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Inorganic Chemical Reasoning Skills: An Exploratory Study into Understanding Students' Choices and Thought Processes

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INORGANIC CHEMICAL REASONING SKILLS: AN EXPLORATORY STUDY INTO UNDERSTANDING STUDENTS' CHOICES AND THOUGHT PROCESSES

A Master's Thesis

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In Partial Fulfillment

Of the Requirements for the Degree

Master of Science, Chemistry

By

Hannah P. Thompson

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Chemistry and Biochemistry

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ABSTRACT

Predicting the products of reactions is a fundamental skill for practicing inorganic chemists. However, the current knowledge of the strategies that students use to solve them is limited. Presumably, instructors of inorganic chemistry courses give complete-the-reaction assessment items hoping that students will use their knowledge of inorganic concepts to solve them; but it is conceivable that a successful student could use heuristics or domain general problem-solving methods. I proposed this study to determine which strategies were used by students when solving complete-the-reaction tasks in inorganic chemistry, and also to make qualitative connections between strategy and accuracy. This was done in order to determine if any problem-solving strategies result in greater task accuracy, and if so, how they promote the greater accuracy. I investigated the strategies of students enrolled in inorganic chemistry courses at a regional, four-year undergraduate institution in the Midwestern United States, using phenomenography as the theoretical framework. For the tasks, I gave participants one reactant and one product of a chemical reaction and asked them to provide the additional reactant(s) and product(s). I conducted semi-structured interviews lasting approximately 45 minutes using a think-aloud protocol. During data analysis, I used transcriptions and accuracy data to qualitatively compare using content analysis to categorize and interpret participant strategies. This study found that participants' overall problem-solving strategy was made of initial steps, strategies, and verification strategies. The main strategy combined means-ends analysis and heuristics. Though each had low relevance to inorganic chemistry classroom concepts, the combination still often resulted in correct answers. While the other strategy components had relevance to inorganic topics, students often struggled with accurate recall of the concept or application to problem solving. The best performing participants engaged in a variety of strategies as needed, based on task category, and they were able to verify their answers before moving on. The results indicate that students are able to solve complete-the-reaction tasks relying on recognition or memorization, rather than class concepts.

KEYWORDS: inorganic, chemistry education, problem solving, phenomenography, prediction of products, chemical reaction analysis

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I: INTRODUCTION

In order to teach students problem-solving strategies that are effective, the instructor should first be able to identify students' successful strategies apart from the unsuccessful ones. In traditional instruction in higher education, identifying such strategies has often been left to the prior experience and intuition of the instructor, who tends to be a content expert. Complete-the-reaction tasks are common questions and assessments in inorganic and general chemistry classrooms, but research into how students strategize as they solve this type of task is lacking. The goal of this study is to identify some of the main strategies used by students when solving complete-the-reaction tasks in inorganic chemistry.

Complete-the-reaction tasks are a common type of assessment where students are given an incomplete chemical reaction and asked to fill in the necessary reactant(s) and/or product(s) in order to make the reaction proceed. Being able to predict, solve, and manipulate chemical reactions is a valuable skill for practicing chemists, especially for those specializing in inorganic chemistry. These tasks can potentially provide a practical way for students to build this skill while using inorganic concepts learned in the classroom. However, without a formal study to gain insight into how students solve inorganic tasks, we cannot know whether the assumption that students engage their knowledge of inorganic chemistry when solving these tasks is valid.

In order to determine the strategies used by students solving complete-the-reaction inorganic tasks, this study used the theoretical framework of phenomenography to conduct a qualitative analysis to identify the success level of research participants and determine the strategies used by successful problem solvers compared to the strategies used by less successful problem solvers.

This study is important for addressing the gap in the existing literature on how students approach similar tasks in inorganic chemistry. Knowing how students work through problems, both effectively and ineffectively, is a key to teaching useful and accurate problem-solving strategies in inorganic chemistry and helping them to build the underlying, fundamental skills.

Personal Statement

I began formulating this project when I was in an Introduction to Inorganic Chemistry classroom as an undergraduate chemistry student. In that class, we were often asked to solve complete-the-reaction tasks, and I often struggled with them. The professor would sometimes put commonly incorrect answers up on the board and explain why they were incorrect, such as using an acidic reactant and formulating a basic product. However, despite knowing this, I proceeded to make that mistake on future tests and assignments. I wondered how I could routinely make the same mistakes without consciously knowing I was making these mistakes until I later looked at an answer key. I also noticed that these questions, while written in an open-ended format, tended to elicit similar responses from my classmates and me. How could students write the same incorrect answer to an open-ended question, and more importantly, why was this occurring? Background research into this topic showed a lack of studies designed to look at student thought processes in inorganic chemistry, particularly for these types of tasks. I developed this study to look at the strategies that students use when solving these tasks, and how those strategies related to obtaining correct answers to those tasks. I believe that this research will be valuable to future students who struggle to solve tasks such as these, and for the educators who teach them.

CHAPTER II: LITERATURE REVIEW

Educators intend to use complete-the-reaction type tasks as a tool to assess and facilitate student learning of fundamental concepts in inorganic chemistry such as acid-base and redox. However, it is unclear whether students solve these tasks in ways that are consistent with the instructors' expectations. The contents of this chapter will summarize the study of complete-the-reaction type tasks, studies related to student processing when learning reactions, discuss the overall structure of inorganic chemistry classrooms today, and finally relate literature to how educators teach reactions.

Inorganic Complete-the-Reaction tasks

To date, there is no published research on student strategies of complete-the-reaction tasks in inorganic chemistry or their prevalence and use in the classroom. However, one research study conducted by Calhoun (1997) attempted to compare the performaces and strategies of students to professors when doing inorganic tasks (referred to here as predict-the-product tasks). Calhoun defined predict-the-product tasks tasks where students are given the reactant(s) and asked to predict the product(s).

Calhoun conducted a qualitative research study in which she recruited 28 participants total consisting of: three undergraduate non-chemistry majors, nine undergraduate chemistry majors, 13 chemistry graduate students, and three inorganic chemistry professors at a large, research-intensive midwestern university. Calhoun defined success as the degree to which the methodologies of the student participants aligned to the professor/content expert participant. The success level of students were also categorized into unsuccessful, partly successful, and mostly successful based on percentage of correctly answered tasks.

Participants of all success levels used various strategies which were defined during the course of the study. A simple strategy most often used by undergraduate non-majors included the domain-general strategy known as the "algebraic" or mathematic method, which she defined as using the charge and number of atoms in one reactant to recombine with atoms in the other given reactant using balancing or formula writing. The algebraic or mathematical method required little experience in chemistry. While the algebraic/methematic approach was functional and successful in obtaining correct answers in some cases such as displacement reactions, where the student can recombine cations and anions easily to obtain an answer, the method as a whole does not take into account many properties at a molecular level such as acidity or oxidation potential (Calhoun, 1997). According to Calhoun (1997), this algebraic approach often breaks down as reactions increase in complexity and the student fails to apply elemental or molecule properties, particularly as the tasks become less familiar to the problem-solver.

In Calhoun's (1997) study, undergraduate chemistry majors often attempted to use acid-base and redox strategies, though they struggled to apply this knowledge effectively. Calhoun (1997) attributed the lack of success in application to the participants' lack of a "simplistic approach" where participants would use the same or similar methodology (consisting of few steps or concepts) for each task regardless of task type (p. 50). Calhoun proposed that the haphazard strategy consisting of the inefficient use of many chemical concepts led to these participants relying heavily on memory or text, and led to their lack of confidence in their knowledge, even though the participants attempted to use more chemical knowledge than when the algebraic method was used almost exclusively. One thing to note was that several students claimed that they had no strategy at all, even though they were using acid-base and redox concepts to solve the problems which indicates a lack of self-awareness or metacognition.

Participant professors were considered completely successful as they correctly answered over 90% of the tasks, while no student participant was considered completely successful. The student participants who were considered successful problem solvers tended to use redox, acid-base, and an organic-centered method as needed, though they sometimes still had trouble differentiating under what conditions each method should be used. The organic method was described as involving the structure and electron movement of the molecules, analogous to using the electron-pushing formalism in organic chemistry. Finally, several students in Calhoun's study, primarily within the undergraduate non-majors group, balanced each reaction to check their answers and catch mistakes as a method of verification. One participant, Greg, described balancing as placing a "net under the trapeze" in order to catch incorrect potential answers (Calhoun, 1997, p. 48).

