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Student Conceptualization of Stoichiometry

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Student Conceptualization of Stoichiometry

A Dissertation
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy
Engineering and Science Education

by
Khushikumari Jawahar Patel-Desai
May 2020

Accepted by:
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Dr. Cindy Lee
Dr. Jeffrey Appling
Dr. Bridget Trogden
Dr. Claire L.A. Dancz
Abstract

General Chemistry (I and II) is a year-long introductory course frequently taken at the start of the college career for STEM-intending students. It is broadly found to be difficult, and many students struggle. Stoichiometry describes the relationships between compounds and elements in a reaction. It is a fundamental concept that is taught in the first semester of General Chemistry as a building block for the understanding of future concepts in second-semester and upper-level chemistry courses. Students have a difficult time conceptualizing stoichiometry because it involves a combination of algorithms and builds off of other fundamentals. However, studies claiming to focus on conceptualization of stoichiometry have actually focused more on solving or conceptualizing chemistry problems using models that have been accepted by chemistry instructors.

The purpose of my study was to develop a framework for understanding how General Chemistry students conceptualize key topics in stoichiometry. Previous studies related to conceptualization focused on content delivery or how the students’ conceptualization aligned with the instructors’ or what is accepted by chemists rather than solely focusing on what students understand. In this study, I used a phenomenographic method to explore the different ways students conceptualize stoichiometry in General Chemistry. I conducted nineteen interviews with students enrolled in General Chemistry II at Clemson University. Incorporated in the results of this study is the analysis of the various ways students conceptualize chemistry. The result of this study is a model which describes the five different ways General Chemistry II students conceptualize stoichiometry. This study fills the literature gap by exploring students’ conceptualizations of stoichiometry using Knowledge Space Theory (KST).

This study will help instructors in higher education recognize that there are different ways students conceptualize the fundamentals being taught within the course, which may not completely align with the instructors’ conceptualization. My study can help other STEM fields reflect upon
conceptualization and the potential to increase retention for STEM programs. To do this, studying students’ conceptualization will help instructors develop curricula that focus on understanding fundamentals along with algorithms which can help students view STEM as achievable, inevitably filling STEM-related jobs in the United States as well as regaining a positive outlook of the field by the general public.
Dedication

For my grandfather, Bhagubhai C. Patel, who taught me to never give up and to consider
any struggle an opportunity to become stronger. I feel like you are always with me. Thank you for
sharing your wisdom, experiences, and life lessons.

To my grandmother, Jeliben Bhagubhai Patel, for blessing me to be successful and inde-
pendent. Thank you for teaching me about strength and determination.

To my sister who reminds me to enjoy life and never lose “the kid” inside of me. I hope I
can continue to be a role model for you. Thank you for reminding me the beauty of love and family.

To my Patel-Desai, Desai, and Trivedi family: mom, papa, mota papa, moti mummy, mom-
myji, papaji, and Jayesh (Jamu).
Acknowledgments

It took a village to help me navigate through my life and graduate school. For that, I am thankful for all the support, guidance, and faith I have received.

First, I would like to thank my mother. You have always been my role model. Without you, I would not be who I am today. You are always there to pick me up when I fall down. You taught me how valuable I am as an individual and how much I can give to the world around me; you taught me to be an independent woman like you. You are not just my mother; you are my best friend and the security blanket I always carry with me. Thanks for letting me be your butterfly. I would not have been able to make it to this point without you.

I would also like to thank my father. Papa, thank you for all your support. Thank you for taking me in as your daughter. Your blessings mean so much to me.

I would like to thank Eliza Gallagher for never giving up on me and being an outstanding advisor and mentor. You helped me become more confident. You have and will always be my academic mother who pushes me beyond what I think I can achieve. Thank you for trusting me with your interns and administrative responsibilities on projects. I have learned so much from working with you, and I look forward to collaborating and working together as colleagues.

I am grateful to my committee for the incredible support and encouragement in my work and my potential. Claire L. A. Dancz, Cindy Lee, Bridget Trogden, and Jeffrey Appling: you have helped me become a well-rounded chemistry education researcher.

A very special thanks to my analysis team, Rachel Lanning and Catherine Kenyon. You both have been amazing in how you are always willing to challenge me to think differently, especially about how to analyze data.

Another special thanks to Courtney Faber for sending me her LiveScribe Pens. Though it may seem small, you helped me with my dissertation, especially with my data collection.
To my academic sisters who have always been there to help me in both my research and my life. Thank you Aubrie Pfirmann, Staci Johnson, Catherine McGough, and Kathy Ehlert.

To my family friends who have helped me with so much including working with me to improve my writing and clean my data presentations. Thank you Lauren Castor, Brittany Aucoin, and Jasmine Amato.

To my Engineering and Science Education family, you have shaped me to become who I am today. We have laughed, cried, argued, challenged, and supported each other. I send positive vibes and best wishes to the ones who are continuing their journey in ESED.

Thank you Ms. Teri for always having a kind smile, a listening ear, mints and Kleenex.

Thank you Lisa, Marisa, Karen, Marty, Kelly, and many others in ESED for your support and guidance.

To my family friends in Tennessee. Thank you to all my aunties for the delicious food. You have taken me in and treated me like your daughter; I am forever grateful.

To my family in India and in the US. Thank you for the encouragements and blessings. Thank you my Patel-Desai, Patel, and Desai family members.

To my Trivedi family, I am grateful to have such an amazing future family. Thank you for accepting me and my family. Thank you for supporting and blessing me.

To my chemistry advisors, Dr. Sujata Guha and Dr. Joshua T. Moore, who helped me attain my Masters. Thank you for your continued support and blessing as I continue my journey to become a chemistry education researcher.

Lastly, Jayesh, thank you for being in my life. Thank you for all the late night calls to keep me company as I worked. I would not have been able to do this without you at my side. Thank you for your unconditional love.
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Chapter 1

Introduction

1.1 The Importance of Chemistry in Today’s World

According to the 2017 *Elements of the Business of Chemistry*, the United States Business of Chemistry is the second largest in the world and the largest as an exporting sector within the country (Figure 1.1) [American Chemistry Council, 2015]. As the world continues to consume products, the demand for chemistry skills and trained educated workers is increasing.

In order to remain a world leader, the United States needs individuals working in science, technology, engineering, and mathematics (STEM) fields to develop new innovative ideas which help drive the US economy [Noo nan, 2017, The White House, 2018]. There are five major segments in the business of chemistry: basic chemicals, specialties, agricultural chemicals, pharmaceuticals, and consumer products.

In order to continue to thrive, the US needs more people learning and collaborating about chemistry across all facets of engagement, from pharmaceuticals to technology (Figure 1.1).
1.2 Chemistry Pipeline

The retention rate of students showing interest in chemistry is declining in many countries [Broman et al., 2011]. Since the early 2000s, education researchers have investigated why the interest in chemistry is dwindling [Broman et al., 2011]. Researchers have found that students become discouraged from studying chemistry because they do not necessarily see the relevance of chemistry in their daily lives. Nations outside of the US do not incorporate applications to everyday situations in their chemistry courses [Broman et al., 2011]. Instructors tend to teach chemistry in a more “pure science” way where they do not include alternative context or everyday application [Broman et al., 2011]. In the US, instructors attempt to connect what they teach in chemistry courses to students' daily lives and future careers. In order to increase students’ interest in chemistry, a deeper understanding of students’ perspective of and experience with chemistry is necessary.

STEM degree programs incorporate knowledge and exposure in science, math, engineering, and technology fields. Without students who want to pursue a STEM degree, the United States will have a difficult time trying to find individuals to fill STEM jobs. Students who feel they are failing are likely to leave STEM [Christensen et al., 2014, Hossain and Robinson, 2012]. In some cases, feeling unprepared results in not pursuing a career in their degree field [Christensen et al., 2014, Hossain and Robinson, 2012]. Even with interest many individuals view STEM as difficult and boring, which also makes them feel unprepared for STEM careers [Christensen et al., 2014, Hossain and Robinson, 2012, PCAST, 2010]. Students with high interest in STEM or who are considered to have high STEM abilities do not necessarily acknowledge their own potential and eventually decide to drop out of a STEM major, leaving STEM jobs unfilled [Hossain and Robinson, 2012].

In recent decades, individuals who are interested in STEM programs become discouraged when they learn about the challenges college students (and those recently graduated) faced in introductory college courses [Al-Mutawah, Masooma AliFateel, 2018, Christensen et al., 2014]. Others have been discouraged because they perceive STEM degrees as boring based on their experiences in common introductory courses, such as math, biology, physics, and chemistry, during their first years in college [PCAST, 2010].
1.3 Struggles in Introductory Chemistry Courses

Many STEM students take introductory chemistry courses as either a requirement or an elective for their intended majors. Introductory (or general) chemistry courses are a requirement for life sciences, engineering and chemistry degrees. Students who take General Chemistry find the course difficult and mathematically challenging at times [Carter and Brickhouse, 1989]. About 27% of students enrolled in General Chemistry at post-secondary institutions fail the course [Cooper and Pearson, 2012, EAB Global, 2018]. Students who find chemistry difficult have a higher chance of dropping out of the course which can potentially affect their decision to persevere towards attaining a STEM degree [EAB Global, 2018].

The large amount of content taught in a science course is one factor influencing individuals to believe that science is difficult [Broman et al., 2011]. With the large content load in science, students have a greater chance of misconceptualizing the ideas taught. Specifically in chemistry, visualization of the problem or concept is where most of the misconception occurs [Broman et al., 2011]. Researchers identified that within the three levels of a chemistry visualization model (macro, sub-micro, and representational levels), students struggle in transitioning between the levels [Broman et al., 2011, Tóth, 2007].

Students fail chemistry because of the struggle to understand the fundamentals taught in class [Woldeamanuel et al., 2014, Cooper and Pearson, 2012]. Stoichiometry describes the relationships between compounds and elements in a reaction. It is a fundamental concept in solving chemistry problems and is an area where many students in General Chemistry struggle [Chandrasegaran et al., 2009, Dahsah and Coll, 2008]. This struggle leads to students not performing well in assessments and others withdrawing from the course [Cooper and Klymkowski, 2013]. Additionally, students who struggle with stoichiometry are more likely to have difficulties in future chemistry courses, with the possibility that they will change their intended degree and leave STEM [Cook et al., 2013].

The purpose of my study is to develop a framework for understanding for how general chemistry students conceptualize stoichiometry. If students understand stoichiometry, they are more likely to pass their general chemistry course, and also to be better prepared for succeeding in higher level chemistry courses, finishing a STEM degree, and pursuing a career in STEM.
Chapter 2

Literature Review

Education researchers have explored various ways to help students understand general content covered in chemistry courses, but how to reach profound understanding is still unresolved. Specifically in chemistry education, researchers found limitations in their studies related to student conceptualization due to the lack of understanding of how students conceptualize problems and fundamental topics. Studies have focused on alignment of broad understanding, performance on assessments, and pedagogies, yet focusing solely on student conceptualization is still a present opportunity for exploration. My study focuses solely on the student conceptualization.

The literature lacks a theoretical framework or model that would help explain the various ways students conceptualize fundamental topics and their relationships when solving stoichiometric problems. Students who are able to solve stoichiometric problems may feel limited in understanding how they are solving those problems or explaining what the information means in relation to the problems [Cameron, 1985].

2.1 The Struggle to Understand Fundamentals

Wolfer (2000) investigated student thinking about stoichiometry and found that students struggle to understand various fundamental principles taught in General Chemistry courses. According to Wolfer, students have a surface level, or limited, understanding of fundamentals such as limiting reactants [Wolfer, 2000]. Additionally, students did not focus on conceptualization in the study of the material because of the lack of emphasis on conceptual questions on assessments.
throughout a science course. Wolfer’s study provided insight that students may understand the concepts but did not apply the understanding when solving chemistry problems. Students only focused on algorithms when solving chemistry problems, which may indicate that students either do not realize that they need to apply concepts when solving problems, or they believe that there is no relationship between concepts and solving problems. Wolfer believed that when it came to instructional practices and resources in understanding stoichiometry, the focus was mainly on computation and algorithms.

Chandrasegaran et al. (2009) studied challenges students faced while solving stoichiometry problems and found that some students were able to understand relationships and meanings of topics in stoichiometry [Chandrasegaran et al., 2009, Gulacar, 2007]. When asked for definitions of topics, students were able to provide the correct details and explanations; however when solving stoichiometry problems, students were not able to apply the definition of topics being used to solve the problem, especially in a scenario they were not familiar with [Chandrasegaran et al., 2009].

Lack of conceptual understanding limits students’ ability to solve chemistry problems. Using Gulacar’s definition, problem solving is “what we do when we do not know what to do to cross the gap between where we are and where we want to be” [Gulacar, 2007]. Problem solving requires tools, methods, and conceptual understanding [Gulacar, 2007]. Learning is the result of interpreting and applying conceptual knowledge in solving problems [Gulacar, 2007], while understanding allows individuals to construct a representation of the problem in order to find a strategy to reach the solution. Without understanding the fundamentals, students will struggle solving and conceptualizing chemistry problems.

Dahsah and Coll (2008) focused their studies on why students struggle in understanding the fundamentals. They found that students struggled to make connections between macroscopic, molecular, symbolic, and graphical levels in order to understand the broad concepts [Arasasingham et al., 2004, Dahsah and Coll, 2008]. Students’ understanding of concepts such as stoichiometry did not align with chemists’ understanding of the concept [Dahsah and Coll, 2008]. Dahsah and Coll’s study specifically looked at Thai high school students’ conceptualization of stoichiometry using the stoichiometry concept questionnaire (SCQ) which consists of multiple-choice questions pertaining to nine topics related to stoichiometry: atomic mass, molar mass, mole, solution, empirical and molecular formula, chemical equations, and quantity relationships in chemical reactions [Dahsah and Coll, 2008]. These questions were developed based on textbook resources and chemistry experts’
agreement of what topics are related to stoichiometry and how the topics are related. Dahsah and Coll’s study indicate that Thai high school students’ conceptualization of the nine topics did not align with the chemistry community conceptualization.

2.2 The Importance of Stoichiometry

Stoichiometry is the description of “the quantitative relationships among elements in compounds among substances as they undergo chemical changes” and one of the most important and complex fundamentals covered in General Chemistry courses [Gulacar, 2007]. It is a threshold concept for General Chemistry courses and requires understanding in making connections with key topics such as dimensional analysis, molar ratio, balancing equations, and chemical reactions. Therefore, if students cannot conceptualize stoichiometry, they are likely to struggle in future chemistry courses.

As mentioned previously in the discussion of Dahsah and Coll’s work, the chemistry community agrees there are nine topics that are essential in conceptualizing and solving stoichiometry problems [Gulacar, 2007] as presented in Figure 2.1.

![Figure 2.1](image)

<table>
<thead>
<tr>
<th>Writing Chemical Equations (WEQ)</th>
<th>Shorthand representation used to describe a chemical reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balancing Chemical Equations (BEQ)</td>
<td>Assuring that the number of atoms for each element in the reactants are equal to the number of atoms for each element in the products and is presented as coefficients in a chemical reaction</td>
</tr>
<tr>
<td>Mass Percent (MP)</td>
<td>Also known as mass composition, a ratio between the mass of an element in a compound and the total mass of all the elements in the same compound</td>
</tr>
<tr>
<td>Empirical Formula (EF)</td>
<td>Simplest atomic ratio of elements in a compound</td>
</tr>
<tr>
<td>Percent Yield (PY)</td>
<td>Percent of how much of a desired product is obtained from a chemical reaction</td>
</tr>
<tr>
<td>Molecular Formula (MF)</td>
<td>The true number of atoms in a compound</td>
</tr>
<tr>
<td>Limiting Reagent (LR)</td>
<td>The reactant that limits the amount of products that can be produced in a reaction</td>
</tr>
<tr>
<td>Mole Concept (MC)</td>
<td>Unit of measurement in the International System of Units (SI) for amount of substance equivalent to Avogadro’s number in a chemical reaction</td>
</tr>
<tr>
<td>Stoichiometric Ratio (SR)</td>
<td>The exact ratio between the compounds and/or elements in a chemical equation</td>
</tr>
</tbody>
</table>

The “roadmap” model is one avenue some General Chemistry I instructors use to visually explain the relationships between the nine topics in stoichiometry. Not all students fully conceptualize how and why the topics are related when using the roadmap [Gulacar, 2007].
2.3 Instructional Focus and Pedagogy

Before identifying why students struggle in solving chemistry problems, it is necessary to explore how students conceptualize topics they need and use in order to solve chemistry problems such as stoichiometry. Research with the focus of studying student conceptualization of stoichiometry has also included various instructional strategies (e.g. unit cancellation), and student problem solving methods in order to solve stoichiometric problems. Tools such as the Barlin Particle Concept Inventory (BPCI), the Mole Concept Achievement Test (MCAT), the Test of Logical Thinking (TOLT), and the Longeot Test (LT) have been used in addition to problem solving mechanisms such as think-aloud in order to observe conceptualization in chemistry (Table 2.1) [Gulacar, 2007].

