F</th>
<th>df1</th>
<th>df2</th>
<th>Sig. F Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.066&lt;sup&gt;d&lt;/sup&gt;</td>
<td>.004</td>
<td>-.002</td>
<td>21.651</td>
<td>.004</td>
<td>.685</td>
<td>1</td>
<td>156</td>
<td></td>
<td>.409</td>
</tr>
</tbody>
</table>

d. Predictors: (Constant), **Average percent chemistry inquiry labs**

Table S4 shows that, for every one-point increase in average percent chemistry inquiry labs, we can expect, on average, a 0.020-point decrease in math-to-physics transfer index (coefficient $C\% = -0.020, t = -0.294, p = 0.769$). For every one-point increase in average percent physics inquiry labs, we can expect, on average, a 0.078-point increase in math-to-economics transfer index (coefficient $P\% = 0.078, t = 1.196, p = 0.233$). For every one-point increase in average percent chemistry inquiry labs we can expect 0.050-point decrease in math-to-economics transfer index (coefficient $C\% = -0.050, t = -0.828, p = 0.409$).

Table S4

**Math to Physics (Dependent Variable) Univariate Coefficients**

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
<th>t</th>
<th>Sig.</th>
<th>95.0% Confidence Interval for B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>Std. Error</td>
<td>Beta</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>(Constant)</td>
<td>40.407</td>
<td>3.718</td>
<td>10.869</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>C Inq Lab Ave %</td>
<td>-.020</td>
<td>.068</td>
<td>-.294</td>
<td>.769</td>
</tr>
</tbody>
</table>

b. Predictors: (Constant), **Average percent chemistry inquiry labs**
Math to Economics (Dependent Variable) Univariate Coefficients

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
<th>t</th>
<th>Sig.</th>
<th>95.0% Confidence Interval for B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>Std. Error</td>
<td>Beta</td>
<td></td>
<td>Lower Bound</td>
</tr>
<tr>
<td>1</td>
<td>(Constant)</td>
<td>40.987</td>
<td>2.165</td>
<td>18.928</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>P Inq Lab Ave %</td>
<td>.078</td>
<td>.065</td>
<td>.095</td>
<td>1.196</td>
</tr>
</tbody>
</table>

c. Predictors: (Constant), **Average percent physics inquiry labs**

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
<th>t</th>
<th>Sig.</th>
<th>95.0% Confidence Interval for B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>Std. Error</td>
<td>Beta</td>
<td></td>
<td>Lower Bound</td>
</tr>
<tr>
<td>1</td>
<td>(Constant)</td>
<td>44.877</td>
<td>3.284</td>
<td>13.664</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>C Inq Lab Ave %</td>
<td>-.050</td>
<td>.060</td>
<td>-.066</td>
<td>-.828</td>
</tr>
</tbody>
</table>

d. Predictors: (Constant), **Average percent chemistry inquiry labs**

Considering the multivariate model for question 10, the effect size shown in Table S5 indicates the predictor variables of physics average percent inquiry labs and chemistry average percent inquiry labs account for approximately 3.3% variance in math-to-physics transfer index ($R^2 = 0.033$, adjusted $R^2 = 0.020$). The predictor variables of physics average % inquiry labs and chemistry average % inquiry labs account for approximately 1.7% variance in math-to-economics transfer index ($R^2 = 0.017$, adjusted $R^2 = 0.004$).

Table S5

**Model Summary of Math to Physics**

<table>
<thead>
<tr>
<th>Model</th>
<th>R Square</th>
<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
<th>R Square Change</th>
<th>F Change</th>
<th>df1</th>
<th>df2</th>
<th>Sig. F Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.180</td>
<td>.033</td>
<td>.020</td>
<td>24.191</td>
<td>.033</td>
<td>2</td>
<td>155</td>
<td>.077</td>
</tr>
</tbody>
</table>

a. Predictors: (Constant), Physics average % inquiry labs, Chemistry average % inquiry labs

b. Dependent Variable: Math-to-Physics Transfer Index

**Model Summary of Math to Economics**

<table>
<thead>
<tr>
<th>Model</th>
<th>R Square</th>
<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
<th>R Square Change</th>
<th>F Change</th>
<th>df1</th>
<th>df2</th>
<th>Sig. F Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.130</td>
<td>.017</td>
<td>.004</td>
<td>21.584</td>
<td>.017</td>
<td>2</td>
<td>155</td>
<td>.267</td>
</tr>
</tbody>
</table>

a. Predictors: (Constant), Physics average % inquiry labs, Chemistry average % inquiry labs

b. Dependent Variable: Math-to-Economics Transfer Index
Table S6 shows that we do not have evidence that average percent chemistry inquiry labs has an effect on either math-to-physics transfer index or math-to-economics transfer index. We also do not have evidence that average percent physics inquiry labs have an effect on math-to-economics transfer index. However, for every one-point increase in Physics percent inquiry labs, we can expect, on average, a 0.170-point increase in math-to-economics transfer index ($METI = 0.170$, $t = 2.263$, $p = 0.025$).

Table S6

Coefficients of Math to Physics

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
<th>t</th>
<th>Sig.</th>
<th>95.0% Confidence Interval for B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>Std. Error</td>
<td>Beta</td>
<td></td>
<td>Lower Bound</td>
</tr>
<tr>
<td>1</td>
<td>(Constant)</td>
<td>38.526</td>
<td>3.763</td>
<td>10.239</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>C Inq Lab Ave %</td>
<td>-.053</td>
<td>.069</td>
<td>-.062</td>
<td>-.771</td>
</tr>
<tr>
<td></td>
<td>P Inq Lab Ave %</td>
<td>.170</td>
<td>.075</td>
<td>.183</td>
<td>2.263</td>
</tr>
</tbody>
</table>

Coefficients of Math to Economics

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
<th>t</th>
<th>Sig.</th>
<th>95.0% Confidence Interval for B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>Std. Error</td>
<td>Beta</td>
<td></td>
<td>Lower Bound</td>
</tr>
<tr>
<td>1</td>
<td>(Constant)</td>
<td>43.835</td>
<td>3.357</td>
<td>13.058</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>C Inq Lab Ave %</td>
<td>-.068</td>
<td>.061</td>
<td>-.090</td>
<td>-1.110</td>
</tr>
<tr>
<td></td>
<td>P Inq Lab Ave %</td>
<td>.094</td>
<td>.067</td>
<td>.115</td>
<td>1.405</td>
</tr>
</tbody>
</table>