Research Related to Chemical Reactions

Stains and Talanquer (2008) studied students' use of symbolic and particulate representations when classifying chemical reactions. They explained that the importance of classification is that it "plays a central role in science, where it is used not only as a way to organize knowledge but also as a powerful predictive tool" (Stains & Talanquer, 2008, p.771). The ability of students to classify chemical reactions may be a part of how students solve complete-the-reaction tasks, since the organization and predictive properties that come with classifications may also apply to these tasks. Stains and Talanquer recruited participants from five different education-levels: first semester general chemistry, second semester general chemistry, first semester organic, students enrolled in advanced courses, and graduate students in the PhD chemistry program. They asked participants to classify reactions by particle behavior (acid-base, redox, or precipitation) and by particle rearrangement (addition, single displacement, or double displacement). The researchers specifically looked for explicit features such as mentions of charge or states of matter, and implicit features such as oxidation number or displacement.

Stains and Talanquer (2008) found that the more experience the participant had correlated with larger types and numbers of created groupings such as acid-base or single/double displacement. They observed participants using implicit features (including chemical properties, displacement, electron/charge transfer, oxidation number, proton transfer, and type of compound) and explicit features (including charges, specific substances, states of matter, and stoichiometry) (Stains & Talanquer, 2008, p. 777). While all participants used both explicit and implicit features to describe representations of chemical reactions, the researchers identified more instances of advanced students identifying and using them than the novice students. The authors explained this finding by saying that novice students may be unable to recognize the features or that the cognitive demand placed upon them was too great to use them effectively (Stains & Talanquer, 2008).

They state that college-level teaching practices rely on the assumption "…that students will be able to recognize the explanatory and predictive power of the ways of thinking in the discipline by mere exposure to the accumulated knowledge, without the need to explicitly reflect on the underlying assumptions and ways of knowing in the field" (Stains & Talanquer, 2008 p.791). They claim that this may cause difficulties for students to develop an understanding of concepts such as classification, particularly in undergraduates.

Graulich (2014) conducted a qualitative study in which she recruited participants from a second semester course in undergraduate organic chemistry. The tasks included a reactant and a product. Graulich asked participants to determine the other reactants needed to complete the reaction by choosing the answer from a multiple-choice list. Graulich found that in the vast majority of participants, the decision-making process relied on associative memory to complete the tasks, of which each method was at least partially successful in obtaining the correct answer. These are examples of heuristic methods, in which a problem solver reduces the effort of decision-making through mental shortcuts (Shah & Oppenheimer, 2008). The heuristic associative methods described by Graulich included attribute substitution (in which problem-solver replaces a complex attribute with a simpler attribute), fluency (decisions made from easily accessed information), and/or associations (decisions made based on cues that trigger remembered information). This study demonstrates that heuristics can be a large part of the students' problem-solving process, and that students' search for heuristic familiarity was often successful (Graulich, 2014).

Inorganic Chemistry Classrooms

While the topics in general and organic chemistry instruction tend to be more standardized across colleges and universities, inorganic chemistry contains a diverse range of topics. There are two main theories for the diversity of topics in inorganic chemistry classrooms (Raker et al., 2015a; 2015b). Raker et al. (2015a; 2015b) outlined these two theories in their research using self-reported surveys of inorganic chemistry faculty. First is the idea that inorganic chemistry topics have been slowly removed from general chemistry classrooms over time, which resulted in inorganic educators needing to teach very basic inorganic content along with the more advanced topics in the same course (Raker et al., 2015b). Second, that general chemistry is a prerequisite course for many professional degrees and more advanced courses, while inorganic courses are typically required for chemistry majors and graduate students, and are not usually a prerequisite course (Raker et al., 2015a). Because inorganic is not typically a prerequisite course, inorganic courses have a flexble nature which can change to fit the needs of the institution. The instructor can customize the curriculum to fit their own areas of interests, their experise, and their comfort levels (Raker et al., 2015b).

Despite the differences possible in inorganic chemistry classrooms, there are similarities in the content that inorganic chemists are expected to learn throughout their undergraduate career. Raker et al. (2015b) noticed different types of inorganic classrooms and catagorized them into four different subtypes in order to examine topic coverage. The subtypes include (Raker et al. 2015b):

1) Descriptive
2) Fundamentals and selected topics
3) Foundation survey: fundamentals
4) Foundation survey: comprehensive

These researchers found that the main topics of focus that each subtype of classrooom had in common (i.e., 50% or more of all courses covered the topic) were atoms and electronic structure, covalent bonding and molecular orbital theory, transition metal complexes and coordination chemistry, symmetry and group theory, solids and solid state chemistry (2015a, p. 976). Acids/bases/solvents, and redox (which are directly related to complete-the-reaction tasks, because they are used as common types of inorganic reactants, products, and reaction types) showed high coverage in every type of inorganic classroom except for "fundamentals and selected topics" classes, where the coverage was low (2015a, p.976).

In the majority of course sub-types, educators could theoretically use complete-the-reaction tasks to assess and practice skills in acids/bases/solvents, redox chemistry, main-group and descriptive chemistry, as well as atoms and use of electronic structures. Thus, complete-the-reaction tasks could be a potentially useful tool if students are using them as intended.

Teaching Complete-the-Reaction Tasks

An inorganic professor named David DeWit (2006) published a practice article describing his approach to teaching complete-the-reaction tasks to his general-chemistry classrooms. His motivation for using these tasks was that predict-the-product assessments were useful to connect the diverse facts, principles and skills that introductory chemistry students needed to learn. He saw these types of problems as a simple way for students to apply their previously learned knowledge in inorganic classrooms and was surprised that students were unable to predict reactivity of simple compounds in practice. DeWit attributed his students' issues with predict-the-product tasks to their lack of understanding of basic principles and inability to use multiple principles at one time. In order to remedy this, he inserted a module near the end of the last general chemistry course (DeWit, 2006). The module lasted three class-periods and contained examples of inorganic predict-the-product task reactions (under the categories redox, decomposition, acid-base, etc.) with educator-guided questions with the class prompting critical thinking steps to arrive at logical products (DeWit, 2006, p. 1625).

While DeWit (2006) did not outline how he led students through the critical thinking process or what he considered important about each question, there are a few points of note. Given the structure of the paper, DeWit gave the impression that he considers identifying the reaction type an integral part of learning how to solve these types of tasks, because spent time and effort to teach each reaction type separately. He also suggests that this module was successful, based on comparing pre- and post-module exam scores of his students.

In a more recent example, Gerasimchuk (2022) wrote about his own experiences teaching complete-the-reaction tasks in his classrooms in the preface of his textbook *Chemical Literacy and Writing Chemical Reactions*. He wrote that students struggle to "grasp the concept of the correct writing of chemical formulas quickly" which causes issues in their current and future classrooms (Gerasimchuk 2022 p. x). He formulated that teaching the skill of writing chemical formulas was possible, and that it would require using methods of descriptive inorganic chemistry and classroom materials such as examples, figures, and task assignments. He said that the necessity of writing a textbook containing this methodology was because, "to date there is no widely available specialized textbook, brochure, or other source which explains how to write correct chemical equations" in a full and complete manner (Gerasimchuk 2022 p. xii). I also echo this sentiment, as articles on teaching chemical reactions (especially through the use of complete-the-reaction or predict-the-product tasks) and how students solve them, are lacking in the current literature.

Literature Summary

Literature surrounding complete-the-reaction tasks in inorganic chemistry is scarce, making it difficult to design educational plans that take into account knowledge of student thought processes. Based on previous research done on complete-the-reaction assessments, student strategies may be domain-general in nature. Domain general practices may contribute to the difficulty that educators currently face when attempting to teach reactions in their own classrooms. Due to the amount of chemical information that complete-the-reaction tasks can assess, they are applicable in nearly all types of inorganic chemistry courses, regardless of the breadth of knowledge the courses cover, as well as applicable in some general chemistry courses as well. Complete-the-reaction tasks are potentially very useful learning tools, but only if the students are using them as such.

CHAPTER III: METHODS

Overview

I designed this study in order to answer the guiding research question, "What strategies are used by students when solving complete-the-reaction tasks in inorganic chemistry?" To answer this, I utilized a qualitative research design along with the theoretical framework of phenomenography. In order to connect the data to usefulness in the classroom, I proposed a secondary research question: "Are there problem-solving strategies that result in greater task accuracy? If so, what are they and how do they promote the greater accuracy?"