According to Gulacar, the LT and TOLT instruments focus on aspects pertaining to thinking and reasoning, while the CAT, BPCI, and MCAT focus on aspects of the chemistry content, but not specifically on stoichiometry [Gulacar, 2007, Sheehan, 1970, Tobin and Capie, 1981, Tobin and Capie, 1984, Cui et al., 2005, Krishnan and Howe, 1994]. Based on Gulacar’s work, the combination of these instruments provided limited insight in exploring student conceptualization of stoichiometry.

Table 2.1: Brief description of survey instrument used by Gulacar

<table>
<thead>
<tr>
<th>Test Name</th>
<th>Focus</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemistry Advancement Test (CAT)</td>
<td>Chemistry content review</td>
<td>Science Geek.net [Gulacar, 2007]</td>
</tr>
<tr>
<td>Longeot Test (LT)</td>
<td>Logical thinking</td>
<td>Sheehan [Sheehan, 1970]</td>
</tr>
<tr>
<td>Berlin Particle Concept Inventory (BPCI)</td>
<td>Conceptualization of particles</td>
<td>Zollman [Cui et al., 2005]</td>
</tr>
<tr>
<td>Mole Concept Achievement Test (MCAT)</td>
<td>Conceptualization of mole</td>
<td>Krishnan [Krishnan and Howe, 1994]</td>
</tr>
</tbody>
</table>

Content visuals and models, such as the “pictorial framework”, have been developed and utilized to help students conceptualize stoichiometric problems. The pictorial framework (Figure 2.2) includes a visualization of ways students can potentially understand and see connections when solving stoichiometry problems [Arasasingham et al., 2004, Cameron, 1985].

Students who use models such as the pictorial framework might look at an example and see how the framework is used and then try to replicate the steps in a similar problem. Once students work on several similar problems using the same steps, they may begin to understand what each step means and eventually be able to solve problems that are more challenging. However models, such as the pictorial framework, are limited in helping students conceptualize the topics and problems they are
solving. Students end up memorizing the steps they see in either the examples from the textbook or from an instructor demonstration [Cameron, 1985, Tóth and Sebestyén, 2009, Taasoobshirazi and Glynn, 2009]. Therefore, students are unable to solve problems that are different or more challenging compared to the examples they see [Tóth and Sebestyén, 2009, Taasoobshirazi and Glynn, 2009].

2.4 Focus of Study

The focus of this study is to develop a model of student conceptualization of stoichiometry. I focus on students enrolled in General Chemistry II because these students are expected to understand the nine topics in stoichiometry, which are taught in General Chemistry I and II courses.

Research Question: What are the different ways General Chemistry II students conceptualize stoichiometry?

2.4.1 Knowledge Space Theory (KST)

Coined by Doignon and Falmagne, Knowledge Space Theory is “the organization of knowledge in students’ cognitive structure described by a well-graded knowledge structure” [Tóth and Sebestyén, 2009].

A knowledge structure is a collection of knowledge states, or “subset of items which may correspond to the knowledge of an actual student” [ALEKS, 2007]. An individual’s knowledge state is a portion of the knowledge structure that they can access and activate to solve problems and make connections [ALEKS, 2007, Tóth and Sebestyén, 2009]. Knowledge structures consists of all possible knowledge states. Figure 2.3 is an example of a simplified knowledge structure with only four topics: moles, molar mass, mass, and molarity. Each box represents a possible knowledge state. In this simplified structure, a student who has not taken any chemistry would most likely have a null knowledge state, or a knowledge state in which the student does not know what moles, molarity, mass, or molar mass mean. As the
If a student learns about chemistry, they would move from a null state to a higher knowledge state such as one of the four topics mentioned in the box. At the end, the goal would be to have the student learn or “master” all the four topics. This would be represented by the knowledge structure that has all four topics. That way a student navigates in mastering all four topics would vary. The lines in Figure 2.3 represents paths between the knowledge states within the knowledge structure.

Behaviorists use Knowledge Space Theory as one approach in understanding how students solve stoichiometric problems, specifically, understanding student’s “knowledge structure” by capturing connections students make between topics, concepts, and fundamentals via a “network” [Tóth and Sebestyén, 2009]. KST can provide a visual representation of the network or knowledge states within a knowledge structure (Figure 2.3).

Falmagne and Doignon used KST to develop an artificial intelligence assessment and learning web-based system called ALEKS® (Assessment and LEarning in Knowledge Spaces). Today, ALEKS® is an artificial intelligence online system that many institutions incorporate in their courses. Using a networking system (like ALEKS®) can help identify how students conceptualize stoichiometry by looking at the possible relationships that can be made with the scenarios that they are given.

KST can help instructors see the various knowledge states students have on stoichiometry and can also include the further breakdown of the nine topics in stoichiometry (Figure 2.1). Chemistry in ALEKS® maps a total of 29 stoichiometric topics, which are grouped into five categories (Table 2.2) and are essentially components of the nine topics and how they are connected (“roadmap”). Table 2.3 provides details of how the topics in ALEKS correlate with Gulacar’s “roadmap.” These topics are connected to one another resulting in a visual network.

<table>
<thead>
<tr>
<th>ALEKS category</th>
<th>Number of topics covered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical Equations</td>
<td>5</td>
</tr>
<tr>
<td>Elemental Analysis</td>
<td>4</td>
</tr>
<tr>
<td>Reaction Stoichiometry</td>
<td>9</td>
</tr>
<tr>
<td>Solution Stoichiometry</td>
<td>7</td>
</tr>
<tr>
<td>Moles and Molar mass</td>
<td>4</td>
</tr>
</tbody>
</table>
### Table 2.3: Correlation between topics from the roadmap and ALEKS categories. The abbreviations are from Gulacar’s roadmap where MC represents Mole Concept, SR represents Stoichiometric Ratio, EF represents Empirical Formula, MF represents Molecular Formula, MP represents Mass Percent, BEQ represents Balancing Chemical Equations, WEQ represents Writing Chemical Equations, LR represents Limiting Reagent, and PY represents Percent Yield.

<table>
<thead>
<tr>
<th>ALEKS Categories</th>
<th>ALEKS Topics</th>
<th>Roadmap Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moles and Molar Mass</td>
<td>Calculating and using the molar mass of elements</td>
<td>MC</td>
</tr>
<tr>
<td></td>
<td>Finding chemical formulae from a mole ratio</td>
<td>SR, EF, and MF</td>
</tr>
<tr>
<td></td>
<td>Finding molar mass from chemical formulae</td>
<td>MC, EF, and MF</td>
</tr>
<tr>
<td></td>
<td>Interconverting number of atoms and mass of compound</td>
<td>MC</td>
</tr>
<tr>
<td>Elemental Analysis</td>
<td>Finding mass percent from chemical formulae</td>
<td>MP</td>
</tr>
<tr>
<td></td>
<td>Solving applied mass percent problems</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Elemental analysis</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Combustion analysis</td>
<td>None</td>
</tr>
<tr>
<td>Chemical Equations</td>
<td>Stoichiometric coefficients</td>
<td>BEQ and SR</td>
</tr>
<tr>
<td></td>
<td>Balancing chemical equations with interfering coefficients</td>
<td>BEQ</td>
</tr>
<tr>
<td></td>
<td>Writing a chemical equation from a description of the reaction</td>
<td>WEQ</td>
</tr>
<tr>
<td></td>
<td>Writing a chemical equation from a molecular movie</td>
<td>WEQ</td>
</tr>
<tr>
<td></td>
<td>Writing the net equation for a sequence of reactions</td>
<td>WEQ</td>
</tr>
<tr>
<td>Reaction Stoichiometry</td>
<td>Using a chemical equation to find moles of product from moles of reactant</td>
<td>MC and SR</td>
</tr>
<tr>
<td></td>
<td>Solving for a reactant using a chemical equation</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Identifying the limiting reactant in a drawing of a mixture</td>
<td>LR</td>
</tr>
<tr>
<td></td>
<td>Solving moles-to-moles limiting reactant problems</td>
<td>LR and SR</td>
</tr>
<tr>
<td></td>
<td>Limiting reactants</td>
<td>LR</td>
</tr>
<tr>
<td></td>
<td>Understanding theoretical, actual, and percent yield</td>
<td>PY</td>
</tr>
<tr>
<td></td>
<td>Theoretical yield of chemical reactions</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Percent yield of chemical reactions</td>
<td>PY</td>
</tr>
<tr>
<td></td>
<td>Reaction sequence stoichiometry</td>
<td>None</td>
</tr>
<tr>
<td>Solution Stoichiometry</td>
<td>Calculating molarity using solute moles</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Calculating molarity using solute mass</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Using molarity to find solute mass and solution volume</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Calculating ion molarity using solute mass</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Dilution</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Solving for a reactant in solution</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Solving limiting reactant problems in solution</td>
<td>LR</td>
</tr>
</tbody>
</table>

### 2.4.2 Concept Maps in Chemistry

Concepts maps are spaces where relationships between concepts or topics are displayed and are used as a component in both teaching and learning approaches [Novak and Gowin, 1984, BouJaoude and Attieh, 2008]. There are no limits on the ways relationships are indicated and topics or concepts can be in words or phrases or images [Novak and Gowin, 1984]. The purpose of concept maps is to allow individuals to visually express relationships and connections between multiple ideas.

For example the roadmap (Figure 2.1) can be interpreted as a concept map.

Researchers have used concept maps as a means to explore student understanding of the concepts taught. Especially in chemistry, concept maps have been used to explore what concepts students recognize and how those concepts connect [Pendley et al., 1994, Regis et al., 1996, Novak and Gowin, 1984]. Similar to the idea of KST, concept maps can provide insight into the relationships and connections students see and make on their own. Though concept maps are valuable in exploring student knowledge, teachers and instructors find them time-consuming as an assessment tool to
evaluate what connections students make between concepts taught [Regis et al., 1996, Pendley et al., 1994]. Instead, educators often provide concept maps such as the roadmap (Figure 2.1) as a visual aid to explain the relationships between concepts with the idea that students will understand and utilize them when learning rather than having students generate concept maps to reflect their own understandings. [Pendley et al., 1994].

2.4.3 Definitions of Terms

In this section, I define terms I use throughout the study. I define these particular terms to clarify how I am using the term and to allow the readers to understand the meaning intended when these terms are used and discussed. The terms described have been defined in different ways in the literature; therefore, to be consistent, I am providing the definitions I used in this study.

**Topics** are the basic ideas or content that are used as building blocks and can be grouped together if there are any connections or relationships. Topics are usually found within textbook chapters and are usually grouped to discuss a bigger idea or concept. For example, **units** is considered a topic because it describes an idea (a unit is an idea or form of measurement such as feet, ounces, and moles). In this study, topics are used to help describe components of a complex idea.

**Concepts** are groups of topics used to cover a complex piece of information or idea. For example, **conversions** (or dimensional analysis) is a concept that collectively connects topics such as units and math. Another way to think about concept is as an umbrella that collectively holds a complex idea.

**Fundamentals** are the basics or foundations. When uncertain if the information is considered a topic or concept, fundamental is used. For example, **units** and **conversions** are intertwined, which can become the building blocks of other topics and concepts such as applying moles in balancing chemical equations. I include the term **fundamental** to allow participants to provide a wider range of details in the interviews and to avoid any form of leading.
Chapter 3

Methodology and Methods

This study has been approved by the Institutional Review Board (IRB) as exempt under the B1 category and is filed as IRB2018-255. All activities were conducted in accordance with ethical guidelines for human subjects research.

3.1 Phenomenography

Phenomenography focuses on the different ways people (e.g., students in General Chemistry) experience a phenomenon (e.g., conceptualizing stoichiometry). Phenomenographic studies seek to “discover the structural framework within which various ways of understanding exist” [Marton, 1986]. The perspective of a phenomenographer is to “classify previously unspecified ways in which people think about certain aspects of reality.” Conducting a phenomenographic study is appropriate to answer my research question exploring the different ways students conceptualize stoichiometry. Based on the literature, students can solve stoichiometric problems and can define topics, but they cannot necessarily describe the topic and how it is used when solving a stoichiometry problem.

The goal of any phenomenographic study is to articulate differences in experience of a particular phenomenon with the intention of developing a framework or model that incorporates those differences [Marton, 1986]. The outcome space in my study is a model of the different ways students conceptualize stoichiometry.

The first step in a phenomenography is to conduct a pilot study in order to refine the interview protocol and get a preliminary sense of what information can emerge [Green and Bowden,
Data from the pilot study are not included in the full data set; at the same time, it is important that the participants in the pilot study are similar to the participants in the full study [Green and Bowden, 2005].

In a phenomenography, sample size is small (less than thirty) and diverse (maximal variation) on factors that may influence the experience. In my study, my focus is on a concept in chemistry, therefore, my sample needs to focus on students enrolled in a chemistry course. Most phenomenographic studies have approximately 20-25 participants and all the interviews are conducted within a month-long time block [Bowden and Walsh, 2000, Green and Bowden, 2005, Hazel et al., 1997]. The number of participants is determined by maximal sampling variation once the bounds of the study have been made. Having a diverse sample helps with the transferability of the results of the study as well as the assurance that the population is closely represented.

Other major factors in a phenomenographic study are the data collection and interview processes. Semistructured interviews are preferred in a phenomenography because it allows the researchers to clarify participants' responses by probing for further details and explanations [Barnard et al., 1999]. Interview protocols for a phenomenography are usually open-ended and reflective such as asking participants to explain their experiences. For example, participants may not have thought about a particular piece of information or experience. It is crucial to make sure that the questions are not leading, while at the same time clarifying any information that is vague or unclear. The purpose of a phenomenography is to capture different experiences, equally. As such, all interviews are conducted before any analysis occurs [Barnard et al., 1999].

The analysis of any phenomenographic study occurs in multiple stages and in multiple iterations in each stage. Interview transcripts are the data specifics that are analyzed. Transcripts are verified and interpreted. Excerpts are selected based on their relevance to the study and grouped based on categories or themes that are developed in all the transcripts collectively. The first stage (or cycle) of the coding process is reading all the interview transcripts and developing a first draft of categories [Bowden and Walsh, 2000]. Each code (category or theme) is bound by a set of criteria which is tested in all the data collected to assure that the codes are applied in the same manner. Transcripts are reviewed multiple times until each code is defined consistently. During each iteration, the researcher rereads the transcripts and modifies the codes that were developed in the previous round. This stage is repeated until the codes are no longer modified. Testing and retesting of the codes continues until the definition and bounds are consistent throughout the data set. The second
stage of the analysis is identifying the relationships that form the outcome space, or model of all the results. Again, multiple iterations occur until all the relationships are identified across all the interview transcripts and reach saturation.

3.2 Timeline of Study

The completion of my research took approximately 18 months. This includes developing and testing the qualification survey for maximal variation, conducting my pilot study, conducting my full study, analyzing my data, and developing my outcome space as shown in Figure 3.1. All of my participants for both the pilot and full study were General Chemistry II students. Details about how, when, and why I recruited General Chemistry II students are discussed later in this chapter. The full study was conducted the semester immediately following the pilot study. Though the pilot study was conducted in the Fall and the full study was conducted in the Spring, both semesters covered the same content. General Chemistry II is traditionally a course taken in the spring semester. General Chemistry II in the fall semester is considered off-sequence. Since I solely focused on the variation of conceptualization, the pilot study did not have to conducted in a Spring semester. More details on the purpose of my pilot study is discussed in this chapter. Data collected in the Spring semester was between the 6th and 9th week of the academic semester which is between the first two scheduled General Chemistry exams.

3.3 Pilot Study

Pilot studies, especially in phenomenography, are used to refine interview protocols, verifying that the focus is on answering the research question. In my study, the final version of my interview

<table>
<thead>
<tr>
<th>2018</th>
<th>2019</th>
<th>2020</th>
</tr>
</thead>
</table>

Figure 3.1 Timeline of all components from collecting and analyzing data to developing my outcome space.
protocol (after refining it during the pilot study) was used for every interview in the full study. I did not make any changes or alter the interview protocol during the full study because it is important to focus on the different experiences of a phenomenon (conceptualizing stoichiometry in my study) rather than “what” or “how” I am asking the questions during the interview. The steps of refining the interview protocol support process reliability because I used the same protocol version within each round and only made changes and alterations in between rounds of the pilot study.

The pilot study was an important part of my study, especially since I only collected the data set once in the full study. The pilot study occurred over three months in Fall 2018. In order to select my participants for both the pilot and actual study, I used a qualification survey, which was a short survey asking questions that helped me select my participants and aim for maximal variation. Since conceptualization cannot be measured directly as it is a latent variable, I wanted to explore what would be an appropriate proxy. I considered ways to achieve maximal variation such as demographics, exposure to chemistry, and confidence.

Demographic variables such as race, gender, and ethnicity have been used in different education research, but none in conceptualization of stoichiometry. Studies analyzing socioeconomic characteristics provide reasons as to why students may struggle in courses, acknowledging family and financial obligations, and an unawareness of resources and how to use them. However, these characteristics do not provide any direct insight to an individual’s conceptualization, so I did not use them as proxies to measure conceptualization.

Depending on the field, the chemistry course requirements for completing a degree program vary. Some fields only require the first semester General Chemistry course, while others require a full year (two semesters) of General Chemistry. Some social science and life science fields consider General Chemistry as an additional science course option. Because chemistry course requirements vary in STEM fields, conceptualization may also vary. Fields that require chemistry incorporate concepts such as stoichiometry in different ways. For example, individuals pursuing an engineering degree may conceptualize stoichiometry with a mathematics focus. I conjectured that students in different STEM fields would conceptualize stoichiometry in different ways.

Studies focusing on the relationship between intended majors and conceptualization suggest that there are differences in conceptualization [Siemankowski and MacKnight, 1971, Stover and Mabry, 2007]. For example, Siemankowski and MacKnight found that there was a difference between science majors with regards to spatial conceptualization where different science majors had different
levels of spatial cognition [Siemankowski and MacKnight, 1971]. There were also differences in spatial conceptualization between science majors and non-science majors [Siemankowski and MacKnight, 1971].

An individual’s confidence was the variable I conjectured would be most appropriate in measuring conceptualization. I hypothesized that if individuals were confident in their knowledge, they would conceptualize stoichiometry as a broad range of topics and connections. If individuals had little to no confidence, then they would be more likely to have a narrow or limited conceptualization of stoichiometry. In my pilot study, I wanted to test the following question: Is variation in confidence in solving stoichiometry problems a good proxy for variation in conceptualization of stoichiometry? For my pilot study, I conducted three rounds, each focusing on a particular variable I wanted to test:

- Round 1: Is there a difference in conceptualization with different levels of confidence in solving stoichiometry problems within the same intended major?
- Round 2: Is there a difference in conceptualization with similar levels of confidence in solving stoichiometry problems in different intended majors?
- Round 3: What additional changes are needed in the interview protocol?

3.3.1 Participant Selection

My participants were students enrolled in General Chemistry II at Clemson University. Based on the most recent course syllabus for General Chemistry, all components of stoichiometry are taught during the second half of General Chemistry I and are reviewed at the beginning of the General Chemistry II course. Therefore, selecting participants enrolled in General Chemistry II allowed me to capture students who had already been taught stoichiometry.

At Clemson University, approximately 500 students enroll in General Chemistry II (CH1020) in each Fall semester. With a large enrollment, I was able to recruit and interview twelve participants for my pilot study. All students enrolled in General Chemistry II (CH 1020) were contacted via email with basic details of the study and an invitation to participate in the study. There was only one instructor teaching all the General Chemistry II sections during the Fall semester. Since I was not able to access a list of all the students enrolled in General Chemistry II, I asked the instructor teaching the
course to send the email with the linked survey. Afterwards, the instructor did not have any involvement in the recruitment process or any other parts of the study. The instructor was not aware of who completed the survey or came for an interview. Emails for recruitment included a link to the qualification survey and were sent out on the last day to withdraw from the course without a “Withdraw” or “W” recorded on official academic transcripts. Individuals who withdraw from the course before the deadline will have no record that they registered or attempted to take the course and therefore, the course will not be on their academic records. Since I recruited participants electronically and by way of the instructor, there was an opportunity for nonresponse bias because participants may either not respond to the email or provide invalid data in the form of random responses to questions in the qualification survey. Random responses in the qualification survey were addressed by the confidence item in the qualification survey. Details of these confidence survey items are discussed next.

I also asked if the participant was currently enrolled in General Chemistry II (Figure 3.2). The combination of when the email with the linked survey was distributed and the enrollment status survey item helped ensure I was recruiting from my desired population: General Chemistry II students.

The qualification survey was expected to take approximately 5 minutes to complete and was open to all students for two weeks. In the survey, I asked students for their name, contact information, intended major, current chemistry course, and confidence in solving nine chemistry problems (Figure 3.2 and Figure 3.3). Using the data from the qualification survey, I separated potential participants based on how they responded to the question regarding confidence in solving some sample chemistry problems to test whether a variation in confidence was a good proxy for variation in conceptualization.

Nine chemistry problems were presented for the confidence prompt. Eight of the nine chemistry problems represented a concept in stoichiometry in no particular order, with the remaining problem being unrelated to the General Chemistry curriculum. To eliminate the bias of answering all the questions as either “extremely confident” or “somewhat confident,” I first looked for how
the students responded to the unrelated General Chemistry problem (Figure 3.4). I expected the response to be “Not at all confident” for this unrelated chemistry problem.

The intention of this particular prompt was to provide an advanced chemistry problem students would not be able to recognize or solve. This particular problem, however, focused on a topic taught in various other courses. For example, a geometry course would emphasize structural transformation and symmetry, whereas an upper level inorganic chemistry course would emphasize point group symmetry. Therefore, participants may have learned this concept in a geometric context even if they had not yet seen it in a chemistry context. Though this particular problem was not the best for filtering biased responses, I was still able to use the other chemistry problem responses to test if a variation in confidence was a good proxy for a variation in conceptualization. If I ended up using confidence as a proxy for conceptualization, I would change this particular non-General Chemistry related problem to another problem that is only covered in an upper level chemistry course such as an organic mechanism problem. If students responded that they were either extremely or somewhat confident in solving this particular question, I excluded them from the interview selection pool. Since I excluded these particular responses, there was a chance I excluded a representative portion of the population I wanted to study.

I followed a three-step process in grouping participants into three bins (Figure 3.5):

1. I excluded participants who responded that they were not enrolled in General Chemistry at the time of the survey or who answered the unrelated General Chemistry problem “extremely confident” or “somewhat confident”.

2. I grouped remaining participants into one of the three bins for the average expressed confidence level: 0-3.4, 3.5-4.4, and 4.5-5.0.

3. I grouped participants by intended major within each bin.

For each test round, I invited participants using the confidence level results and intended major results from the qualification survey. I made a histogram with three bins using the confidence level responses by calculating the average expressed confidence level of the eight chemistry problems for each participant. After the histogram with three bins was made, I looked at the intended major responses for each bin and selected a major that appeared in each bin. If there were multiple majors
appearing in each bin, or multiple students with the selected major in the same bin, I selected at random from that group. This selection process was to help verify if the variation in confidence levels could be used as a proxy for the variation in conceptualization. When asking questions from the interview protocol, I looked for the depth of details the participants provided for each response. If students provided minimal details in describing terms or explaining the connections between terms, they were likely to have minimal conceptualization of stoichiometry. I will later discuss why variation in confidence proved not to serve as desired.

### 3.3.2 Data Collection

All interviews were conducted in the same interview room in order to ensure all environmental conditions remained consistent. Additionally, only one person conducted all interviews to
ensure process reliability. All data were collected within a three week time span as suggested by the structure of a phenomenography as well as making sure that all participants had a similar experience and exposure to what was being taught in their chemistry courses.

### 3.3.3 Interview Protocol

I had three components in my interview protocol:

1. Discuss what stoichiometry means to the participant.

2. Identify topics students believe are essential in solving stoichiometry and how the topics connect with one another.

3. Solve stoichiometry problems and discuss the process/actions they took to solve.

Participants used marker boards, markers, LiveScribe™ pen, notebook, and notepads throughout the interview time.

### 3.3.4 LiveScribe™ Pen

All participants were introduced to the LiveScribe™ pen, including its basic functions, purpose in the interview, and how to use it. The pen contains a special ink and micro recorder that allow the researcher to revisit what was being said at specific points where something was written. The LiveScribe pen records what is written on a special paper which was provided to the participants (Figure 3.6). It also audio records what people are saying during the time a person uses the pen. As a researcher, this allowed me to go back and capture what my participant said at the time they were using the pen. In addition to asking the participants to think out loud as they solved the stoichiometry problems, I was also able to look at the order of actions each participant used to solve the problems as a way to capture what they were thinking. That way if the participant solved the problems in silence, I was able to still capture the order of what they wrote and any low tone or whispered communications.
3.3.5  Concept Map Generation

In the interview, I asked participants about the relationships between topics used in solving selected problems related to stoichiometry by means of a card activity in which they wrote their responses on a LiveScribe™ notepad to answer the following questions:

1. What topics or fundamentals do YOU believe are essential in order to understand stoichiometry? Can you write them down on the LiveScribe™ materials provided?

2. What topics or fundamentals do YOU believe are essential in order to solve stoichiometry problems?

As part of this activity, I asked each participant if they saw any relationship between the concepts. If they did, I also asked the participants to place all the note cards in a way that showed how the participant saw the relationships. The goal for this particular activity was to see what relationships and connections the participants could identify in the way they conceptualize stoichiometry.

Since the focus of my study was to explore the different ways stoichiometry is conceptualized, questions regarding their prior knowledge or resources they used in order to understand stoichiometry were not included as a part of my study.

3.3.6  Solving stoichiometry problems

In the interview, participants were asked to solve four stoichiometry problems (Appendix D). All four problems were the same which helped ensure process reliability since each participant had the same level of difficulty problems to solve. Participants were given all four problems at the same time, which allowed them to pick and choose the order they wanted to solve them. Participants were instructed to solve or attempt to solve one problem at a time. I mentioned that they may or may not have seen a particular problem and it was fine if they were not able to solve it. Those who struggled in completing the problem were asked to discuss the steps and approaches they believed were needed in order to solve the problem. Participants were also given the opportunity to go back to a previous problem to either change their responses and/or reattempt solving the problem.

In between each problem solved, participants were asked to further discuss or explain the steps taken to solve the problem as well as topics they mentioned while solving the problems. For each
topic discussed, I asked how important the topic was in understanding and solving stoichiometry. I followed up by asking if and why they believed each topic was essential in understanding and solving stoichiometry. These sets of questions were repeated for each problem solved.

### 3.3.7 Round 1: Similar major but different average confidence

The goal for this round of the pilot study was to see if there was a difference in conceptualization within the same major but in different confidence bins. I chose intended majors in the engineering/general engineering field. Though the intention was to recruit one participant from each bin, I was not able to recruit a participant in the first bin. After contacting the participant three times, I decided to no longer reach out to that particular participant. At the end, I ended up recruiting two individuals in the second bin and one in the third bin for a total of three participants for this round (Figure 3.7). All three had engineering as their intended major. At Clemson, students who intend to pursue a degree in engineering do not declare a specific discipline in engineering until their sophomore year. Before then, they are General Engineering majors. Therefore, students who intended to declare specific disciplines such as bioengineering and chemical engineering were all grouped together with General Engineering.

![Figure 3.7](image-url) Flow chart of participant process for Round 1 in the pilot study. The chart shows the participants I actually ended up recruiting.

I followed the interview protocol and noticed that the participants mentioned that there is a difference between understanding and solving stoichiometry problems. Additionally, asking these questions after each problem provided an opportunity for the participants to expand and recall topics they believed were essential in stoichiometry. The solving stoichiometry problems given to the participants were numbered and were on two sheets of paper (two problems per sheet). As a researcher, I realized that numbering the problems could make the participants feel like they have
to solve the four problems in a particular order.

At the end of this round, I made the following changes in the interview protocol:

1. Added two questions:

   (a) What topics or fundamentals do YOU believe are essential in order to understand stoichiometry?

   (b) What topics or fundamentals do YOU believe are essential in order to solve stoichiometry problems?

2. Removed the numbering of the stoichiometry problems and put them on individual half sheets to allow the participants the freedom to look through all the problems and solve them in the order they want.

   Since all three participants were engineering majors, I was able to specifically focus on if the difference in confidence in answering chemistry problems was a good proxy for the difference in conceptualization. All three students focused on the math or “algorithms” when it comes to conceptualization of stoichiometry. All participants in this round also mentioned moles, molar mass, and molarity as topics they believed were essential in understanding/solving stoichiometry problems. Based on testing to see if confidence is a good proxy for conceptualization, conclusions drawn from the results in this round indicated that a variation in confidence does not mean there is a variation in conceptualization.

3.3.8 Round 2: Participants with different majors but similar average confidence

For the second test round, I wanted to further investigate if there is any relationship between confidence and conceptualization by looking a participants with similar average score in confidence but different intended majors (Figure 3.8). I invited participants who had different intended majors but were in the same second bin in the histogram.

Since I already looked at General Engineering, the participants invited in for this round of the pilot study were non-engineering majors. The participants who accepted the invitation and were interviewed had intended majors of biochemistry, packaging science, psychology, and German.
For this round, I tested the new interview protocol changes discussed from the first round as well as seeing if these participants had similar conceptualizations of stoichiometry. The German major participant mentioned that they no longer were in the General Chemistry course before we conducted the interview. I decided to interview this participant because they had just recently withdrawn from the course. I could still capture how they conceptualized stoichiometry and see if I needed to refine my interview protocol. During the interview, I asked all of my participants what their intended major was to verify what was recorded in the survey.

The interview protocol worked well, but I also incorporated asking the relationship between understanding and solving stoichiometry. Asking this particular question helped me see a much closer view of how students conceptualize stoichiometry. No additional adjustments or additions to the interview protocol were made. I paid close attention to the time span of each interview and found that on average, each interview was slightly over ninety minutes.

From this round of testing, I found that despite the fact that all four participants were in the same average score bin in confidence, they all presented different perspectives on conceptualizing stoichiometry. I also finalized the interview protocol which I used in my full study. This pilot study round confirmed that variation in major is a good proxy for variation in conceptualization.

### 3.3.9 Round 3: Final refinement of interview protocol

For this round of the pilot study, I recruited one student from each bin and made additional efforts in recruiting participants in the bin with the average score ranging from 0.0 to 3.4 (Figure 3.9). This final round was mainly focused on confirming that a variation in confidence does not help with maximal variation. It also allowed me to finalize the interview protocol.

I recruited four participants for this last round of testing: one each from the first and third
bins and two from the second bin. I used the most recent changes of the interview protocol for all four interviews. In this round, I confirmed my method to select participants for maximal variation and my interview protocol with no additional changes.

### 3.3.10 Conclusions drawn from pilot study

The diversity in the sample for my pilot study focused on the variation in confidence in solving chemistry problems and what the students’ intended major was at the time they took the survey. Since I wanted to achieve maximal variation, having a range of different intended majors and a range of confidence levels was used in selecting participants for the pilot study. Initially, I hypothesized students with minimal conceptualization would be likely to feel less confident. Based on the results I gathered from test rounds one and two, I concluded that a variation in confidence in solving chemistry problems was not a good proxy for conceptualization of stoichiometry but variation in intended major was relevant. I decided to remove all questions related to confidence from the qualification survey. I used the modified version for my full study to recruit and invite participants.