Data collection consisted of semi-structured participant interviews, which I coded into categories in order to determine patterns and trends pointing towards participant problem-solving strategies. I further examined these strategies with respect to task accuracy.

Research Model and Theoretical Framework

I used a qualitative approach for this study, with phenomenography as the theoretical framework. Because the aim of this study was to understand the previously-unknown descriptive strategies, the qualitative approach was chosen over the quantitative model. The qualitative model is better suited for this type of study as the descriptive nature of this model allows for discovery and definition of category of behavior, while quantitative would be a better fit for discovering the prevalence of that behavior once defined.

Marton (1994) defines phenomenography as "… the empirical study of the limited number of qualitatively different ways in which various phenomena in, and aspects of, the world around us are experienced, conceptualized, understood, perceived, and apprehended" (p. 4424). Phenomenography is often described as a "second-order approach" because it is not used to examine a phenomenon or the individual's experiences with the phenomenon (Orgill, 2007). Rather, phenomenography is used to investigate peoples' conceptualizations of their experiences with a phenomenon. Additionally, phenomenographical research seeks to identify the limited, but different ways of those conceptualizations.

Site and Context of the Study

The study took place at a regional, four-year institution in the midwestern United States. The institution is primarily-undergraduate. The chemistry department, where the participants were recruited, contained a graduate Master's program. At this university, it is common for a large number of students to transfer from community colleges or other four-year institutions, where they may have taken their first year or two of chemistry courses.

I recruited participants from inorganic I and advanced inorganic chemistry courses. Inorganic I primarily focused on main group elements, atomic structure, bonding theory, acid-base theory, redox theory, reactivity, and coordination theory fundamentals. The structure of Advanced Inorganic for that semester included expanding upon the previous topics, ligands, as well as inorganic crystalline structure and nomenclature. The course professor frequently used complete-the-reaction tasks through homework and extra-credit portions on tests. The instructor gave students examples of correct complete-the-reaction tasks through answer keys, class demonstrations, and gave students handouts in the form of packets pertaining to complete-the-reaction tasks. For example, one packet referenced common mistakes the professor wanted them to know, while another listed Acids, Bases, Salts, and Oxides in lists and provided "algorithms" (simplified chemical reactions in which the instructor categorized each term, such as "Acidic Oxide + Base → Salt and water").

Participants

After receiving approval from the Internal Review Board (IRB), I recruited a total of eight participants on a voluntary basis. Criterion purposeful sampling was the method of choosing participants. As summarized by Palinkas, et al. (2015), criterion purposeful sampling is a participant sampling method for qualitative research in order to select "information-rich" cases that are applicable to the area of study (p. 533). In this study, I chose the criteria that the participant must be a voluntary student in an inorganic chemistry course. This is because the goal of the study is to observe the strategies of inorganic students in particular, and random sampling of a general population would not demonstrate the desired level of content knowledge. Table 1 (below) summarizes the participant information, including the class where I recruited them from, and information gathered from the personal background portion of the interviews. In addition, five of the participants took all previous chemistry courses at the current institution, two took one semester at a community college, and one participant (Martha) took the majority of courses at a different four-year midwestern institution, including her first year of inorganic chemistry.

I began the recruitment process by first obtaining permission from the inorganic classes' instructor. Then, I described the research study to students during a lecture class, handing out an informational recruitment sheet (see Appendix A) with a place for a student to provide their name and university email address if they were interested in participating. I kept the collected papers in a locked and secure location, and only used the collected information to contact prospective participants. The assignment of pseudonyms took place at the beginning of data collection in order to protect confidentiality, which is included in Table 1.

Table 1
Summary of participant information

Participant	Class Recruited	Graduate / Undergraduate	Major / Minor (If Specified)	Previous Chemistry Classes Taken That the Participants Were Able to Remember/Name	Most Comfortable Topic in Inorganic	Least Comfortable Topic in Inorganic
Ashley	Introduction to Inorganic	Undergraduate	Chemistry / Biology and Spanish	General chemistry (two semesters), Organic chemistry, analytical chemistry, Instrumental chemistry	Nothing specified	Redox reactions
Daisy	Introduction to Inorganic	Undergraduate	Chemistry	General chemistry (two semesters), Organic chemistry (two semesters), analytical chemistry, Physical chemistry, instrumental chemistry	Review of topics covered in previous classes, first two groups on the periodic table	D-block metals
David	Advanced Inorganic	Graduate	Chemistry	General chemistry (two semesters), Organic chemistry, Physical chemistry (two semesters), Biochemistry, Introduction to Inorganic chemistry	Elemental properties including periodic trends	Crystallographic and optical topics
Martha	Advanced Inorganic	Graduate	Chemistry	General chemistry (two semesters), Biochemistry (one semester), Instrumental analysis, Quantum mechanics, Physical chemistry (one semester), inorganic, one semester undergrad/ one semester graduate,	Lab work, electron orbitals' effects on properties and trends	Topics involving heavy memorization

				environmental chemistry, Organic chemistry (three semesters)		
Misaki	Introduction to Inorganic	Undergraduate	Biochemistry	General chemistry (two semesters), Organic chemistry (two semesters), Biochemistry (one semester)	Review of topics covered in previous classes	Ligands and metals
MJ	Advanced Inorganic	Graduate	Biochemistry	General chemistry (two semesters), Organic chemistry, Physical chemistry (two semesters)	Nothing specified	Symmetry rotations and planes
Steve	Introduction to Inorganic	Undergraduate	Chemistry / Math Motives	General chemistry (two semesters), Organic chemistry (two semesters), analytical chemistry, Biochemistry (one semester)	Acid-base tasks	Acidic and basic oxide recognition
Stu	Introduction to Inorganic	Undergraduate	Chemistry / Foundations of Interdisciplinary Sciences	General chemistry (two semesters), Organic chemistry, analytical chemistry,	Transition metals and ligands	Topics involving heavy memorization

Data Collection

Materials

Before data collection began, I obtained and modified materials in preparation for participant interviews. The course instructor directly gave me the tasks which I used for this study along with an answer key denoting one correct answer per task. I modified the formatting of these materials for use in this study and developed three other tasks without assistance for use as practice reactions. For the practice reactions, I remembered three of what I thought were simple chemical reactions of three different categories: composition, redox, and decomposition. I kept the full reactions for the answer key, and erased reactants or products to mimic the structure of the complete-the-reaction style tasks. I left the first practice reaction task as a complete reaction in order to serve as an example. The full list of materials included: the directions, practice tasks, reaction chain one, reaction chain two, reaction chain three, and an answer key. The tasks given to participants are shown in Table 2 and Figure 1. For the purposes of this study, tasks will be listed as "reaction chain/practice"."task number on that page" For example: Practice reactions, task three will be designated P.3, while reaction chain one, task three will be designated 1.3.

Table 2
List of all tasks

Task Number	Given reactant		Blank Space		Given product		Blank Space
P.1 (given)	Na	+	**Cl_2**	→	NaCl	+	**-**
P.2	K	+		→	KOH	+	
P.3	H_2CO_3	+		→	CO_2	+	
1.1	B	+		→	BCl_3	+	
1.2	BCl_3	+		→	K_3BO_3	+	
1.3	K_3BO_3	+		→	H_3BO_3	+	
1.4	H_3BO_3	+		→	B_2O_3	+	
1.5	B_2O_3	+		→	B	+	
1.6	B	+		→	MgB_2	+	
1.7	MgB_2	+		→	B_2H_6	+	
2.1	Li_2CO_3	+		→	Li_2O	+	
2.2	Li_2O	+		→	LiF	+	
2.3	LiF	+		→	Li	+	
2.4	Li	+		→	LiOH	+	
2.5	LIOH	+		→	LiCl	+	
2.6	LiCl	+		→	$LiSO_4$	+	
3.1	$AlCl_3$	+		→	Al	+	
3.2	Al	+		→	Al_2S_3	+	
3.3	Al_2S_3	+		→	$Al(NO_3)_3$	+	
3.4	$Al(NO_3)_3$	+		→	$Al(OH)_3$	+	
3.5	$Al(OH)_3$	+		→	$K[Al(OH)_4]$	+	
3.6	$K[Al(OH)_4]$	+		→	$AlCl_3$	+	

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Principal Investigator: Gautam Bhattacharyya

Please write in the necessary **reactant** (if one is required) for the equation to logically proceed. If heat or electrolysis is needed for the reaction to occur, write that as well.

Then, write in any additional **products** that may occur from this chemical reaction if they exist.

Balancing is not required for this exercise.