### 3.4 Full Study

The full study took place in the spring 2019 semester, immediately after conducting the pilot study. The changes made in the pilot study, including removing items from the survey questions and adding questions in the interview protocol, were implemented in the full study. No changes in the survey or interview protocol were made during the full study data collection period. Methods of analysis are discussed in the next chapter. Here, I discuss participant recruitment and data collection in the full study.
3.4.1 Participant recruitment

I followed the protocol of having the instructors email their students the qualification survey. For this data collection period, I had multiple instructors. In the email to the instructors, I provided a brief summary of the intentions and goals of my research emphasizing that all I will be asking are the students’ conceptualization, and nothing about the teaching style or structure of the course. I reached out to all General Chemistry II instructors via email on the last day to drop a course without a “W” on the academic transcript with simple instructions to send the qualification survey link (included in the email) to all the students enrolled in their sections. The window the survey was open was approximately two weeks. After the first week, I also went to meet each instructor in person to see if they had any questions or concerns about my request and research. Again, it was emphasized to the students that the instructors had no role in my study. The timing to recruit and select participants after the qualification survey was between the first two chemistry exams so that participants would not be as stressed and I would have a higher response rate. Table 3.1 provides details about the number of responses from the survey.

<table>
<thead>
<tr>
<th>Number of responses</th>
<th>Intended Major</th>
<th>Number of participants interviewed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Agricultural Mechanization and Business</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Animal and Veterinary Sciences</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>Biochemistry</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Bioengineering</td>
<td>1</td>
</tr>
<tr>
<td>13</td>
<td>Biological Sciences</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>Chemistry</td>
<td>3</td>
</tr>
<tr>
<td>1</td>
<td>Chemistry and Microbiology</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Electrical Engineering</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Environmental and Natural Resources</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>Food Science and Technology</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Genetics</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>Genetics and Biochemistry</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Health science</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>Language and International Health</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>Management</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>Microbiology</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>Nursing</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>Packaging Science</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>Psychology</td>
<td>0</td>
</tr>
</tbody>
</table>

As seen in Table 3.1, I had nineteen different intended major responses. My goal was to recruit at least one participant from each of the represented majors. I had difficulties recruiting two of the nineteen majors. For majors with more than one participant, I randomly selected one to invite for the interview. I gave them a one week time span to set up a time to be interviewed; if
they did not respond, I went back and randomly selected another participant in that same major. For majors with only one student, I made a maximum of three attempts. I contacted each invited participant via email to schedule a time to conduct the interview.

3.4.2 Interview

My first set of recruitment emails were sent the day after the first chemistry exam. I wanted to conduct all my interviews between the first two chemistry exams. The gap between the two exams was three weeks. In order to avoid test anxiety, I waited until the first exam was complete. If I had attempted to recruit right before the first exam, I may have not received a high rate of responses. All interviews took place at the same location with the same interviewer and same set of materials as suggested by my methodology. At the beginning of each interview, I provided a brief introduction of myself and the purpose of this study. I requested a consent to audio record the interview and emphasized that neither the instructor nor the participants’ performance in the course plays any role in the research. At the end of the interview, I asked each participant to choose a pseudonym to represent their responses in an anonymous way.

3.4.3 Data collection and processes

All interviews were transcribed using a secure third-party service that transcribes audio files using artificial intelligence. All interviews were conducted, transcribed, and verified before any analysis. Verification occurs when one listens to the audio recording of the interviews as they read the transcripts, with the goal of checking the accuracy of the transcripts. Since transcripts are the primary source of data, it was crucial to verify that all transcripts matched what was audio-recorded verbatim. All transcripts were verified within a two-week time span. Once all transcripts were verified, I began my analysis. Additionally, I took pictures of the concept maps students developed during the interview. Each concept map was labeled from zero to four to help indicate timeshots in the interview (Table 3.2). All data were labeled and saved under participant pseudonyms.
### Table 3.2: Description of codes used for participant concept maps

<table>
<thead>
<tr>
<th>Map number</th>
<th>Occurrence during the interview</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Concept map developed before solving any chemistry problems</td>
</tr>
<tr>
<td>1</td>
<td>Concept map developed after solving one chemistry problem</td>
</tr>
<tr>
<td>2</td>
<td>Concept map developed after solving two chemistry problems</td>
</tr>
<tr>
<td>3</td>
<td>Concept map developed after solving three chemistry problems</td>
</tr>
<tr>
<td>4</td>
<td>Concept map developed after solving all chemistry problems</td>
</tr>
</tbody>
</table>
Chapter 4

Analysis

Data analysis occurred after all the interviews were conducted, transcribed, and verified in order to follow the expectations of a phenomenography and avoid bias in the data collection phase. The analysis process consisted of coding interview transcripts and concept maps participants developed during the interview. Analysis included cycles of coding and modifying codes in order to develop categories for my model. I incorporated excerpts from transcripts in order to verify and justify how I interpreted and analyzed the concept maps. In this chapter, I discuss and justify the process used to analyze the data.

Before coding any data, it is important to remove any information that can potentially allow re-identification of the participants. At the end of the interview, every participant was asked to provide a pseudonym. Each transcript and all associated data were referred to by the pseudonym. All analysis began after the data were de-identified. Since I did not ask about gender identity, I will refer to all participants using they/them pronouns rather than gender specific pronouns such as him or her.

I had a research team to help me analyze portions of my data. The team consisted of two graduate mathematics students who are experts in graph theory, and my committee with collective expertise in education research methodology and chemistry. I took the lead in all aspects of the data analysis. My research team helped assure that I was interpreting and analyzing my data in an unbiased way, addressing both procedural and communicative validity as described by the Q3 Framework [Walther et al., 2013]. My research members probed and challenged various codes and explanations throughout my analysis and interpretation of my results. Details pertaining to how my
research team was involved are discussed in this chapter where relevant.

In order to ensure meaningful results, I have carefully designed my study to address concerns related to validity and reliability of my results. Validity is the trustworthiness that the data accurately gauges what researchers intend to measure. Reliability is the consistency of the data. Researchers who conduct phenomenographic studies have also explored some of the common concerns related to the accuracy of the data interpretations as well as assuring that the outcomes are meaningful to the intended audience [Åkerlind, 2012]. Phenomenographic researchers need to focus on translating individuals’ experiences of a phenomenon [Åkerlind, 2012]. Assuring that I was interpreting and making claims solely based on what my participants discussed helped address interpretive validity [Åkerlind, 2012, Maxwell, 1992].

Memoing is the process of writing down your own thoughts, opinions, and feelings as a researcher throughout the study [Birks et al., 2008]. Memoing is crucial in any qualitative study because it reminds the researcher to focus on the participants’ responses without judging what they say. I memoed before, after, and throughout each interview I conducted, as I coded all the interview transcripts, and while building my model. Additionally, memoing addressed evaluative validity, assuring that I did not include my opinion or judge the data I coded [Maxwell, 1992].

4.1 Coding

One of the first parts of coding focused on gathering and organizing all data collected. As part of the first cycle coding, I went through all transcripts applying attribute and descriptive codes. The goals of these particular types of codes are to label the data and provide basic characteristic information such as who, what, where, and how the data was collected [Saldaña and Univerzita, 2010]. This way the data can be selected and grouped by a particular type of characteristic. Using Saldaña’s terms, attribute codes describe factors associated to a participant without identifying personal information [Saldaña and Univerzita, 2010]. In this study, attribute codes included major, pseudonym, and date and time the interview was conducted. Table 4.1 provides details on participants and their intended major.

In addition to attribute codes, I applied descriptive codes where large chunks or excerpts were coded. Descriptive codes allow the researcher to further organize data for deeper analysis [Saldaña and Univerzita, 2010]. In this study, descriptive codes were applied to excerpts pertaining
Table 4.1: Participants and majors in the full study

<table>
<thead>
<tr>
<th>Pseudonym</th>
<th>Major</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aaron</td>
<td>Agricultural Mechanization and Business</td>
</tr>
<tr>
<td>Ashley</td>
<td>Animal and Veterinary Sciences</td>
</tr>
<tr>
<td>Harry Potter</td>
<td>Biochemistry</td>
</tr>
<tr>
<td>Zara</td>
<td>Bioengineering</td>
</tr>
<tr>
<td>Morgan</td>
<td>Biological Sciences</td>
</tr>
<tr>
<td>Elizabeth</td>
<td>Chemistry</td>
</tr>
<tr>
<td>David</td>
<td>Chemistry</td>
</tr>
<tr>
<td>Jerry</td>
<td>Chemistry</td>
</tr>
<tr>
<td>Oscar</td>
<td>Chemistry and Microbiology</td>
</tr>
<tr>
<td>Parker</td>
<td>Electrical Engineering</td>
</tr>
<tr>
<td>Alexandra</td>
<td>Environmental and Natural Resources</td>
</tr>
<tr>
<td>Amanda</td>
<td>Food Science and Technology</td>
</tr>
<tr>
<td>Daniel</td>
<td>Genetics</td>
</tr>
<tr>
<td>Miriam</td>
<td>Genetics and Biochemistry</td>
</tr>
<tr>
<td>Lola</td>
<td>Health Science</td>
</tr>
<tr>
<td>Jane</td>
<td>Language and International Health</td>
</tr>
<tr>
<td>Jackson</td>
<td>Microbiology</td>
</tr>
<tr>
<td>Lisa</td>
<td>Nursing</td>
</tr>
<tr>
<td>Spider-Man</td>
<td>Packaging Science</td>
</tr>
</tbody>
</table>

to a particular prompt. For example, I assigned a code for every essential excerpt pertaining to the responses from the interview protocols and anything of interest in my study such as “What topics or fundamentals do you believe is essential in understanding stoichiometry?” The descriptive codes allowed me to filter out or pull out data for further analysis. I gathered participants’ response to the prompt mentioned and began my analysis of topics they were discussing.

I also grouped concept maps in order of when they were developed (Table 3.2). Each participant had opportunities to develop and modify their initial concept map (concept map 0) throughout the interview. I asked each participant if there were any additional topics or fundamentals they wanted to add to their concept maps after they attempted or solved a chemistry problem. The excerpts associated with the concept maps were data I further analyzed in the first coding cycle. The excerpts provided each participant’s explanation of how concept maps were built and modified. For example, Oscar described their thought process as they were organizing the topics they believed were essential to stoichiometry (Figure 4.1):

Oscar: Okay. So I’m thinking is you got your unit conversion. So you got like grams liters, kilograms, milliliters, and then you’ve got your metric units which all those are metric ...

...you have to know the molar mass of substance which you would have to go through
Oscar included details and specific examples when explaining why and how topics are connected when developing the initial concept map. For instance, Oscar points out the importance of molar mass and how the value of knowing the molar mass can help find the mole which can be found using the periodic table. In the initial concept map, Oscar represents this by drawing an arrow from “Periodic table usage” to “how to find molar mass/number of particles of a substance” and moles.

All participants were asked to discuss their thought process as they developed and changed their concept maps in order to fully capture the connections and relationships they made between topics they identified as essential.
4.2 Preliminary Analysis of Concept Maps

All concept maps were coded iteratively based on the concept map labels (0-4). Within each set, I looked for patterns such as lines drawn between topics, the physical organization of topics, the topics listed, circles drawn around topics, and other visual organizational structures incorporated in the concept maps. For example, concept maps that had circles around a cluster of topics were grouped into one category.

I carried out the same process for all five concept map sets independently, looking at topics and the visual arrangement of those topics. At this stage, I only looked at the concept map images and did not consider the transcripts. I separated concept maps 0-4 because I wanted to see the similarities and differences between the maps within the same set.

My categories became descriptive codes which were refined after iterations of code modifications. Once defined, I had another member of the research team regroup the maps based on the category definitions I provided to test for validity in my groupings and code definitions. This team member had a background in qualitative analysis but limited background in chemistry. Having a researcher without a chemistry background helped me ensure that I did not bias the groupings by inserting my own knowledge and expertise in chemistry during my analysis process. The categories of description that developed after multiple iterations are shown later.

4.2.1 Concept Map Set 0

I took all concept maps labeled 0 and grouped them based on visible patterns. The goal was to explore and analyze topics the participants identified before solving any stoichiometric problems during the interview.

At this stage, I focused on the visual arrangements of the topics in the concept maps. For example, Aaron’s concept map 0 had topics that were grouped and each group was connected in a linear way, therefore this concept map was grouped under the \textit{Linear with focus on conversion (Grouping)} category (Figure 4.2). Most of the topics focused on units and unit conversion.

In contrast, concept maps that had similar topics
arranged linearly, but without grouping, were placed under the *Linear with focus on conversion (No Grouping)* category (Figure 4.3). For example, Daniel arranged topics indicating that one topic is needed before proceeding to the next topic and so forth. Daniel did not have any topics grouped and the four topics they listed were related to the idea of conversion.

![Figure 4.3 Daniel’s concept map 0](image)

This process a total of seven distinct categories for concept map set 0 (Table 4.2).

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear with focus on conversion (grouping)</td>
<td>Concept map had topics organized in groups and related to conversions in a linear way</td>
</tr>
<tr>
<td>Linear with focus on conversion (no grouping)</td>
<td>Concept map had topics organized and related to conversions in a linear manner</td>
</tr>
<tr>
<td>Unit focus with examples (with arrows)</td>
<td>Concept map had topics organized and related to units and did not include arrows</td>
</tr>
<tr>
<td>Math and chemistry connections (simple-within grouping)</td>
<td>Concept map had both math and chemistry topics grouped</td>
</tr>
<tr>
<td>Math and chemistry connections (simple- no within grouping)</td>
<td>Concept map had both math and chemistry topics</td>
</tr>
<tr>
<td>Math and chemistry connections (complex)</td>
<td>Concept map had both math and chemistry topics with many connections</td>
</tr>
<tr>
<td>Monolithic</td>
<td>Concept map had only one or two topics</td>
</tr>
</tbody>
</table>

### 4.2.2 Concept Map Set 1

Concept Map Set 1 consisted of the modified concept maps participants generated after attempting to solve one chemistry problem. Again, I analyzed the topics and connections between topics to see how the topics were organized without reference to the groups determined for Concept Map Set 0. In the immediate aftermath of working a stoichiometry problem that called for writing a balanced chemical equation, participants added both math and chemistry topics to their maps,
although not all participants added both. The categories that emerged from this analysis included both content and organization as defining characteristics. Participants who included both math and chemistry topics and who organized the topics in a linear or nearly linear manner were categorized as Process (Math and Chemistry) Linear.

For example, Daniel’s concept map 1 included both chemistry and math topics that were arranged as if this is a process Daniel utilized when understanding stoichiometry. As seen in Figure 4.4, Daniel’s concept map describes a process where they believe vocabulary is necessary to use moles and unit conversions which leads to calculator skills and end with checking for logical sense and accuracy. Overall, Daniel’s concept map 1 was categorized as Process-Math and Chemistry (Linear) because there were topics that are considered either a math or chemistry topic and the topics were arranged in a linear fashion.

On the other hand, Parker’s concept map 1 only had chemistry topics and no math topics (Figure 4.5). Parker’s concept map 1 was grouped under the Conceptual-Chemistry category. The topics Parker included in their concept map did not indicate a process because there was no arrow drawn between the topics. The lines connecting the topics represent conceptual connections rather than a linear step-by-step process.

Concept map set 1 included topics and connections that represented a process or conceptual approach. There were seven distinct categories found in this particular set (Table 4.3).