Practice reactions:

1. $Na +$ Cl_2 $\longrightarrow NaCl +$ nothing

2. $K + \quad \longrightarrow KOH +$

3. $H_2CO_3 + \quad \longrightarrow CO_2 +$

Figure 1
Direct representation of what participants were given: Page one including directions for P.1 – P.3 (See Appendix B)

I formatted the directions and practice tasks to be on a single page (see Figure 1 and Appendix B), and each reaction chain was on a separate page. The second page included only reaction chain one which focused on the element boron, the third page included reaction chain two focusing on lithium, and the last page included reaction chain three focusing on aluminum. Each reaction chain was intended to emphasize the chemical transformations of a different element, while the practice reactions were unrelated. I initially developed the practice reactions as an exercise for participants to practice the think-aloud protocol and hopefully become more confident in the format of the tasks. I provided the answer key on individual pages identical to the practice reactions and reaction chains one through three, but with red pen in a clear script denoting the correct answer within the blank spaces. Table 3 shows a condensed version of the answer key for reference (also located in Appendix C).

Table 3
Condensed Answer Key (See Appendix C)

Task Number	Given reactant		Key Reactant(s)		Given product		Key Product(s)
P.1 (given)	Na	+	**Cl_2**	→	NaCl	+	**-**
P.2	K	+	**H_2O**	→	KOH	+	**H_2 (g)**
P.3	H_2CO_3	+	**-**	→	CO_2	+	**H_2O**
1.1	B	+	**Cl_2**	→	BCl_3	+	**-**
1.2	BCl_3	+	**KOH**	→	K_3BO_3	+	**KCl + H_2O**
1.3	K_3BO_3	+	**HCl**	→	H_3BO_3	+	**KCl**
1.4	H_3BO_3	+	**Heat**	→	B_2O_3	+	**H_2O**
1.5	B_2O_3	+	**Mg**	→	B	+	**MgO**
1.6	B	+	**Mg**	→	MgB_2	+	**-**
1.7	MgB_2	+	**HCl**	→	B_2H_6	+	**$MgCl_2$**
2.1	Li_2CO_3	+	**Heat**	→	Li_2O	+	**CO_2**
2.2	Li_2O	+	**HF**	→	LiF	+	**H_2O**
2.3	LiF	+	**Electrolysis**	→	Li	+	**F_2**
2.4	Li	+	**H_2O**	→	LiOH	+	**H_2 (gas)**
2.5	LIOH	+	**HCl**	→	LiCl	+	**H_2O**
2.6	LiCl	+	**H_2SO_4**	→	$LiSO_4$	+	**HCl**
3.1	$AlCl_3$	+	**Na**	→	Al	+	**NaCl**
3.2	Al	+	**S**	→	Al_2S_3	+	**-**
3.3	Al_2S_3	+	**HNO_3**	→	$Al(NO_3)_3$	+	**H_2S (gas)**
3.4	$Al(NO_3)_3$	+	**LiOH**	→	$Al(OH)_3$	+	**$LiNO_3$**
3.5	$Al(OH)_3$	+	**KOH**	→	$K[Al(OH)_4]$	+	**-**
3.6	$K[Al(OH)_4]$	+	**HCl**	→	$AlCl_3$	+	**KCl + H_2O**

Additionally, I obtained the class textbooks, which contained a periodic table for reference, and the class packets and handouts which students commonly used to solve complete-the-reaction tasks for homework or study. These were available for the participant to reference so that memorized knowledge would not be a barrier to problem-solving. Additionally, I provided blank paper for scratch-work, pens, pencils, and erasers.

I recorded each participant interview with a video camera. The video recording captured only the voice and hands of the participant in order protect his or her confidentiality. I did not share the recording with anyone. The primary data I used was the video camera recordings, along with physically answered tasks.

Interview protocol

The overall protocol consisted of three main sections: Preliminary Questions, Tasks, and the Answer-Key, in which the method of data collection would be the "think-aloud" methodology. The "think-aloud" method of data collection is a technique in which participants are to speak aloud "words in their mind" as they complete a task (Charters, 2003, p. 68). This is an effective qualitative method given that the researcher carefully chooses tasks and carefully interpretates participants' words, treating them as "quasi-researchers" (Charters, 2003, p. 68).

I developed an interview protocol to ensure that all participants had the same or similar format of interview and minimize differences that would impact the results from this study. Appendix D lists the full interview protocol as used in the study (also see Figure 2). To help me remember the specific details of each step of the interview process, I added several annotations to the interview protocol submitted to the IRB. Furthermore, I used the term "experiment" as a term of convenience for myself, realizing that the research detailed herein is not an experimental design. I developed the Preliminary Questions section in order to make each participant feel welcome to the interview, ensure that each person knew and had time to look over the Informed Consent document (Appendix E), and to gain knowledge of each participant's background in chemistry. I wanted to know about their previous chemistry classes, where they had taken them, and which aspects of inorganic chemistry they felt most or least comfortable with, so that I could analyze this information for additional insight into strategy use.

Project Title: Inorganic chemical reasoning skills: An exploratory study into understanding students' choices and thought processes

Principal Investigator: Gautam Bhattacharyya

Interview Protocol

Background Questions

- Please tell me your major and your year in school
- In addition to your inorganic chemistry course, what other chemistry courses have you taken so far? Of those which were at MSU?
- What are your overall experiences in inorganic chemistry? Which topics do you feel are the most difficult? The easiest? Why?
- What are your future career plans? How do you see the material in this course fitting in to those plans?

Tasks

Please write in the necessary **reactant** (if one is required) for the equation to logically proceed. If heat or electrolysis is needed for the reaction to occur, write that as well.

Then, write in any additional **products** that may occur from this chemical reaction if they exist.

Balancing is not required for this exercise.

Practice reactions:

1. $Na + Cl_2 \longrightarrow NaCl +$ nothing

Figure 2
Interview protocol page 1 as summitted to the International Review Board (IRB) (See Appendix E)

The interviews were semi-structured so that I could ask follow-up questions, as needed, to each participant. These questions were flexible, so that I would be able to respond to participant's comments or writings during the interview. Finally, I created the Answer Key section so that participants would have the opportunity to look back at their work with additional information and perhaps revise their responses if they so wished.

The interviews

I conducted each interview, except for Steve's interview, which was completed by Dr. Gautam Bhattacharyya, due to my inexperience conducting participant interviews. We conducted each interview in an office that allowed privacy for participant confidentiality without being unduly isolated for personal safety reasons. There, before each interview, I set up the camera and tested it to ensure that it was functioning properly and that it would only show the workstation and hands of the participants, even in the act of turning the video camera on and off. I also set up reference material, scratch-paper, writing utensils, and erasers.

I began each interview by introducing myself, welcoming each participant to the study and giving him or her a voluntary informed consent form (see Appendix E). Multiple copies were available, and I specifically gave one to the participant to keep. This was to ensure that the participant knew his or her rights as a research participant, including confidentiality, that this was not a test or any type of assessment, that they were free to leave at any point, and that his or her participation did not affect their standing within the university or classroom. After the participant indicated that s/he completed reading the form, I asked the participant if s/he had any questions. I then informed him/her of the video data collection and its mechanics. Then, I asked the participant demographic questions. Here, I also asked each participant if s/he would like to choose a pseudonym, which allowed me to refer to him or her from that point onwards in a way that would protect their confidentiality.

To begin the Task section, I gave each participant the first page, which included the instructions and practice reactions. Before they began to work on it, I asked them to think-aloud as they solved the tasks and explained that there were three more pages of reaction chains after this one as well as an answer key (so that the interview was not surprising at any point). Then the participant began working on the tasks using the "think aloud" method of data collection. During periods where s/he had completed a task or section, I would ask about something they wrote down or said. If s/he was silent for a length of time, but still working, I would ask the participant what s/he was thinking about to ensure that s/he was still using the "think aloud" method. Once the participant indicated that s/he was completed working on the practice reactions (typically by setting the paper aside, leaning backwards in his or her chair, or verbally indicating), I made sure to thank them for using the "think aloud" method and asked them any additional questions about their work. Once the participant finished answering, I provided reaction chain one.

As the participant began working on the section, I would ask questions during breaks or long pauses. During this time, in addition to elucidating strategy questions, I would also ask the occasional question as a follow-up, such as: "What would you do on a test if you didn't have this book to look up information" or to clarify a previous statement, such as: "Which acid-base theory are you talking about here?"