4.2.3 Concept Map Set 2

The next set of concept maps were additional modifications participants made to their individual concept maps. A new theme emerged at this stage with the appearance in many cases of
<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process-Math (linear)</td>
<td>Topics are organized in a linear way that looks like a mathematical process</td>
</tr>
<tr>
<td>Process-Math (non-linear)</td>
<td>Topics are organized in a non-linear way that looks like a mathematical process</td>
</tr>
<tr>
<td>Process-Math and Chemistry (linear)</td>
<td>Topics are organized in a linear way that looks like a combination of mathematical and chemistry process</td>
</tr>
<tr>
<td>Process-Math and Chemistry (non-linear)</td>
<td>Topics are organized in a non-linear way that looks like both a mathematical and chemistry process</td>
</tr>
<tr>
<td>Conceptual- Chemistry</td>
<td>Topics are mostly chemistry concepts</td>
</tr>
<tr>
<td>Conceptual- Math and Chemistry (simple)</td>
<td>Topics are mostly Chemistry and Math concepts and are organized in a simple fashion</td>
</tr>
<tr>
<td>Conceptual- Math and Chemistry (complex)</td>
<td>Topics are mostly Chemistry and Math concepts and are organized in a complex fashion</td>
</tr>
</tbody>
</table>

Table 4.3: Categories and descriptions for Concept Map Set 1

one or more end goals in the concept map structures. Identifying a defined goal was based on how the topics were arranged on the concept maps. Ashley’s concept map 2 had one end goal and the overall focus was on solving chemistry problems (Figure 4.6). Ashley’s concept map 2 incorporated topics involving chemistry and was organized in a linear fashion with arrows drawn between topics. When following the arrows, the “final goal” topic was at the end. Ashley’s concept map did not have any topics pertaining to mathematics, only chemistry, and was grouped under the Solving Chemistry Problem Focus (one path to one end goal) category.

Unlike Ashley, Zara modified their concept map by labeling topics that they considered as chemistry related and math related, implying the presence of both solving and understanding aspects of stoichiometry (Figure 4.7). Zara’s map did not have any topics grouped but the organization of the topics incorporated both topics that needed to be understood and steps that needed to be used to solve a chemistry problem.
Zara’s map was grouped under *Solving & Understanding Chemistry Problems (all groups/topics connected)* category.

I had six distinct categories after analyzing and grouping Concept Map Set 2 as shown in Table 4.4.

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solving &amp; Understanding Chemistry Problems (all groups/topics connected)</td>
<td>Topics are organized in a way that looks like a combination of solving and understanding. Topics that are grouped together are connected and topics that are not grouped are also connected.</td>
</tr>
<tr>
<td>Solving &amp; Understanding Chemistry Problems (at least one group/topic not connected)</td>
<td>Topics are organized in a way that looks like a combination solving and understanding. Some topics are grouped. Some groups and/or topics are connected.</td>
</tr>
<tr>
<td>Solving Chemistry Problem Focus (one path to one end goal)</td>
<td>Topics are organized in a way that looks like it is focused on solving Chemistry problems with one way to reach one end goal.</td>
</tr>
<tr>
<td>Solving Chemistry Problem Focus (multiple paths to one end goal)</td>
<td>Topics are organized in a way that looks like it is focused on solving Chemistry problems with multiple ways to reach one end goal.</td>
</tr>
<tr>
<td>Solving Chemistry Problem Focus (no defined end goals)</td>
<td>Topics are organized in a way that looks like it is focused on solving Chemistry problems with no end goal.</td>
</tr>
<tr>
<td>Solving Chemistry Problem Focus (multiple end goals)</td>
<td>Topics are organized in a way that looks like it is focused on solving Chemistry problems with multiple end goal.</td>
</tr>
</tbody>
</table>

### 4.2.4 Concept Map Set 3

Although the differences in the role of end goals that emerged in analysis of Concept Map Set 2 were still present, the type and extent of grouping among topics gained prominence in categorizing Concept Map Set 3. Topic groupings included, for example, circles drawn around groups of topics.

Lisa’s concept map is an example of how topics were grouped and how both individual topics and groups of topics were connected (Figure 4.8). Based on the arrangement of the topics and circles and lines drawn around the topics, Lisa’s concept map 3 was grouped under the *All topics/groups connected (no defined end goal)* category.
In contrast to Lisa’s concept map 3, Morgan’s concept map 3 had topics organized in a way that had one clear end goal: units (Figure 4.9). Morgan wrote numbers near some of the topics which helped indicate that “unit” was the end goal topic and was grouped under All topics/groups connected (single end goal) category. Although Morgan’s concept map 3 did not indicate groupings within the topics, all the topics were nonetheless connected in some way with either a line or an arrow.

After analyzing all the concept maps in set 3, I had five categories which focused on grouping topics and identifying end goals as described in Table 4.5.

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>All topics/groups connected (no defined end goal)</td>
<td>All grouped and individual topics connect with no defined end goal</td>
</tr>
<tr>
<td>All topics/groups connected (multiple end goals)</td>
<td>All grouped and individual topics connect with multiple end goals</td>
</tr>
<tr>
<td>All topics/groups connected (one end goal)</td>
<td>All grouped and individual topics connect with one end goal</td>
</tr>
<tr>
<td>At least one group/topic not connected (one topic isolated)</td>
<td>All but a single topic are grouped or individually connected</td>
</tr>
<tr>
<td>At least one group/topic not connected (one group not connected)</td>
<td>All but a grouped topic are grouped or individually connected</td>
</tr>
</tbody>
</table>

### 4.2.5 Concept Map Set 4

Concept Map Set 4 was the last version of concept maps the participants generated. They were produced after participants had attempted all four chemistry problems. The final problem involved percent yield and as a result, most of the concept maps were modified to include ideas related to percent yield if they weren’t already present. However, not all participants chose to add those ideas to their concept maps, which yielded the first major distinction in analyzing this set of concept maps. For this particular set, the patterns I saw emerging categories related to yields. If the concept map did not include percent yield as a topic, then it was grouped as either No percent yield with no mention if any type of yield or No percent yield with mention if a type of yield (actual or theoretical).

Jane’s concept map did not include any type of yield in their concept map and was grouped under the No percent yield (No mention of any type of yield) category (Figure 4.10).
Spider-man included percent yield in their concept map 4 (Figure 4.11). Furthermore, Spider-man’s concept map 4 indicates that percent yield was the overall end goal. Based on the organization of topics and including percent yield as an end goal, Spider-man’s concept map was categorized as *Percent yield (Single final end goal)*.

Concept map set 4 categories focused on how the topics and overall arrangement was associated to the “percent yield” topic as shown in Table 4.6. I found six distinct categories all focusing on some aspect of yield. The categories also include possible groupings and end goals.

**Table 4.6: Categories and descriptions for Concept Map Set 4**

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent yield (not grouped or connected)</td>
<td>Concept map included percent yield but was not grouped with or connected to other topics</td>
</tr>
<tr>
<td>Percent yield (one final end goal)</td>
<td>Concept map included percent yield as a single final end goal</td>
</tr>
<tr>
<td>Percent yield (one of many possible end goal)</td>
<td>Concept map included percent yield as one of the final end goals</td>
</tr>
<tr>
<td>Percent yield (in a connected group)</td>
<td>Percent yield is grouped with other topics. This group of topics connected with other groups or individual topics</td>
</tr>
<tr>
<td>No percent yield (no mention of any type of yield)</td>
<td>No type of yield was not topics seen in concept map</td>
</tr>
<tr>
<td>No percent yield (mention of actual or theoretical yield)</td>
<td>Percent yield was not in the concept map, but other yields were</td>
</tr>
</tbody>
</table>
4.2.6 Link Analysis

I examined the sequence of five concept maps for each participant to see how the maps changed. The categories from each concept map stage were displayed on a poster in order to help visualize the next part of the analysis. I followed how each participant’s concept map transitioned and explored whether multiple participants followed the same or similar paths. Once displayed on the poster, I followed the path to compare the pattern between the maps of each stage for each participant. For example, Aaron and Alexandra were both grouped in the same theme for their initial concept map (map 0) (Figure 4.12 and Figure 4.13) which was the *Unit Conversion Process (linear process no examples)* category and had the same grouping in their second concept map (map 1) (Figure 4.14 and Figure 4.15), which was the *Process-Math (linear)* category. These participants were initially grouped under the same category which indicates that they most likely had similar conceptualization of stoichiometry.

![Figure 4.12](image1.png) Aaron’s concept map 0  ![Figure 4.13](image2.png) Alexandra’s concept map 0

![Figure 4.14](image3.png) Aaron’s concept map 1  ![Figure 4.15](image4.png) Alexandra’s concept map 1

This process of examining the pathways of all concept maps for each participant was continued with all 19 participants (Figure 4.16). The idea to follow each participant was based on the idea of link analysis.

Link analysis is most commonly used in detective-like shows and movies, where investigators use a string to connect people and evidence to find out a source or identify an individual. It
has more recently been adapted for use in identifying themes emerging across participants in phenomenographic analysis [Gallagher et al., ND]. I used this method to help me trace the path of concept maps for each participant. The initial goal was to see if a group of participants’ concept
maps followed the same or similar developmental path. I wanted to see if there were any participants who were grouped together under the same category for each concept map.

However, there were no obvious patterns that emerged, so I needed additional tools to further investigate how the topics were connected. To do this, I worked with two members of the research team to redraw all the concept maps for organization purposes. Both members have a background in mathematics, specifically in graph theory. In this study, I used concepts from graph theory to further analyze the data. The following sections describes the analysis process using the graph theory lens.

4.3 Graph Theory

Graph theory is a branch of mathematics that studies the properties and relations within a graph [West et al., 2001, Bondy et al., 1976]. A graph is a set of vertices and a set of edges that connect the vertices [West et al., 2001, Bondy et al., 1976]. In this context, the chemistry topics the students listed in the concept maps were considered the vertices in our graphs. The connections made between these topics in the concept maps were defined to be the edges. Definitions of vertices and edges are discussed below.

- **Vertex**: Vertices are the fundamental units of a graph [West et al., 2001]. In this study, each vertex represents a topic participants identified during the interview. Each vertex is represented as a numbered dot in the diagrams.

- **Edge**: An edge is a pair of vertices that are connected by an arc. In my study, edges are the connections between topics articulated by participants [Bondy et al., 1976]. For instance, several students identified and connected *moles* with *molar mass* as two important concepts related to each other, therefore, I would see an arc connecting *moles* and *molar mass*.

- **Diagram**: A diagram is a space that includes vertices and edges. Every participant has their own diagram that I interpreted as concept maps.

- **Degree of a vertex**: The degree of a vertex represents the number of edges that are connected to the vertex [West et al., 2001]. For example, *moles* connected to *molar mass*, *units*, and *math* would have degree three.
Graph theory has been applied in various fields, from computer science and mathematics to linguistics to physical and life sciences [West et al., 2001, Bondy et al., 1976]. I used the concepts of graph theory to support the initial analysis of results. Although I did not use a graph theoretical approach during the entire analysis process, I adopted and modified the terms used in graph theory.

### 4.4 Developing Vertex List

As the first step in this analytic process, I developed an initial master list of all the topics the participants wrote when generating their concept maps (Table 4.7). Once all the topics were listed, I grouped topics into categories based on how closely the topics were related.

![Figure 4.17](image_url) Sample of consolidation of topics participants identified and discussed during the interview

The purpose of grouping topics was to further consolidate topics to help with analyzing the concept maps and examining how participants saw connections or relationships between topics. For example, one category was *types of attraction* which included inter- and intra-molecular forces (Figure 4.17). Since both forces are types of attractions, I grouped them together. Some groupings had a wider range of topics such as *proportions*. In this particular consolidated topic, all the topics had a common theme of ratios. For example, Aaron and Ashley both described *subscripts* as the amount of moles contained in a compound:

Aaron: These are the uh subscript. Super uh superscripts? Subscripts? They just represent the number of moles of each compound.

Aaron’s description of *subscripts* focused on relating it to moles whereas Ashley went into greater detail explaining how the subscript represents a ratio using ammonium as an example. Participants often described subscripts as a relationship between the number of a particular element in a compound or molecule. Empirical and molecular formulas both incorporate subscripts which are described as proportions.
Khushi: You have H3 that three is a subscript and the H2 and the two is a subscript. Can you tell me a little bit more about those numbers?

Ashley: right? Umm So for any 3 in 1 mole of ammonium, there’s and an imaginary subscript of one with the nitrogen so there’s one mole of nitrogen and three moles of hydrogen. And so hydrogen and nitrogen that are diatomic

As topics were grouped, I also tested the codes to see if any would cause issues in the original participant concept maps. For example, Amanda’s concept map included organization and visualize as topics (Figure 4.18). Since Amanda drew a line from organization to visualize and visualize did not connect to any other topics, we were able to consolidate these two topics into the problem solving skills topic.

My goal was to connect the topics within the code to the participants’ concept maps. If the topics were not connected or grouped in the participants’ concept maps, I recoded or regrouped the topics. In total after going through all the topics identified by participants and/or discussed in the interview and regrouping, my initial master list consisted of 39 codes (Table 4.7).

The initial master list was the basis for an initial master diagram in which topics were grouped based on similar conceptual characteristics. In order to organize all the topics from the master list, I grouped topics based on how they connected to each other based on understandings from chemistry. There were six groupings which will be referred as “themes” from here on out: Core Tools and Concepts, Chemical Reactions, Chemical Equations, Atomic Structure, Energy, and States of Matter. Organizing the topics into themes made it easier to see emerging patterns in the visual representation of the data.
### 4.5 Developing Individual Diagrams

I developed a tentative master diagram that comprised all the initial codes (Figure 4.19). The arrangements of the numbered dots (vertices) does not represent the closeness of the relationship or connections between topics. Graphs are a way of capturing relationships between ideas that do not depend on a fixed position in space. Therefore, the arrangements of the vertices does not matter in the core concepts of graph theory that I leveraged to carry out analysis. Topics were positioned as numbered points on the diagram grouped within the six identified themes. I then used the transcripts to expand the list of vertices. The list of topics in Table 4.7 became my provisional codes. While coding, I also wrote down additional topics that were not included in the master list. For example, Jackson mentioned the topic *solution* but they did not incorporate it in any part of the concept maps:

Jackson: So yes, I still get confused with it. But um, but yeah, those are the concentrations and just basically solutions in general.

Jackson did not include solutions in the concept map because they did not believe it was essential to stoichiometry:

Jackson: So I’m not going to say it but, um, I guess solutions? I don’t know. I don’t

---

**Table 4.7: List of topics after iterations of consolidation**

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Grouping</th>
<th>Identifier</th>
<th>Grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>moles</td>
<td>21</td>
<td>chemical equation</td>
</tr>
<tr>
<td>2</td>
<td>molarity</td>
<td>22</td>
<td>coefficients</td>
</tr>
<tr>
<td>3</td>
<td>molar mass</td>
<td>23</td>
<td>unit conversions</td>
</tr>
<tr>
<td>4</td>
<td>math</td>
<td>24</td>
<td>significant figures</td>
</tr>
<tr>
<td>5</td>
<td>periodic table</td>
<td>25</td>
<td>state of matter</td>
</tr>
<tr>
<td>6</td>
<td>percent yield</td>
<td>26</td>
<td>problem solving skills</td>
</tr>
<tr>
<td>7</td>
<td>actual yield</td>
<td>27</td>
<td>chemical reactions</td>
</tr>
<tr>
<td>8</td>
<td>theoretical yield</td>
<td>28</td>
<td>vocabulary</td>
</tr>
<tr>
<td>9</td>
<td>units</td>
<td>29</td>
<td>Law of Conservation of Mass</td>
</tr>
<tr>
<td>10</td>
<td>Avogadro’s number</td>
<td>30</td>
<td>chemistry nomenclature</td>
</tr>
<tr>
<td>11</td>
<td>mole ratio</td>
<td>31</td>
<td>Law of Conservation of Energy</td>
</tr>
<tr>
<td>12</td>
<td>limiting reactant</td>
<td>32</td>
<td>experimental design</td>
</tr>
<tr>
<td>13</td>
<td>molality</td>
<td>33</td>
<td>periodic trends</td>
</tr>
<tr>
<td>14</td>
<td>limiting + excess reactants</td>
<td>34</td>
<td>proportions</td>
</tr>
<tr>
<td>15</td>
<td>excess reactant</td>
<td>35</td>
<td>types of charges</td>
</tr>
<tr>
<td>16</td>
<td>balancing equations</td>
<td>36</td>
<td>polyatomic</td>
</tr>
<tr>
<td>17</td>
<td>dimensional analysis</td>
<td>36</td>
<td>structure specific</td>
</tr>
<tr>
<td>18</td>
<td>mass</td>
<td>38</td>
<td>atoms</td>
</tr>
<tr>
<td>19</td>
<td>relationship between atoms and molecules</td>
<td>39</td>
<td>types of attractions</td>
</tr>
<tr>
<td>20</td>
<td>nuclear stoichiometry</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

45
Figure 4.19  First version of diagram consisting of all initial codes. The location and distances between topics are irrelevant in graph theory and irrelevant to how I analyzed topics and connections.
know if that’s stoichiometry or not.

I continued to look for topics such as solutions, solutes, and solvents that individuals discussed and incorporated those topics into the list of vertices.

After coding all the transcripts the first time, I went back and refined some of the codes as well as added codes that were not in the participant concept maps but were mentioned in the interview. I also reorganized the topics to further help visually analyze the data. I continued to recode all the transcripts each time using the most recent refined master list. Recoding occurred until no additional topics were identified. The final codebook and codes consisted of a list of 50 topics (Figure 4.20).

Using these 50 codes, I created a visual representation of each transcript by marking all the codes on top of the tentative map on an individual transparency films (Figure 4.21). Each participant transcript was drawn on its own transparency with only the codes marked from what was found in the transcript. The intention of having individual transparency films was to help identify all the overlaps I saw between the participants.
From the fifty topics, there are over $1.1 \times 10^{15}$ possible knowledge states, which is nearly impossible to analyze individually. In order to analyze how and what connections students are making in a more manageable way, I looked for patterns which would be a part of my model of different ways students conceptualize stoichiometry. In this case, since there are a large number of knowledge states, the fifty topics were grouped into themes which helped me analyze my data in a manageable way. Since these fifty topics were based on what the participants identified, the knowledge structure was based on a novice perspective and includes topics such as *nuclear stoichiometry* that might appear nonsensical to a chemist.

After the final coding pass for refining the list of vertices, I went back to each transcript and coded for any connections participants discussed. I recorded each connection on the participants’ transparencies which had the topics already identified and marked. Connections were represented by different types of arcs to represent different types of connections (Table 4.8).

There are three types of edges used in this study which are presented and described in
Table 4.8: Examples of codes for edges

<table>
<thead>
<tr>
<th>Edge Type</th>
<th>Edge Symbol</th>
<th>Description</th>
<th>Example Excerpts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bidirectional</td>
<td>↔</td>
<td>two topics are linked where topic 1 needs topic 2 and topic 2 needs topic 1.</td>
<td>Going back from converting from moles to grams and grams to moles ummm. and that it’s not really basic math; I might put that like with basic math.</td>
</tr>
<tr>
<td>One direction</td>
<td>→</td>
<td>one topic is required in order to get to the other topic</td>
<td>Umm... Then if you were to need to calculate molarity in order to get your moles</td>
</tr>
<tr>
<td>Arc</td>
<td>−</td>
<td>two topics are connected but with no direction</td>
<td>These are the uh subscript. Super uh superscripts? Subscripts? They just represent the number of moles of each compound.</td>
</tr>
</tbody>
</table>

Table 4.8. Each type of edge represents a particular type of relationship participants discussed. A double headed arrow was used when two topics were described as dependent on each other. For example, a bidirectional arrow was used when a participant described that moles were needed to get to grams and grams needed to get to moles (Figure 4.22).

Amanda: Going back from converting from moles to grams and grams to moles ummm. and that it’s not really basic math; I might put that like with basic math.

A single headed arrow was used to represent that a topic was related in one way, meaning one topic is required to get to the other topic. For example, one participant mentioned needing molarity to find the number of moles (Figure 4.23):

Amanda: Going back from converting from moles to grams and grams to moles ummm. and that it’s not really basic math; I might put that like with basic math.

Ashley: Umm... Then if you were to need to calculate molarity in order to get your moles

I used an arc with no arrows when a participant described that two topics were connected but did not indicate that either was dependent on the other, just that they are related or go together. Any time a participant used the term “represent,” I coded that as an arc, or edge, in the diagram (Figure 4.24).
Aaron: These are the uh subscript. Super uh superscripts? Subscripts? They just represent the number of moles of each compound.

I went through each transcript to identify and code excerpts pertaining to connections between topics and used one of the three edges to code each instance.
Chapter 5

Intermediate Results

From the analysis, I identified topics my participants recognized and connections they were able to make between the topics. In this chapter, I define the terms I use to discuss aspects of the results and discuss topics most identified by participants along with the various connections made.

In addition to terms adapted from graph theory, I used the term theme. Themes are groups of vertices within a diagram. I have six themes in the diagram: Core Tools and Concepts, Chemical Reactions, Chemical Equations, Atomic Structure, Energy, and States of Matter. I grouped chemistry topics into one of the six themes based on chemistry connections/relations I saw as an expert. For example, endothermic and exothermic are vertices that were clustered together under the Energy theme. For each participant’s diagram, I identified and counted the number of vertices and edges (Figure 5.1).

The majority of the participants had almost the same numbers of topics and edges in their diagrams. Out of 50 topics, no one mentioned all 50 but most identified and discussed about half of the topics. The total number of topics was slightly greater than the number of edges in most, but not all, diagrams. Many of the participants had topics that did not have any edges. There were a few topics in some of the participants’ diagrams that had multiple edges, which is not represented in this histogram. This histogram provides only the overall count found in each diagram, but little information on conceptualization.

This histogram indicates that all nineteen participants had mid-level knowledge states, with some topics present and others missing. It does not allow us to identify a specific knowledge state for any individual. Furthermore, the large number of possible knowledge states is difficult for instructors
to sort through. Instead of considering all possible knowledge states separately, I looked for patterns of topics that grouped together. Details about specific topics and edges are described next.

Of the fifty topics from the master list (Table 4.20), six topics were common across all participants: moles, molarity, percent yield, limiting reactant, balancing equations, and mass (Table 5.1). *Moles* was also the only topic with degree 1 or higher for every participant, meaning there was at least one edge between *moles* and another topic. Since *moles* was identified by every participant, this means that all think of *moles* when conceptualizing stoichiometry. Additionally, participants also indicated that *moles* is connected to other topics when conceptualizing stoichiometry.

**Table 5.1:** Six topics (vertices) were mentioned by all 19 participants. These six topics were in either Core Tools and Concepts, Chemical Reactions, or in Chemical Equations theme.

<table>
<thead>
<tr>
<th>Topics</th>
<th>Vertex</th>
<th>Theme</th>
</tr>
</thead>
<tbody>
<tr>
<td>moles</td>
<td>1</td>
<td>Core Tools and Concepts</td>
</tr>
<tr>
<td>molarity</td>
<td>2</td>
<td>Core Tools and Concepts</td>
</tr>
<tr>
<td>mass</td>
<td>8</td>
<td>Core Tools and Concepts</td>
</tr>
<tr>
<td>limiting reactant</td>
<td>19</td>
<td>Chemical Reactions</td>
</tr>
<tr>
<td>balancing equations</td>
<td>27</td>
<td>Chemical Equations</td>
</tr>
<tr>
<td>percent yield</td>
<td>16</td>
<td>Chemical Reactions</td>
</tr>
</tbody>
</table>
5.1 Moles as a Central Concept

I counted the degree for moles in each diagram. Once I recorded the total degree for moles in each participant’s diagram, I went back and recorded how many connections moles had to topics outside the Core Tools theme. From these counts, I grouped the diagrams based on the number of themes the mole connected with and came up with four groupings: “Limited”, “Minimal”, “Moderate”, and “Extensive”.

Participants in the “Limited” grouping connected moles with topics only within the Core Tools and Concepts theme. Participants who were grouped in this category had few edges connecting moles to other topics. Topics connected to moles were entirely within the same Core Tools and Concepts theme. Jane’s diagram is a diagram that was grouped as “Limited” (Figure 5.2).

Jane had only one edge with moles. Though Jane does identify that moles is part of stoichiometry, they do not see many connections to other topics. Jane’s connection about the moles would be in the “Limited” category. Throughout the interview, Jane never indicated additional connections with moles.

Participants who were grouped in the “Minimal” category had moles connected to at least one topic in only one theme outside the Core Tools and Concepts. These individuals described more than one topic connecting with moles, but the topics were only in one theme. Ashley is an example of “Minimal” (Figure 5.3).

Ashley’s diagram had a degree of four for moles, but only one of the edges connected to a topic outside the Core Tools and Concepts theme. Individuals in this grouping identified multiple topics as
being connected with moles, but the connection were limited to one theme.

Participants in the “Moderate” grouping had multiple edges connecting moles to topics in two or three themes. This means that participants see connections between moles with topics that are in multiple themes. For example, Oscar has moles connected to topic in three themes outside of the Core Tools and Concepts (Figure 5.4).

Participants in the “Extensive” grouping meant that moles was connected to all or most of the themes. Exploring the topics moles connected with provides insight on the breadth of how students conceptualize stoichiometry. For example, Daniel discussed several different connections between moles and topics (Figure 5.5). Many of these topics were outside of the Core Tools and Concept theme, which indicates that Daniel has an “Extensive” view of how moles is connected to other topics in their conceptualization of stoichiometry.

5.2 Specific Topics and Their Relationships to Moles

Since moles was the only topic (vertex) every participant identified with degree 1 or higher, I wanted to see how the other five topics related to moles when conceptualizing stoichiometry. When a topic was identified as “isolated,” the topic was mentioned and defined but never connected with any topic. Almost all participants had at least one topic that was identified as “isolated.” Though no connections were discussed, the participants did indicate it as a topic in conceptualizing stoichiometry. Fig-
Figure 5.6 provides visual examples of each of the five groupings discussed using \textit{limiting reactant} (vertex 19) and how it relates to \textit{moles}. For each of the five topics (vertices), I explored the connections each participant made with \textit{moles}.

I found that each of these five topics (vertices) fell into one of five categories: not connected to any other topics (isolated) (Figure 5.6a), connected to other topics, but not to \textit{moles} (Separate) (Figure 5.6b), connected to \textit{moles} through an indirect path passing through other themes (Distant) (Figure 5.6c), connected to \textit{moles} through another core topic, but not connected directly to \textit{moles} (Close) (Figure 5.6d), or connected directly to \textit{moles} (Direct) (Figure 5.6e).

A classification as “separate” indicates that the participant did identify and discuss connections to the topic, but there was no connection with \textit{moles}. Topics such as \textit{percent yield}, \textit{actual yield}, and \textit{theoretical yield} were topics that were often connected together, but not with moles (Figure 5.4). For example, Oscar described \textit{percent yield} as \textit{actual yield} over \textit{theoretical yield} but never connected it with \textit{moles}:

Oscar: I think [percent yield] actual over theoretical for percent yield, but I can’t quite remember but I’ll know once I solve the problem because if I get over a hundred and then be a problem,

Classification as “distant” indicates that the participants did make connections with \textit{moles} but the connection was through other topics that connected to \textit{moles}. Daniel’s diagram provides an example of how \textit{limiting reactant} (vertex 19) and \textit{moles} (vertex 1) are related (Figure 5.5). In Daniel’s diagram, \textit{limiting reactant} was connected with \textit{reactants} and \textit{products}, which in turn were connected to \textit{moles}.

Topics identified as “close” were connected to one topic either in the same theme as that topic or in the Core Tools theme, with that topic then connected directly to \textit{moles}. For example, in Daniel’s digram the topic \textit{chemical reactions}, (vertex 21) is connected to balancing equations (vertex 27) which is connected to \textit{moles} (vertex 1). Daniel is most likely to recognize a relationship between \textit{chemical reactions} and \textit{moles}.

Topics identified as “direct” shared an edge with \textit{moles} directly. Oscar mentioned a “direct” connection between \textit{moles} and \textit{molar mass} by describing the connection as the \textit{moles} is a component of \textit{molarity} (Figure 5.4).

Oscar: one mole is equal to like the molar mass of the substance, which is grams per
Figure 5.6  Visual description examples of how a topic connects or does not connect with the moles. There are five potential ways a topic is associated with the moles. In these figures, I used \textit{limiting reactant} (red dot) as an example topic and how it relates to moles (yellow dot) which are indicated as the red paths.

(a) Diagram of \textit{limiting reactant} as “isolated” from moles.

(b) Diagram of \textit{limiting reactant} as “separate” from moles.

c) Diagram of \textit{limiting reactant} as “distant” from moles.

d) Diagram of \textit{limiting reactant} as close to moles.

e) Diagram of \textit{limiting reactant} as “direct” to moles.
mole. makes sense

5.2.1 Limiting Reactant and Moles

Considering all of the participants and how they discussed the connections limiting reactant had, there was a wide range of ways limiting reactant related to moles. No matter how many connections moles had, some participants did not see connections between moles and limiting reactant. Limiting reactant is determined by balancing the chemical equation. The coefficients in a balanced equation represents that number of moles. So it is crucial for students to recognize that there is a relationship between limiting reactant and moles. As shown in Figure 5.7, very few participants mentioned a direct connection between limiting reactant and moles.

![Histogram of how participants connected limiting reactant to moles. The y-axis represents the count of participants in the given category.](image)

**Figure 5.7** Histogram of how participants connected limiting reactant to moles. The y-axis represents the count of participants in the given category.

5.2.2 Percent Yield and Moles

The majority of the participants identified percent yield as a separate topic that was not connected to moles even by a path through other topics. What this implies is that percent yield is a topic all participants identify when conceptualizing stoichiometry, but they do not see any connection with the moles. There were a handful of participants who indicated that percent yield had a connection with moles but only one who described a direct connection. Referring back to the roadmap in Chapter 2, percent yield is one of the nine major topics. More specifically, percent yield and moles are connected in the roadmap yet many of the participants did not describe any
connections between these topics.

Figure 5.8 Histogram of how participants connected percent yield to moles. The y-axis represents the count of participants in the given category.

5.2.3 Balancing Equations and Moles

The connections participants saw between balancing equations and moles were quite different compared to limiting reactant and percent yield. Participants who had a “limited” connection with moles were more likely to not connect moles with balancing equations. Most did not make any direct connections between balancing equation and moles. In a balanced equation, the coefficients represents the number of moles. From Figure 5.9, we see that although most of the participants did not see a direct connection between the two topics, they did recognize a close connection. For example, Amanda mentioned the coefficients as the number of elements, but did not mention moles:

Amanda: Umm, so like the coefficient so over here I didn’t have any because there was nothing to like their the elements are equal on both sides so I don’t have to add anything but like for example if there was umm... like two potassium molecules on the side. I would have to make this. I have two potassium molecules. Like I have to put a 2 here

Students like Amanda may not recognize that a balanced equation relates to having an appropriate proportion of moles for both the products and reactants. This may imply that they may not realize that the coefficients in a balanced equation represents the number of moles. This may add cognitive load in solving stoichiometric problems as they may need an additional processing step even when they describe a close but indirect connection.
Figure 5.9  Histogram of how participants connected balancing equations to moles. The y-axis represents the count of participants in the given category.

5.2.4 Molarity and Moles

Molarity is another topic all participants identified and discussed during the interview. As seen in Figure 5.10, the majority of the participants made a “close” or “direct” connection between molarity and moles. Very few participants saw no connection between molarity and moles. This result indicates that participants, for the most part, are able to see and discuss connections between molarity and moles.

David had a “direct” connection between molarity and moles. The number of connections David made with moles was fairly large. David mentioned how the definition of molarity helps with solving for a certain amount of moles:

David: You can use the coefficients kind of for, um, you can use them in molarity sometimes just because it is in terms of moles. Moles over liters and if liters don’t change then the only instance that matters is the top part which is the moles.

As described by David, molarity is concentration with moles over liters as the unit. Since David indicated that moles is a component of molarity, they made a direct connection between the two topics. This clear description that David provided is one way molarity is introduced in General Chemistry courses.

Amanda discussed that molarity is part of stoichiometry, but did not discuss how or if molarity was even connected to moles.
Amanda: So don’t we learn how to convert between like molarity and molality and different concentrations? Which was new in like how like we’d get a problem and let’s say molarity and then I would ask you like to convert it to molality and then good kind of that with a osmotic pressure...