After the participant completed the three reaction chains, I provided the answer key. I asked the participant to continue using the think-aloud data collection protocol to compare and contrast their answers with the key. I made sure to emphasize that the key was only one possible correct answer for each task and that other correct answers may be possible. The participants looked at and commented on their answers that matched the key and those that did not. In case of the latter, I asked follow-up questions to better elicit potential reasons for the discrepancies.

Data Analysis

Transcriptions

I performed verbatim transcription of each video, including annotations with participant gestures. I performed the first rough transcription through listening to the videos and repeating the dialogue into a voice transcription software included in a Word document. At that time, I made some notes on the time of the video when transcribing, particularly when starting a new reaction chain or if I perceived that too much time had passed since I last made a time note. I did this as a way to refer back to a specific point in the video.

As the first transcription contained many errors, I performed multiple passes through each transcription. During this part in the transcription process, I separated the dialogue from the researcher and participant by paragraph breaks and added headings and subheadings whenever the task or topic changed in order to separate the information in a way that I could easily reference. The headings and subheadings included more time markers. For clarity, I considered punctuation carefully, and sometimes omitted filler words such as "um" and "like." I did this for clarity in reading, and it may pose a limitation of the data since questions of judgement may not be as easily determined through the transcription. Also omitted were specific phrases or names that would reveal the participant's identity. There were several words or phrases that I could not decipher from the video where the inability to record perfectly, overlapping speech, or a low volume voice such as mumbling resulted in loss of meaning. Any phrase that was completely incomprehensible, or if I was unsure of the phrasing, I denoted using the phrase "[unintelligible]," and did not include it in the analyzed data.

Due to a corrupted video, no video or transcription exists for the participant denoted by MJ past task 2.1 (Reaction Chain 2, Task 1). As a result, much of the process was lost and only the practice reaction tasks and the tasks in reaction chain one were able to be analyzed for verbalized patterns.

Coding

The coding process took place through the use of qualitative content analysis. Content analysis is a research method in which researchers can identify themes and/or categories by carefully preparing the data, developing categories and a coding scheme, checking the consistency of the coding scheme, and drawing conclusions (Zhang & Wildemuth, 2009). For this study, I developed the codes directly from the data transcriptions (in vivo) (Vollstedt & Rezat, 2019). After examining the nature of the data collected, I determined that there were three promising segmentations of data which could provide discernible patterns. These were dividing the data by participant, by task, and by task type (acid-base / redox). From there, I could further divide the data by successful and unsuccessful based on accuracy.

Coding By participant, By task, By category.

I started with the "By participant" segmentation to code. I re-drew any relevant handwritten drawings using Word and/or Excel tools as necessary to ensure confidentiality. Then I went through each transcript focusing on verbalizations describing strategies for each task. During my first read-through, I made notes on a separate sheet of paper or Word document to keep track of codes and code categories in the form of memos, which developed as I incorporated all eight transcriptions. At this time, I noticed that while I initially intended on the practice reactions data to be lesser to the reaction chains in terms of data collection, there were a lot of codes within the practice reactions and there was no reason to discard them.

To assess coding consistency, and create an easily referenceable document for data analysis, I coded each transcription by person again, making notes on each task on a separate word document, called "Analysis-By-Person." This process also allowed me to examine codes that I noticed in one transcript with all the other ones. This recursive process is reminiscent of constant comparative analysis, which is used in grounded theory (Glaser, 1965). The "Analysis-By-Person" document was a running commentary for each participant across every task. For each task, I made notes on actions that the person took, key words and phrases, and inserted direct quotes. Each section within the document started with the participant's pseudonym, then the sections: Introductions, Practice Problems, Reaction Chain 1, Reaction Chain 2, Reaction Chain 3, and Other Mentions/Notes. The Introductions section summarized the answers that participants provided at the beginning of the interview. The Practice and Reactions sections contained at least one memo on each, individually labeled, task that the participant completed, and also included the participant's answers for ease of reference to specific statements. The Mentions/Notes section at the end of each participant contained any statements that particularly stood out as interesting, but not directly relevant to solving the task, and for memos on that participant's overall strategy.

Because my descriptions in the "Analysis-By-Person" document were so thorough for each task, I was able to re-arrange the data into a new document called "By-Task." In this document, each section started with the task number. Under each task, every participant had their own subsection containing memos on problem-solving strategies. This way, I could analyze overall strategies and patterns for particular tasks across every participant.

I also further analyzed the “Analysis-By-Person” document to separate acid-base from redox tasks, by making memos while looking back and forth at different tasks in their respective categories. The analysis of the redox tasks led to the realization that participants treated the different types of redox tasks differently, so I amended the overall category and analyzed the different redox types separately (Traditional redox, Composition, and Decomposition). I also compared “By task” to analyze the similarities and differences in participant responses when students provided the same correct answer and the same incorrect answer. The final coding scheme per category is listed in Appendix F.

Coding qualitative accuracy.

To begin coding the “Correctness category,” I first wrote each participant's written answer down in a typed format (to ensure handwriting would not be identifiable). Then, through the use of the key and through the assistance of an expert chemist, I determined every task to be either correct or incorrect with no partial credit given. I did not make a partially correct category for this study, since creating boundaries around a third category of partial correctness was not helpful in terms of this study nor my goal to qualitatively review accuracy of participant answers compared to strategy. Note that I marked an answer correct if the reaction did not require heat, but the student provided heat anyway, and notation (such as an arrow to represent precipitation or gas formation) did not affect the outcome of correctness. However, for task 3.2 (reaction chain three, task 2) many students were unsure of the elemental state of sulfur. As the knowledge of specifically sulfur's elemental state was determined irrelevant to the study, I marked any state of sulfur as correct.

I listed the number of correct per attempted questions in table form and, thus, I was able to analyze both for overall correctness and for correctness by category for each participant. All data was analyzed in terms of percentages, so for ease of analysis, I gave all correct reactions one "point," and all incorrect answers zero. If the student left the task blank without attempting to use strategies or reasoning, I marked the task as skipped and did not include it in the data as either correct or incorrect. This is because skipped tasks did not contain any observed analyzable strategies, and thus would not contribute to the research goals of determining links between accuracy and strategy. However, if the participant attempted the task and intentionally left it blank, it was marked as incorrect, and I analyzed the attempt for strategies.

Regrettably, the first participant's (given the pseudonym Steve) tasks contained two typographical errors: task 3.6 was a repeat of task 2.6, and in task 1.4 I accidentally included the compound B_3O_3 in place of B_2O_3. Note that the B_3O_3 error was verbally corrected during the interview process. For correctness data, I marked task 3.6 as not attempted, and task 1.4 as correct since he provided a chemically reasonable answer that considered B_2O_3 after the verbal correction. I also needed to split Steve's interview into two sections because the answer key was mistakenly not available during his initial interview. I corrected these errors directly after Steve's interview. All subsequent interviews did not contain these typographical errors. In addition, all subsequent participants accomplished the answer key portion and task answering portion in a single sitting.

Once correctness data for each participant, each task, and each type of task were determined, I compared them against each other and with the other coded segments, "By person" and “By task” and “By task category,” to obtain qualitative insight. This was not a linear process. Determining which tasks were correct and which were incorrect occurred at approximately the same time as initial transcription, but analysis to category memos occurred late in the process. This led to the creation of the descriptive categories of participant problem solving strategies outlined in chapter IV.

Strategy development from transcript analysis.

Using the three data segmentations – By Participant, By Task, and By Reaction Type, along with the accuracy data, I reviewed the strategies to find the qualitatively different ones that were used. For example, I combined all the strategies for the correct answers to a given task to identify all the “successful” approaches. After doing the same for all of the different sets of data as described in the previous subsections, I noticed that there were a small variety of problem-solving trajectories that participants used. These were placed in a flow-chart diagram, which is presented in the next chapter.

Coding the answer key.

Finally, I analyzed the Answer key portion, which I did separately from the rest of the coding. I used a similar methodology as the rest of the coding process. I created additional headings within the transcriptions, so that I knew which statements pertained to which task based on context clues, gestures, or participant statements. In reading over the transcriptions line-by-line, I performed the comparative analysis and made memos. In this case I made memos in the form of a Word document labeled “Answer Key” where memos were the headings, and underneath were quotes from the transcriptions, organized by person. By the end of the comparative analysis, I obtained useful categories under the broad categories of when the answer was the same as the key, and when the answer was different than the key (See Chapter IV: Answer Key).