...So, we have the molarity and then milliliters, maybe I guess solve the moles and put it to grams? Umm, And then trim it from that. limiting reactant. that’s how I would approach that, umm. Yeah.

Amanda recognized the information they gathered (molarity and milliliters) was relevant but was uncertain about how it related to moles and mass. Amanda also identified that molarity is a concentration but never described the units or connected it with moles. Instead, Amanda associated molarity and molality as concentrations. Though Amanda explicitly did not connect molarity with moles, they did think that molarity was a tool to find moles, which would be considered a “close” connection.

The roadmap described in Chapter 2 does not incorporate molarity in the nine topics; however, General Chemistry courses often incorporate molarity as a topic in stoichiometry.

5.2.5 Mass and Moles

Nearly all participants discussed that there is a direct relationship between mass and moles as shown in Figure 5.11. The majority of the participants provided details that mass is used to find
moles and/or moles is used to find mass. The majority of the participants described the relationship that moles and mass are components to molarity. Therefore, if participants see a “direct” or “close” connection between mass and moles, they are likely to see connections between moles and molarity.

Miriam provides a correlation between grams and moles:

Miriam: When I think of right? That’s stoichiometry, right. Is like we go from grams to like... Trying to go from grams to moles and you can like convert from like grams of like Na to grams of chloride or whatever.

The roadmap incorporates mass in Mass Percent which is connected to moles in the roadmap. Almost all participants referred to grams, which is a unit of mass. The relationship with grams to moles is generally discussed as molar mass in General Chemistry courses. Many stoichiometry problems require molar mass as a step when solving.

![Figure 5.11](image.png)

**Figure 5.11** Histogram of how participants connected mass to moles. The y-axis represents the count of participants in the given category.
Chapter 6

Various Ways of Conceptualizing Stoichiometry

6.1 Categories of Description

In my outcome space, I present five distinct categories of description of the various ways students conceptualize stoichiometry. My intermediate results helped develop my categories of description. As discussed in the previous chapter, all participants identified and discussed six topics: moles, mass, molarity, balancing equations, percent yield, and limiting reactant. These topics were in one of the three themes: Core Tools and Concepts, Chemical Equations, and Chemical Reactions. Since all participants discussed topics in each of the themes, I was able to conclude that these three themes are the common and core parts of students’ conceptualization of stoichiometry. This became essential when developing my outcome space. I used my intermediate results to help develop my outcome space. My intermediate results focused on aspects pertaining to topics and connections. The idea of looking at the variation of topics and connections allowed to see what students focused on. Topics from three themes (Core Tools and Concepts, Chemical Reactions, and Chemical Equations) were discussed by all participants in some shape or form. As mentioned earlier, the six topics all participants identified were grouped in one of the three themes: Core Tools and Concepts, Chemical Equations, and Chemical Reactions. Therefore, having a category of description solely on the focal point of the Core Tools and Concepts was not ideal because every participant discussed topics and
connections in that particular theme. Because all participants mentioned connections with topics in all of these themes, I combined the themes into one cluster: “Core.”

6.1.1 Category 1: Core Focused

Some of the participants focused on topics and connections in only the three themes that every participant touched. Participants who focused only on these three themes were categorized under Core Focused Conceptualization. Instructors would consider these participants to have a narrow conceptualization of stoichiometry. Topics such as moles, balancing equations, mass, molarity, and percent yields are essentials to stoichiometry. Instructors will often use these six topics when introducing stoichiometry. Additionally, these six topics are also mentioned in the roadmap visual model discussed in Chapter 2. Individuals in this category are more likely to focus on topics pertaining to what was shown in the roadmap visual model.

6.1.2 Category 2: Core-Matter Focus

Participants in this category conceptualize stoichiometry with not just core tools and chemical equations and reactions but also topics that fall under the States of Matter theme. The topics and connections participants described in this particular category incorporated topics such as solutions, solutes, and solvents in addition to the six topics clustered in the “Core.” Individuals in this category recognize topics pertaining to states of matter as a part of their conceptualization of stoichiometry. They are more likely to have a macroscopic and real-life application approach to conceptualization of stoichiometry. What this indicates is that these participants have a slightly broader way of conceptualizing stoichiometry compared to the participants in the previously discussed category.

When explaining stoichiometry, an individual in this category would include topics such as solutes and solvents and connect it with molarity which are topics from the States of Matter theme in addition to Core cluster themes. The focus is on the idea of how reactions are based on solutions and how the states of matter of reactants will determine what the products will be and in what state of matter.
6.1.3 Category 3: Atomic Core-Matter Focus

Participants in this category conceptualize stoichiometry with a focus on Atomic Structure and States of Matter in addition to Core Tools and Chemical Equations and Chemical Reactions. Topics and connections between the Atomic Structure, States of Matter, and the “Core” clustered themes are described by participants in this category. Students with this focus are likely to conceptualize stoichiometry with topics pertaining to the interactions between atoms and molecules in various states of matter such as solutions, for example. Participants in this category are more likely to think about what is going on inside a solution or when solutions are mixed which can explain why some chemical reactions occur. Additionally, this particular type of conceptualization indicate that students see how aspects of both the states of matter and atomic structure are a part of stoichiometry. Topics such as elements, solutions, and atoms are connected to each other and come from three different themes: Core Tools, Chemical Equations, Chemical Reactions, Atomic Structure, and States of Matter themes.

6.1.4 Category 4: Atomic Core-Energy Focus

Participants in this category conceptualize stoichiometry with a focus on Atomic Structure and Energy in addition to Core Tools and Chemical Equations and Chemical Reactions. This type of conceptualization indicates that students would be able to conceptualize stoichiometry with a combination of Atomic Structure and Energy themes along with “Core.” Topics such as atoms, exothermic, and attractions all pertain to how elements and compounds interact and is an example of what students described in this category. Individuals in this category are more likely to include a focus on interactions at an atomic level when conceptualizing stoichiometry.

6.1.5 Category 5: Holistic Focus

This category is where participants incorporate and focus on all the themes from the master diagram in Figure 4.21. These individuals have a broad conceptualization of stoichiometry which indicates that the participants identify and make connections between topics across multiple themes when conceptualizing stoichiometry. Students are able to see and describe many topics and connections across all chemistry areas. Though participants in this category did not discuss all fifty topics, they discussed multiple topics and their connections between all themes from the master diagram.
Students made connections within and between all themes to conceptualize stoichiometry. Their topics and connections expands to other themes. This does not imply that topics in one theme are connected to all other themes, rather topics from one theme may connect to different themes but not between each other. For example, consider limiting reactant and percent yield, which are both in the Chemical Reaction theme. Though students may or may not connect these two topics to each other, percent yield may connect to a topic in Chemical Equation theme while limiting reactant might connect to a topic in Core Tools and Concepts theme.

### 6.2 Outcome Space

The categories of description can provide an insight on the various ways students conceptualize stoichiometry. The categories describe aspects in ways to conceptualize stoichiometry, each having a unique set of focus. In particular, we can see that this variation is a range of different focuses when conceptualizing stoichiometry (Figure 6.1).

<table>
<thead>
<tr>
<th>Category Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Core Focus Conceptualization</td>
<td>Only Core Tools and Chemical Reactions and Chemical Equations are the themes that were focused on when conceptualizing stoichiometry.</td>
</tr>
<tr>
<td>2. Core-Matter Focus Conceptualization</td>
<td>In addition to Core Tools and Chemical Reactions and Chemical Equation, one additional theme was also focused on when conceptualizing stoichiometry.</td>
</tr>
<tr>
<td>3. Atomic Core-Matter Focus Conceptualization</td>
<td>In addition to Core Tools and Chemical Reactions and Chemical Equation, Atomic Structure theme and States of Matter were additional themes focused on when conceptualizing stoichiometry.</td>
</tr>
<tr>
<td>4. Atomic Core-Energy Focus Conceptualization</td>
<td>In addition to Core Tools and Chemical Reactions and Chemical Equation, Atomic Structure theme and Energy were additional themes focused on when conceptualizing stoichiometry.</td>
</tr>
<tr>
<td>5. Holistic Focus Conceptualization</td>
<td>All themes were focused when conceptualizing stoichiometry.</td>
</tr>
</tbody>
</table>

Figure 6.1 Outcome Space: Categories of Description of the various ways Students Conceptualize Stoichiometry. Each horizontal row represents an additional focused theme when conceptualizing stoichiometry.

Each of my participants fall into one of the five categories presented in the outcome space. Each category represents the different focus participants had when conceptualizing stoichiometry. Although participants identified similar collections of topics related to stoichiometry, the ways they conceptualized connections between topics varied. Participants in Category 1 explicitly focused on topics such as balancing products and reactants when asked to conceptualize stoichiometry, all represented in the “Core.” I had participants’ incorporate topics from the States of Matter theme...
such as solutes, solvents, and solutions and how those topics are components in conceptualizing stoichiometry in Category 2. In Category 3, participants incorporated topics from States of Matter theme such as solutes, solvents, and solutions and Atomic Structure such as atoms and molecules in addition to the “Core.” Participants that focused on the “Core” along with Atomic Structure and States of Matter themes were grouped into Category 4. The only difference between Category 3 and 4 is that Category 3 incorporates Energy but not States of Matter and Category 4 incorporates States of Matter but not Energy. Category 5 presents a focus incorporating several topics and connection amongst all the themes. Details on the implication from this outcome space and study are discussed in the next chapter.
Chapter 7

Discussion

My model provides information on the different ways students conceptualize stoichiometry including topics identified and how they connect with each other. This study purely looked at how General Chemistry students conceptualized stoichiometry. I took an in-depth approach and allowed participants to identify and describe connections they saw without comparing to chemistry experts. Participants in my study identified and described connections that were not described in the visual roadmap.

7.1 Connections to Conceptualization Studies

As educators, we recognize that stoichiometry is complex. This model provides additional information that can help educators see what areas we can focus more on when teaching stoichiometry. For example, my outcome space indicates that some students do not see any association between states of matter and stoichiometry. Though we embed states of matter into the stoichiometry curriculum, we can be more direct in explaining why states of matter are important and related to stoichiometry. At the same time, my model indicates that students recognize and see only portions of the topic in the “roadmap” of stoichiometry such as balancing equations and moles. General Chemistry students who learn about stoichiometry range from having a narrow to broad conceptualization of stoichiometry. As instructors, this model can help us see and identify topics and connections we may want to expand on explaining when teaching stoichiometry. Instructors can also use this information to explore alternative pedagogical ways to help students see and make
connections between topics. Findings from my study will lead to additional studies that explore factors that affect conceptualization as discussed in detail later in this chapter. This model does provide categories of the range of conceptualization, but does not provide insight on how it relates to performance and persistence directly.

7.1.1 Roadmap

Gulacar’s roadmap consists of nine topics and how they connect based on what chemists agree to be true [Gulacar, 2007, Dahsah and Coll, 2008]. In my study, I noticed that collectively, all nine of the topics were identified and discussed by some participants. However, based on my model and intermediate results, only four out of the nine topics were identified by all of my participants: percent yield, balancing chemical equations, limiting reactant, and the mole concept. Additionally, none of my participants drew a concept map that looked similar to the roadmap. Furthermore, the least number of topics identified by a participant was thirteen topics, not nine. Some of the topics participants identified in my study were topics that are embedded in the nine topics from the roadmap. For example, some participants mentioned products, reactants, and Avogadro’s number as topics. All three of these topics are part of the description mentioned when describing the nine topics in Gulacar’s roadmap [Gulacar, 2007].

Gulacar’s roadmap is one type of visual that can be used in teaching stoichiometry but I do not know if any of my participants’ instructors had used this particular visual since that information would be out of the scope of my study. Furthermore, none of my participants drew a concept map that looked like any of the visuals instructors may use when teaching stoichiometry such as the pictorial framework [Gulacar, 2007, Arasasingham et al., 2004, Cameron, 1985].

7.1.2 Knowledge Space Theory

Knowledge Space Theory (KST) is yet another avenue researchers have used in exploring how students solve chemistry problems. This theory provides insight on some of the topics students are able to connect [Tóth and Sebestyén, 2009]. Studies that incorporated KST as a way to explore student conceptualization looked at alignment with chemists’ view of mastery under the assumption that if a student was able to solve a problem or answer a question correctly, then that would mean that they possessed particular knowledge states [Tóth and Sebestyén, 2009]. Though this
information is useful, there is an assumption that the student was able to see and make the same connections as described in a given knowledge state. In my study, I had several participants who identified a group of topics and made connections between those topics in a similar way. For example, several participants mentioned that percent yield is defined as actual yield over theoretical yield. The relationship between these three topics would provide information regarding the student’s current knowledge state. Likewise, I had participants who described percent yield but were not able to solve a chemistry problem involving percent yield. Their knowledge states are arguably less robust as they may not be able to see or apply connections between concepts when solving problems. This aligns with what Chandrasegaran and Gulacar discussed in their studies [Gulacar, 2007, Chandrasegaran et al., 2009]. Though parts of my study touch on the idea that students may be able to understand and make connections to topics, they may not be able to apply that knowledge to solve chemistry problems.

Additionally, KST identifies that there are knowledge states that have groups of topics connected, but the details of how they are related does not exist. Knowledge states only provide connections between topics, not how or why topics connect. Such details are important as it can identify what individuals understand or misunderstand. The purpose of my study was not to look for what students understand or misunderstand, but I was able to capture discussions that can provide insight into that issue. For example, some students mentioned that the coefficients in a balanced equation represent the number of moles needed for the reaction to occur while others claimed that coefficients represented the mass. Though participants from both groups were able to properly balance a chemical equation, they may not have the appropriate knowledge state.

7.1.3 Concept maps

Each participant developed a series of concept maps on topics they believed were related to stoichiometry. The concept maps provided an opportunity for my participants to discuss and show the topics and relationships between topics [Novak and Gowin, 1984, Pendley et al., 1994, Regis et al., 1996]. All concept maps were developed based solely on what the participant thought of and without any terms or definitions provided to them. Concept maps were modified throughout the interview as participants solved chemistry problems. All participants altered their concept maps at least once, indicating that activated knowledge played a role [Paul and Elder, 2001]. Some participants discussed additional topics as they solved chemistry problems and as they further elaborated on topics they
initially mentioned. Though concept maps provide a visual of how multiple topics or related, they can end up not having sufficient details about the relationships [Regis et al., 1996, Pendley et al., 1994]. For example, I mentioned in my analysis that the concept maps only provided information about what the participant believed was essential in understanding stoichiometry. If I had not probed and asked for the participants to further explain or describe some of the relationships, I would not have been able to provide details such as having different types of edges defined in my codebook. Additionally, if a participant drew a single arrow connecting two topics, that could mean that one topic is needed to in order to get the second topic, or could represent a stage in a process for solving a chemistry problem.

One reason STEM is considered difficult is because students struggle understanding the fundamentals taught in introductory courses such as stoichiometry. My model will help explain some of the different ways General Chemistry students conceptualize stoichiometry which can help instructors and curriculum developers find ways to help students understand stoichiometry. If students can understand stoichiometry, they are more likely to pass their General Chemistry course, which can affect their decisions in pursuing a degree.

7.2 Delimitations and Limitations

Delimitations and limitations, or boundaries, are essential in any qualitative study. They help keep the study focused and aligned with the research question(s). Delimitations are the boundaries of the study set by the researcher while limitations are known to be conditions that are outside of the researcher’s control. In this section, I describe the delimitations I set and limitations I encountered in my study.

7.2.1 Delimitation

I did not ask questions related to demographics such as gender, race, or ethnicity because that information was not necessary for exploration of differences in stoichiometry conceptualization. In order to ensure a diverse sample that maximized variation in the ways students conceptualize stoichiometry, I used participants’ intended majors to structure my sample. The participants in my research who took General Chemistry II at Clemson University included engineering, biology, physics, and chemistry as their intended majors. With the boundary of only looking at General
Chemistry II students, I was not able to interview participants from every STEM major because not all STEM fields require both General Chemistry I and II courses. A future direction from this aspect of the study would include exploring the extent General Chemistry is a required course for the major and how that affects conceptualization of stoichiometry. In particular, it would be interesting to determine if there is an association between program requirements and the ways students conceptualize stoichiometry. Results from this future study might contribute to discussions on whether the General Chemistry curriculum needs to be changed based on the extent of the course requirement as well as on student major.

In order to ensure that the subjects of my study had knowledge of stoichiometry, I restricted my sample to General Chemistry II students; stoichiometry is taught throughout the second half of General Chemistry I and final exams would interfere with my data collection. Therefore, I decided to conduct my study and select participants enrolled in General Chemistry II. General Chemistry II courses have a large enrollment of approximately 1,500 students in the spring semesters, so I was easily able to recruit 19 students for my study. Additionally, stoichiometry is reviewed at the beginning of the course curriculum in General Chemistry II before the first test. I conducted my full study right after the first test in General Chemistry II.

Finally, all my participants were enrolled at Clemson University. I specifically selected Clemson University because of the large class enrollment in General Chemistry I and II, and because all the sections are synchronized so that all the students take the common American Chemical Society (ACS) standardized exam. Because I bounded my study to one university, I have no way of knowing if I captured a good representation of those who take General Chemistry courses in the nation. Chemistry course requirements at this institution may differ from other institutions such as small liberal arts colleges and community colleges.

7.2.2 Limitations

Since I recruited through email, students who responded may not be the best representation of the General Chemistry II population. Those who responded may not represent the full range of majors enrolled in General Chemistry II. Even after selecting for maximal variation among the responding sample, I likely did not capture the full variation in the population. Since I was not able to directly email the students enrolled in General Chemistry II, I asked the General Chemistry
instructors to send out a drafted email to their students. In order to ensure that I did not connect
my participants with their instructor, the instructors did not include me in the email distribution. I
did not know exactly when the instructors distributed the emails, but I could approximate the date
based on when students completed the qualification survey. With the low response rate of less than
twenty percent, there is a chance that some of the instructors did not distribute the email linked
survey to their students.
Chapter 8

Conclusion

One of the foundational topics in general chemistry is stoichiometry, which describes the relationships between compounds and elements in a reaction. Students often struggle with stoichiometry, affecting their performance not only in general chemistry but also in other STEM courses that rely on stoichiometric concepts. My dissertation is a phenomenography of the different ways general chemistry students conceptualize stoichiometry.

Phenomenography looks at different ways people (e.g., students in General Chemistry) experience a phenomenon (e.g., conceptualizing stoichiometry). Pilot studies play a huge role in phenomenography as they help researchers capture maximal variation and refine interview protocols.

The purpose of this study was to explore the different ways students conceptualize stoichiometry in General Chemistry. The results indicate that there are different ways students conceptualize stoichiometry, specifically the number of connections students make between topics and the types of connections students make between topics in stoichiometry. My study developed a model of five categories of ways students conceptualize stoichiometry. Conceptualization of stoichiometry and how it relates to persistence and performance would be a future study developed from this research. Having a model which incorporates how students conceptualize stoichiometry will provide a foundation for assessing differences in teaching styles to support deeper conceptualization in addition to the use of algorithms in General Chemistry.

I developed a model of the different ways student conceptualize stoichiometry. The model was developed based on interview data and participant-developed concept maps. Although participants identified similar collections of topics related to stoichiometry, the ways they conceptualized
connections between topics varied. From the model, I used chemistry topics participants identified within stoichiometry and grouped them in major chemistry clusters: States of Matter, Chemical Equations, Chemical Reactions, Energy, Atomic Structures, and Core Elements. Though all participants identified a set of chemistry topics associated with stoichiometry, the ways the topics connected varied. The model articulates categories of connections students form.

I developed the model from my study to contribute to the improvement of the chemistry curriculum by chemistry instructors and chemistry education researchers. Studies in chemistry education research have revealed that students struggle in introductory chemistry courses and find the course difficult. This study adds to the literature in both general education and chemistry education research by identifying that the different ways students conceptualize stoichiometry may not align with their instructors’ conceptualization.
Chapter 9

Future Directions

My study is theoretical in nature, rather than a study of a particular instructional method or intervention. However, the results from my study can help initiate research related to administrative and practitioner practices. In this chapter, I discuss potential projects that branch off from my study. These projects are only some of the many projects that can come out from my study.

9.1 Factors Affecting Student Conceptualization of Stoichiometry in General Chemistry

In order to consider some of the factors that affect conceptualization, I believe developing a survey instrument can provide some insight on some of these factors and their associations with conceptualization. I plan to combine my model of student conceptualization of stoichiometry (SCS) with existing models for persistence to look at some of the factors such as institutional factors, environmental factors, and student academic profile. I will have two components driving this study: 1) developing a survey using the model and 2) implementing the survey by distributing it to General Chemistry students. This will allow me to specifically look at associations between student performance and conceptualization as well as separately compare course structures and conceptualization.

I will use my model of SCS to develop a survey instrument to capture SCS. Optional components of the survey will include blocks related to factors that might affect SCS such as Rovai’s composite model which includes individual, environmental and institutional factors [Rovai, 2003],
These factors are known to affect persistence.

The overall goal of this project will be to develop a survey which categorizes students based on their conceptualization with optional blocks related to factors that may affect SCS such as institutional and environmental factors. I plan to develop a survey instrument with 15-24 items for each of the following blocks: SCS, environmental factors (course structure, classroom environment, etc.), and student academic profile (intended major, current academic year, etc.). The SCS block will be the core of the survey followed by the optional blocks based on the purpose of administering the survey. The survey development will undergo thorough test-retest for survey consistency, survey fatigue, face and content validity, and reliability. The purpose of developing the conceptualization survey is so other education researchers can use it to explore additional factors related to SCS.

For example, the 4C/ID model contains four interrelated components for complex learning and associated instructional methods: learning tasks (promote schema construction which can lead to developing problem solving work patterns), supportive information (transferring knowledge to learning tasks or bridging/ connecting prior knowledge), just-in-time information or JIT (instructors work out examples that incorporate skills and knowledge used explicitly), and part-task practice (extra practice to reinforce learning tasks) [Van Merriënboer et al., 2002]. Overall this model focuses on helping instructors guide students not just solely on how to solve problems, but also on understanding what the problem is asking and what the solution(s) mean. In traditional chemistry instructional approaches, students are usually expected to read the textbook or content and then regurgitate the information in assessments. Many focus on the explanation followed by the application process especially in traditional lecture courses [Evans et al., 2008]. A study using the SCS survey would allow empirical testing of the effect of implementing the 4C/ID instructional model versus traditional approaches on student conceptualization of stoichiometry.

9.2 Student Conceptualization of Other Fundamentals in Chemistry

Following a similar methodology and methods, another extension of this work involves investigating the different ways chemistry students conceptualize other foundational ideas such as quantum numbers and energy in General Chemistry or mechanisms in organic chemistry. Organic chemistry is another chemistry course some STEM-intending students take as part of their program
requirement. Mechanisms in Organic Chemistry focus on the process of an organic reaction. Details of mechanisms in Organic Chemistry are usually taught throughout the two-part Organic Chemistry courses.

The outcome for this particular study would be a model of the different ways students conceptualize each of the following foundational ideas: quantum numbers (in General Chemistry), energy (in General Chemistry), and mechanisms (Organic Chemistry). Similar to the results and model of my study on student conceptualization of stoichiometry, these future models would only provide an insight into what students think, but the models could serve as the foundation for developing additional survey items to look at factors affecting student conceptualization.

9.3 Instructor Conceptualization of Stoichiometry

My research provides details on the different ways student conceptualize stoichiometry. What about the instructors? Do the students’ conceptualization of stoichiometry align with their instructors’ conceptualization of stoichiometry? Another branch or future direction is to explore the different ways General Chemistry instructors conceptualize stoichiometry and to what extent students’ conceptualization align with their instructors. Gulacar’s roadmap of stoichiometry was based on agreement among chemistry experts. Looking at the different ways instructors conceptualize stoichiometry could help describe why students conceptualize stoichiometry in different ways.
Appendices
Appendix A  Recruitment Emails

Email recruitment draft template

Subject line: Talk to us about chemistry for $20

Body:
A research team here at Clemson University is interested in how students think about chemistry concepts in general chemistry.

We are looking for a wide range of thinking, so it doesn't matter how you are doing in the course. Participants will be interviewed three times over the course of the semester. Each interview will last about an hour. All responses will be kept completely confidential.

During each interview, we will ask questions about how you are thinking about concepts in general chemistry. We may also ask you to explain some of your thinking on test questions from your class. Your instructor will not know who is taking part in the study and who is not.

If you are selected to participate, you will receive a $20 gift card as an incentive at the completion of each interview.

If you are interested in participating in the study, please click on the link below to sign up. Not everyone who registers will be invited to be interviewed. The last day to complete the survey is [date].

LINK TO QUALTRICS
If the link above does not work, copy and paste the following url directly into your browser:

URL ADDRESS
Email template to invite participants for interview

Subject: We want to know how YOU think about chemistry!

Dear [student],

Thank you for completing our online survey. We have selected you as a participant in our study and would like to schedule the first one-hour interview with you. All responses will be kept completely confidential.

During each interview, we will ask questions about how you are thinking about concepts in general chemistry. We may also ask you to explain some of your thinking on test questions from your class. Your instructor will not know who is taking part in the study and who is not. Most interviews will take place in Holtzendorff, but if that presents difficulties for you, we can find another location. This is not a formal interview, so you do not need to prepare for anything.

Please click on the following link to schedule a date and time for the interview. Once we receive your schedule, we confirm a date, time, and location of the interview.

[link to ScheduleOne]

If the link does not work, copy and paste the following URL.

[url address]

Thanks,

“Khushi”
Appendix B  Qualification Survey

6/27/2016

Conceptualizing Stoichiometry Qualification Survey

Q1  Welcome!
Dr. Eliza Gallagher and Khushi Patel are inviting you to take part in a research study. The purpose of this study is to understand how students think about key concepts in general chemistry.
We are looking for a wide range of thinking, so we would love to talk to students who feel that they are struggling with the material, those who feel they completely understand the material, and those in the middle. Participants will be interviewed three times over the course of the semester. Each interview will last about an hour. All responses will be kept completely confidential.
During each interview, we will ask questions about how you are thinking about concepts in general chemistry. We may also ask you to explain some of your thinking on test questions from your class. Your instructor will not know who is taking part in the study and who is not.
If you are selected to participate, you will receive a $20 gift card as an incentive at the completion of each interview.
If you would like to participate and are at least 18 years old, please answer the following questions. We will contact you within the next two weeks if you are selected for participation. If selected, you are not obligated to participate, and participants may exit the study at any time for any reason.

☐ I consent and am 18 or older, begin the survey
☐ I do not consent, I do not wish to participate

Condition: I do not consent, I do not ... is Selected. Skip To: End of Survey.

Q3 Thank you! Let’s start with some basic information.

Name

Email address

Phone number

Q4 Do you receive test messages at the phone number you provided? (Please take a moment to ensure your contact information is correct because this is how we will get in touch with you regarding gift card incentives and focus group scheduling.)

☐ Yes
☐ No

https://lemsonconecas.as1.qualtrics.com/ControlPanel?ClientAction=EditSurvey&Section=SV_4VeW90ZI3k3Qg8B&SubSection=&SubSubSection=&Page=1
Q5. If you are selected for an interview, how may we reach you? (Select all that are acceptable.)
- Email
- Phone call
- Text

Q10. Which gender category do you most closely identify with?
- Men/men
- Women/women
- Non-binary
- Decline to disclose

Q27. What course are you currently taking?
- CH 1010
- CH 1020
- Neither CH 1010 nor CH 1020

Q14. Are you planning on taking CH 1020 next semester?
- Yes
- No

Q20. We will use the information in this survey to identify people to invite for a series of on-campus interviews. Each interview will last approximately 60 minutes. Everyone who participates in an interview will receive a $20 gift card. Participants can receive a total of $60 in gift cards. If you are identified as a potential participant for the interviews, may we contact you using the contact information you provided?
- Yes
- No
Appendix C  Interview Protocol

Spring 2019 Date: ___________________  Time: ___________________

Student conceptualization of Stoichiometry in General Chemistry
Semi-structured Interview Protocol

Introduction: Thank you for coming to talk to us today. My name is _________________.
I am asking your permission to audio record this interview. The audio recording will be deleted
once the study is completed. Could you please confirm for the record that you give your consent
for us to record this interview? ____________________________________

Thank you. Today, we’d like to ask you some questions about your conceptualization of
stoichiometry. Your responses will be reported in an unidentifiable way and won’t be linked
to you personally. If you feel uncomfortable with any question, you may choose not to answer
it, and you’re free to stop the interview and leave at any point. Do you have any questions
before we start? __________

Interview Questions (NOTE: The interviewers may skip some of these questions, or may
ask follow-up questions to probe more deeply as needed, but the scope of the questions will
remain on student’s conceptualization of stoichiometry.)

☐ What are you currently learning in your General Chemistry Course?
☐ What other topics have you covered in class so far in this semester?

☐ What does stoichiometry mean to you?

*(NOTE: The next set of questions involves the participant using a LiveScribe Pen.)*

For the following set of questions, we would like you to use the LiveScribe pen and paper
provided. The LiveScribe pen records what you write on the paper provided. It will only record
what you wrote and what you say during the time you use the pen. Do you have any questions
before we start? _______________

Index cards activity:

☐ What topics or fundamentals do YOU believe are essential need in order to understand
stoichiometry? Can you write them down on the index cards provided? (Probe for meaning
of each response listed) *** 1 word/ phrase per card
☐ What topics or fundamentals do YOU believe are essential need in order to solve
stoichiometry problems?
☐ Could you show me the relationship between any of the topics YOU see by organizing the
topics in a way that makes sense to you? Feel free to draw anything to show any connections.
☐ Explain the differences between understanding stoichiometry and solving stoichiometry
problems?
Solving Stoichiometry Problems

☐ We would like you to solve the following problems

***If students ask if they solved the problems correctly, respond by saying that the correctness of the answer is not what is important; we just want to know how you are thinking when solving the problem.

☐ Can you tell me more about [CONCEPT] (*drawn from the attached list*), based on prior responses?

☐ How important is [CONCEPT] in solving stoichiometry?
☐ How important is [CONCEPT] in understanding stoichiometry?

☐ What topics/fundamentals do YOU believe are essential in understanding stoichiometry? Explain.

☐ What topics/fundamentals do YOU believe are essential in solving stoichiometry problems? Explain.

For the sake of confidentiality, we won’t use your actual name today in analyzing or reporting the results from this study. Instead we would like to use a pseudonym. What would you like for us to use?

Pseudonym selected by participant: ______________________________

Thank you, PSEUDONYM.
Appendix D  Chemistry Problems

These are the four chemistry problems I had all participants solve during the interview session. Each problem was presented on a separate half-sheet of paper. All four problems were presented at the same time, arranged in the order shown below but without numbering. Most, but not all, participants worked the problems in the order presented here.
Write the balanced chemical equation for the chemical reaction where potassium superoxide (KO₂) solid reacts with carbon dioxide (CO₂) gas to form potassium carbonate (K₂CO₃) and oxygen (O₂) gas.

When 30.0 mL of 0.10 M AgNO₃ is added to 30.0 mL of 0.10 M NaCl, aqueous NaNO₃ and solid AgCl are formed. How much solid AgCl is produced?
In the diagram above the paired open spheres represent H₂ molecules and the paired solid spheres represent N₂ molecules. When the molecules in the box react to form the maximum possible amount of ammonia (NH₃) molecules, what is the limiting reactant?

Ammonia is produced in accordance with this equation.

\[ \text{N}_2(g) + 3\text{H}_2(g) \rightarrow 2\text{NH}_3(g) \]

In a particular experiment, 0.25 mol of NH₃ is formed when 0.50 mol of N₂ is reacted with 0.50 mol of H₂. What is the percent yield?
Appendix E  Participant Diagrams

The diagrams included here are based on analysis of the full transcript and the sequence of concept maps generated by each participant. Each is presented using the master diagram of 50 topics as discussed in Figure 4.21 and the edges described in Table 4.8. The participant diagrams are included in alphabetical order by pseudonym.
References