Ethical Considerations

I obtained Institutional Review Board (IRB) approval (see Appendix G) before any participants were recruited. I made one amendment during the study, with IRB approval, to expand recruitment from only an Introductory to Inorganic course to also include participants from an Advanced Inorganic chemistry course (see Appendix H).

Either I or Dr. Gautam Bhattacharyya informed each participant that they may leave at any point during the study without consequences during the recruitment process, in an email that provided interview times, and before the interview began. They were also made aware that there were only minimal risks associated with this study.

I took steps to ensure the confidentiality of the participants, which was a priority. I scheduled the interviews over a secure university email address. The interviews took place in a secluded area where the participants hopefully felt at ease, and their identity was protected – i.e., passersby would not be able to see or hear the participants during the interview. All documents pertaining to the participant during and after data collection, including data analysis and reporting of results, referred to the participant only by their pseudonym.

The primary and secondary investigators kept all collected data. We kept digital data on secure, password protected laptops and backed up on a password protected flash drive. Physical notes and papers are kept in a locked location that only the primary and secondary investigators could access. No one other than the primary or secondary investigator viewed the video recordings and hard copy data, and no physical data contained identifying information of the participant.

Limitations

There are several limitations of this study that I acknowledged and mitigated. First, this study takes place at a four-year public institution in Southwest Missouri, using problems in the same format of the inorganic chemistry classes within that institution. Therefore, the results may not transfer to students in all institutions across the United States. However, I hope that choosing a task type that is common to inorganic chemistry courses nationwide will help mitigate this limitation.

Because I chose the tasks from previous years' tests, there is a chance that the participants may have seen these exact problems before. The mitigation of this limitation occurred through the structure in which the instructor conducted the course test (from which those tasks originated). The course instructor did not allow students to take the tests home with them or take pictures of them. Also, as the tasks were part of an extra credit section, it is possible that some students did not attempt the tasks at all. As such, even if a participant took this particular class, it is unlikely that the student would remember or memorize the solutions to these specific tasks. Additionally, the data indicates that there was no such familiarity.

This study assumed that participants completed these tasks to the best of their ability, and that any anxiety or stress of my recording or questioning them did not significantly affect their performance. The study treated participants as representative of their class and of students who have taken similar inorganic chemistry classes before or will take it in the future.

Role of Researcher and Researcher Bias

My role in this study was as a "Participant Observer" where I studied the group of participants by both engaging in the activity and by observing the participants while they took part in the activity (Kawulich, 2005). Through this role as the researcher, I learned about the participants' problem-solving approaches and strategies through my physically being there in the research space, observing their actions, and asking interrogating questions throughout the process which are key roles for the Participant Observer (although my adoption of this role contained no deception which can be common for the Participant Observer) (Kawulich, 2005).

My personal bias as the researcher comes primarily from taking these inorganic courses and solving complete-the-reaction tasks before the formulation of this study. I completed the same classes that the participants did, including answering these exact tasks and other similar tasks during my time in inorganic chemistry. At the time, my personal strategy was to categorize each reaction compound as acid, base, salt, or oxide for acid-base tasks, then use algorithms and a memorized pool of compounds to solve. Or I would assign oxidation states for redox tasks and then use a pool of memorized oxidizers or reducers to complete the task.

I attempted to mitigate any biases towards my own typical strategies by carefully coding the data so that any instance that led to an answer (correct or not) I defined as a strategy. I made an effort not to assign judgements to any strategy (ex. calling one strategy "good" or saying one was "better") unless I had a reasonable metric and method of comparison (ex. higher score of correctness). I also ensured that all memos and final categories from the coding had sufficient and clear primary participant quotes to ensure that any conclusions that I drew were directly from primary data.

CHAPTER IV: RESULTS AND DISCUSSION

Introduction

The coding process as described in Chapter III resulted in a large number of patterns, trends, and potential explanations for this study's primary Guiding Research Question: "What strategies are used by students when solving complete-the-reaction tasks in inorganic chemistry?"

In order to organize the data, the structure of this chapter will follow the overall process flow that participants used to solve the inorganic tasks, and I will describe and discuss the findings at the end of each section. By analyzing the overall similarities between participants (as described in the coding process), I proposed a decision tree for problem solving, shown in Figure 3 and described as follows:

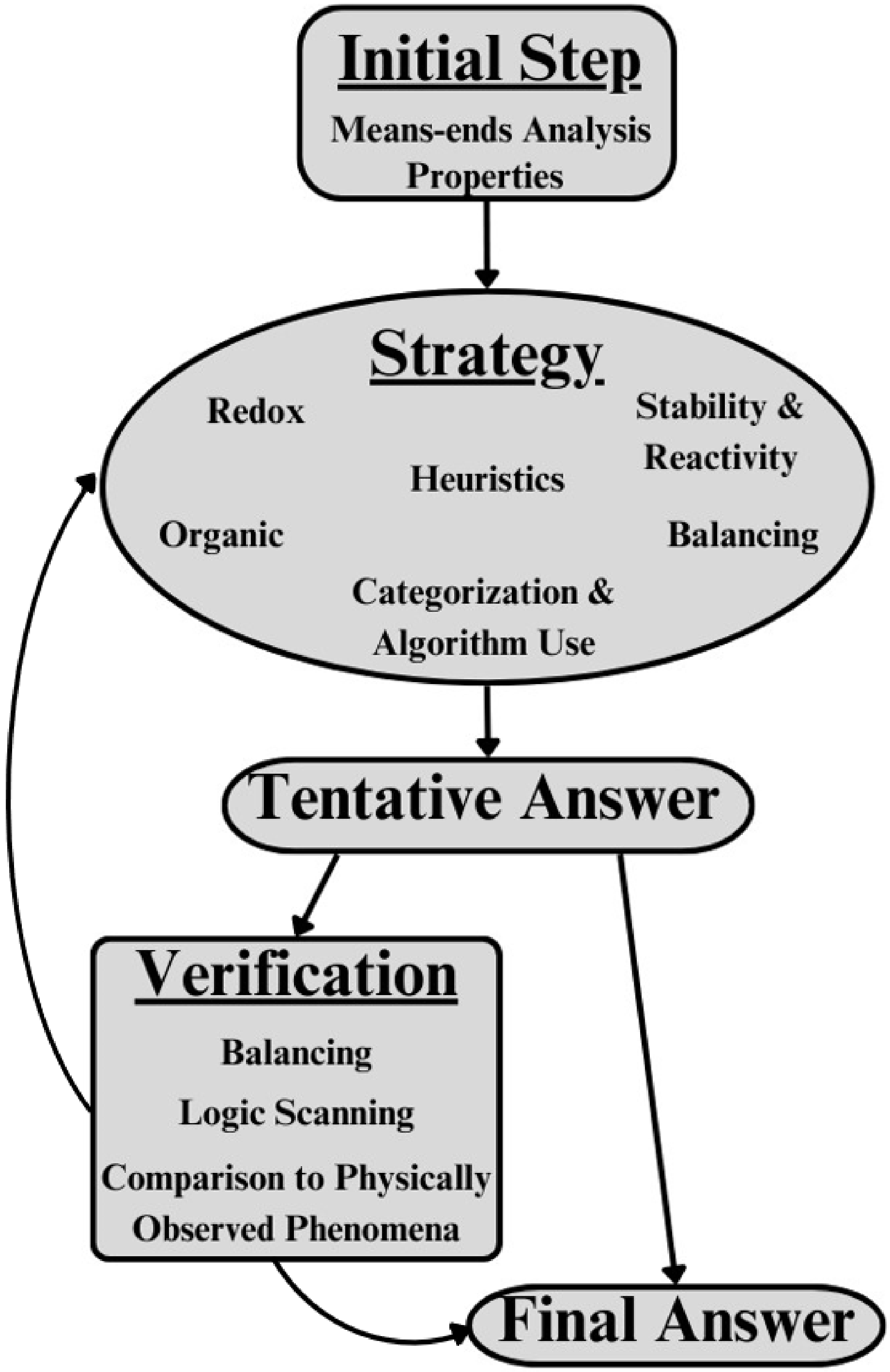

Figure 3
Flowchart describing the overall problem-solving behavior of participants

First, the participant looked at the task and demonstrated one or more initial step, which consisted primarily of a means-ends analysis (where s/he compared initial and final states, and noted any differences), or the participant commented on an innate property of any compound or compounds listed in the task. This chapter discusses these initial steps and their effects on the subsequent problem solving under the "Initial Steps" heading, which includes the "Means-ends analysis," and "Properties subheadings."

Then, the participant used one or more strategies until s/he reached a tentative answer. A participant was often cued to a specific strategy either because s/he recognized something in the task as a cue (Initial Steps) or because s/he used a consistent overall strategy regardless of reaction type or category. The strategies also had varying degrees of success and varying degrees of relevance to classroom topics. This chapter will discuss each of these strategies and their success metrics under the heading "Notable Strategies" which consists of "Categorization and algorithm use," "Redox strategies," "Stability and Reactivity," "Organic strategy," "Balancing as a Problem-solving Strategy," and "Heuristics" subheadings. While heuristics are typically unconscious mental-shortcuts, they played a large part in participants obtaining a final answers, and thus it will be discussed with the other problem-solving methods.

After the participant reached a tentative answer, s/he often moved to a verification step, where the most common and the most successful method to find errors was balancing the reaction. If s/he did not notice an error, s/he chose the tentative answer as the final answer. If the participant discovered a potential error, s/he would either attempt to rework the task using the same or different strategy, or s/he would ignore the potential error and choose the tentative answer as the task's final answer. I discuss the types of verification and their utilization in searching for errors under the heading "Verification Strategies," which consists of "Balancing as a verification strategy," "Logic scanning," and "Comparison to physically observed phenomena" subheadings. In the last part of the study, participants compared their chosen answers with a pre-made answer key. The section "Answer Key" will discuss the participants' comments during that comparison.

The structure of the participant decision tree will help navigate the strategies, connections, and cues that students use to solve complete-the-reaction tasks in inorganic chemistry. This chapter will discuss the efficacy of each strategy through integrating the solving process parts with task correctness analysis.

Success

Comparisons relating to correctness data are meant for qualitative analysis only, since there were not enough participants or tasks for a full statistical analysis. Nonetheless, it is informative to understand the strategies that tend to lead to correct answers, as opposed to those that do not. Once this chapter establishes correct versus incorrect answers and their patterns, I will discuss the relationship between correctness and strategies throughout the remainder of this chapter. Table 4 below summarizes the full correctness data.

To determine accuracy data, I classified each completed task as either entirely correct or not correct with the help of a content expert. A correct answer would lead to a productive chemical reaction. However, an incorrect answer was missing a component, added a component that should not be there, or combined elements in a way that would not be possible. For ease of data analysis, a 1 denotes a correct answer, and an X denotes an incorrect answer. I only included data on attempted tasks because the focus of this study is on the relationship between success and strategy. I denoted skipped tasks by "N/A."

Table 4

Correct answers where 1 is correct, X is incorrect, and N/A is not attempted: Percent correct calculated by taking the number of correct answers for each task divided by number of attempted

Task Designation	Steve	Stu	Ashley	Misaki	Daisy	David	MJ	Martha	Percent correct by Task
P.1					GIVEN				
P.2	1	1	1	1	X	1	1	X	**75%**
P.3	1	X	1	X	X	1	1	1	**63%**
1.1	1	1	1	1	1	X	1	X	**75%**
1.2	X	X	X	X	X	X	X	X	**0%**
1.3	1	1	X	X	X	1	1	1	**63%**
1.4	1	X	1	1	N/A	1	X	X	**57%**
1.5	1	1	X	X	N/A	X	X	X	**29%**
1.6	1	1	1	1	N/A	1	X	X	**71%**
1.7	X	X	X	X	N/A	X	1	X	**14%**
2.1	1	X	1	X	X	1	1	1	**63%**
2.2	1	X	1	X	1	1	X	1	**63%**
2.3	1	1	X	X	X	X	X	1	**38%**
2.4	1	1	1	1	X	1	1	1	**88%**
2.5	1	1	1	1	1	1	X	1	**88%**
2.6	1	X	X	X	1	1	X	1	**50%**
3.1	1	X	1	N/A	X	N/A	X	X	**33%**
3.2	1	1	1	1	1	N/A	X	1	**86%**
3.3	1	1	1	N/A	X	N/A	X	1	**67%**
3.4	1	X	X	1	X	N/A	1	1	**57%**
3.5	1	1	1	N/A	X	N/A	1	1	**83%**
3.6	N/A	1	X	N/A	X	N/A	1	N/A	**50%**
Percent Correct by Participant	**90%**	**57%**	**62%**	**47%**	**29%**	**67%**	**48%**	**60%**	

Table 5 represents an alternative view of the data and denotes task category. Note that Tasks 2.4, 2.5, 3.2, and 3.5 had a very high percentage of correct answers, which fall into the categories of redox, acid-base, composition, and decomposition, respectively. On the other hand, tasks 1.2, 1.5, 1.7, and 3.1, had a low percentage of correct answers, which fell into the category of acid-base, redox, acid-base, and redox, respectively. Therefore, I concluded that there was no direct trend between success and reaction category. However, when factoring in Table 6, which shows the relationship between participant success and category of task, data analysis showed that composition tasks had the highest success rate of any other category on average.

Table 5
Type/Category of task as designated by the Answer Key

Acid-base	Redox	Composition	Decomposition
1.2	P.2	1.1	P.3
1.3	1.5	1.6	1.4
1.7	2.4	3.2	2.1
2.2	3.1	3.5	2.3
2.5			
2.6			
3.3			
3.4			
3.6			

Table 6
Percent correct per task category calculated by number of correct answers divided by number of tasks attempted in each category (categories determined by designation on key).

Task Type	Steve	Stu	Ashley	Misaki	Daisy	David	MJ	Martha	Average %Correct by category
Acid/Base	75%	44%	33%	29%	38%	67%	44%	75%	**51%**
Redox	100%	75%	75%	67%	0%	67%	50%	25%	**57%**
Composition	100%	100%	100%	100%	67%	50%	50%	50%	**77%**
Decomposition	100%	25%	75%	25%	0%	75%	50%	75%	**53%**

I also organized the data in order to look at each reaction chain (see table 7). Because each reaction chain focused on a different element, I wanted to know if the elemental change impacted performance. Reaction chain one focused on the element boron; reaction chain two, lithium; reaction chain three, aluminum. The data indicates that the majority of the participants performed roughly equivalently on the chains focusing on lithium and aluminum, and that they were least successful with the chain centered on boron.

Table 7
Percentage of correct tasks in each reaction chain: calculated by the number of tasks correct divided by number of tasks attempted in each reaction chain

Participant	Practice	Reaction Chain One	Reaction Chain Two	Reaction Chain Three
Steve	100%	71%	100%	100%
Stu	50%	57%	50%	67%
Ashley	100%	43%	67%	67%
Misaki	50%	43%	33%	100%
Daisy	0%	33%	50%	17%
David	100%	43%	83%	-
MJ	100%	43%	33%	50%
Martha	50%	14%	100%	80%
Average	**69%**	**43%**	**65%**	**69%**

The fewest number of students attempted reaction chain three, with four participants electing to skip at least one task in that reaction chain (See Table 4).

Initial Steps

When beginning analysis, I was interested in how the students first approached the task, in addition to the eventual problem-solving strategies, and how these two might be related. This is because the first approach was a probable way for me to elucidate how the participant is interpreting the task. I was likely to gain insight on the portions of the task that caught the participants' attention and may cue them towards a specific strategy. For this study, I defined an initial step as the first actions taken when approaching a task, which do not directly lead to an answer (in contrast to a participant strategy, which was defined as a series of steps that have the potential to lead to an answer - i.e., acid-base, redox, etc.). An initial step consisted of the verbalized first idea, thoughts, or observations of the participants. The two main categories of initial steps, as indicated through analysis, are first: means-ends analysis, and second: intrinsic properties of any of the species in the reaction.

Means-ends analysis

All eight of the participants used means-ends analysis at some point in their problem-solving processes, where they gained information about the task by looking for the differences in the types of elements between the reactants and the products. In order to determine if a participant was using a means-ends analysis, their language was analyzed for key words and phrases. Typically, the participant would say something similar to "I have a [Element A] and I need a [Element B]" that led to my designating the phrase as a means-ends analysis. I observed this behavior to some degree in all eight participants, which indicates that they considered the step a useful tool in obtaining information about the task.

Stu described his use of means-ends analysis after he solved task 1.4 as follows:

> *"So, I guess my main thought process is whenever I look at this problem right here, I look at what element both sides have in common, and I look at what is not there."*

In this way, Stu was able to compare both sides and look for what elements both sides have in common, as well as what is missing from the reaction.

David began the problem-solving process of task 1.6, saying, *"So, going to the next one. Well, there's magnesium here [referring to the product]. There's none over here [referring to the reactant's side of the reaction]. So, this [referring to magnesium] has to come in at some point."*

David thus determined that magnesium would have to be in his answer, on the reactant's side of the reaction, because of his comparison.

In another way, MJ explained why she compared the initial and final states in task P.2, saying,

"...you know, in general, in a reaction if you see K and OH you need those atoms present on the other side."

MJ explained how she used the comparison of the reactants' and products' sides of the reaction to determine what elements she should include (and on which side of the reaction) as demonstrated by her final answer for task P.2 below (Figure 4, where the underlined sections denote her answers).

$$K + \underline{\mathbf{NaOH}} \rightarrow KOH + \underline{\mathbf{Na}}$$

Figure 4
Task P.2 as answered by MJ

Although students often used domain specific strategies (discussed below) after a means-ends analysis comment, there were no noticeable links between the initial use of a means-ends analysis followed by strategies incorporating the chemical characteristics of the substances involved in the reaction. Instead, there was a link between means-ends analysis and the use of heuristics as a strategy. For example, Ashley stated in task 1.2, *"So, the next one. I see I need like a potassium and oxygen so I'm going to put KOH"*

Here, Ashley identified the "missing" elements in the task using the means-ends analysis, and then answered the task immediately. She likely used heuristics to speculate the remaining information. However, since heuristics was used so frequently throughout the study by all the participants, more research would need to be done to determine the strength and frequency of this link between means-ends and heuristics as a strategy.

Means-ends analysis is broadly used by problem solvers, and is not limited to inorganic chemistry, making it a domain-general strategy. Note that some tasks would not reveal any new information from the use of means-ends analyses, as all elements were present on both sides of the equation (see task 3.1, for example). Although the information gathered from means-ends analysis did not appear to be a cue to any particular subsequent strategy, it often resulted in the use of heuristics. One of the reasons for this relationship may be that means-ends analysis does not reveal any chemical characteristics of the species involved. Nonetheless, this analysis appeared to be useful to obtain information on a large number of tasks and helped participants to avoid incorrect answers that would include the omission or addition of an element(s).

Properties

I observed a second category of initial steps when participants would comment on the inherent properties of an element, compound, or compounds present in the task. While the means-ends analysis was focused on the "missing" parts of the task, the properties initial step was focused on the present segments of the tasks and demonstrated an attempt to understand the chemical meaning behind the letters on the paper. For example, in task P.2, Steve said,

"So, we've got potassium, right? So, that's a pretty reactive metal....,"

in which, he made an initial comment about the reactivity of one of the given compounds. As an initial step, the recognition and comments on properties helped the participants gain potential insight on task type (i.e., acid-base or redox types of tasks) and appeared to be cues to particular, domain-specific strategies. The types of observational comments are as follows: acids or bases, stability or reactivity, or change in oxidation state.

Properties: Acid / Base.

The most common comment on properties was a recognizable acid or base. If they were observed, participant comments on a salt or oxide would also be grouped in this category because acid-base equations can also include salts and oxides. However, participants did not specifically mention salts or oxides as an immediately recognized property at this stage of their problem-solving process. The recognition of acids and bases then often led to other students using other compound types during the solving phase, called the Categorization and Algorithm Use strategy. For example, Daisy said on task 2.5,

> *"And then this one [LiOH] is a base. 100% know that…"*

In this case, she noticed a base first with very high confidence. This led to a strategy where she classified the rest of the compounds as follows:

> *"…And I think this [LiCl] is a salt. So, base plus acid is a salt and water, I think. Sounds right. OK. OK so. We have this chlorine and we're going to have to find water, so I'm just gonna do like HCl as an acid. And then we have the water. Good."*

It appeared that Daisy used the identification of the base to proceed and categorize another compound in the task as a "salt." In these participants' inorganic class(es), the instructor gave them general "algorithms" to use such as "acid + base → salt + water." Since she categorized a base, a salt, water, and then chose a known acid as a solution, it appears that she used this inorganic algorithm to solve the task. This is the "categorization and algorithm use" strategy, which is discussed further below. Though she did note the presence of the salt, it was not part of her initial perception of the given reaction.

Other examples included Steve in task 1.3, who commented on an acid,

> *"So now we've got this [K_3BO_3]and we're trying to get back into an acid [H_3BO_3] So, in order to get it from a salt to an acid, just intuitively I'm gonna write a strong acid, so why not just like H_2SO_4. So, we'll get the other salt. That would be potassium sulfate, in this case."*

And task 3.4 where Steve noticed a base,

> *"So, aluminum nitrate to aluminum hydroxide? This is some sort of acid-base. Er, not acid-base. Salt and base, it looks like. I would do KOH because I really like potassium nitrate stuff. Yeah, you know they make rocket fuel."*

In the first example, Steve initially commented on an acidic product (H_3BO_3), and in the second example he knew that one of the compounds was a base. In task 1.3, Steve appeared to specifically choose H_2SO_4 because it was a "strong acid" and then knew that it would yield the "other salt". Therefore, the recognition of a known base led to the "Categorization and Algorithm Use" strategy.

It is important to note that the appearance of the property initial step of regarding comments on an acid, base, salt, or oxide looks very similar to the strategy of categorization (the action of placing a compound into the category of acid, base, salt, or oxide), so it was sometimes difficult to differentiate between the strategy and initial step. As such, I only counted the comment as a "Property" initial step if it was one of the first comments when looking at the task.

The same is true for the rest of the "property" initial steps, as they often cued to specific strategies, and thus were sometimes hard to distinguish from strategy.

Properties: Stability / Reactivity.

Other comments included initial statements regarding stability and reactivity. These comments were very frequent for participants Stu and Steve. In these initial property statements, they first noticed that a given compound contained a property relating to either stability or reactivity, which led to the strategy "Stability and Reactivity." Students used this initial step for information gathering for both acid-base tasks as well as traditional redox and decomposition tasks.

For example, in P.2 Steve said,

"So, we've got potassium, right? So, that's a pretty reactive metal…."

and in P.3 he said

"So, next one. We got carbonic acid. Carbonic acid isn't super stable…"

In both of these examples, his initial reaction was about the inherent properties of the given compound, the first being reactivity while the second being stability. These comments affected how he solved the tasks. For example, in P.2, the reactivity cued Steve to a reactivity-based recognition strategy.

> *"So, we've got potassium right? So that's a pretty reactive metal, so you give that bad boy some water and he's gonna go boom. Boom boom, OK and we're gonna get two products. We're gonna get the hydroxide and we're also gonna get hydrogen gas, hence the boom boom boom, right?"*

In this way, the noticed reactivity appeared to cue to a known explosive reaction, which included water and a gas.

Similarly, in task P.2, Stu appeared to immediately recognize potassium as a reactive element, saying,

> *"OK. I see potassium. I see an OH. The best way to get an OH with a reactive metal is probably water."*

In this example, Stu recalled that potassium is a reactive metal, and then used that reactivity to obtain an answer that contained an OH group.

In these examples, the participants chose their answers based on information they noticed initially. These property cues were based in inorganic concepts and have potential to lead students to methodologies grounded in the chemical characteristics of the species involved in the reaction. The strategy section "stability and reactivity" discusses this further below.

Properties: Change in Oxidation State.

The final group of initial comments were related to oxidation states and had the potential to cue to redox strategies.

For example, in task 1.7, Steve immediately used a redox strategy. When asked what made him think to use oxidation reduction, he replied,

> *"Well, when I'm just looking at this ionic compound [reactant MgB_2], I guess I just saw a lot of hydrogens over here [B_2H_6] and I was like there's no way that could be the same oxidation state, so."*

In this case, he made an educated guess that there was a change in oxidation state by first noticing the number of hydrogens. Through assigning oxidation states, a problem solver can easily confirm his observation, and determine that boron would go through a reduction process which requires the use of a reducing agent. The process of assigning oxidation states and choosing a reducing or oxidizing agent is the Redox strategy. Note that Steve was the only participant to successfully implement the redox strategy over the course of this study. Therefore, the majority of quotes and observations about strategy come from Steve. He also noticed more oxidation changes as (initial steps: properties) than other participants, likely due to his familiarity with the concepts and strategies compared to others.

Another redox property comment was noticing that one of the given parts of the task was in its elemental state, meaning that its oxidation state was zero. For example, in task P.2, I asked Misaki what made her think that the reaction was redox, and she replied,

> *Well, this one made me thought [sic.] because I had the same K, but in this case, we have another one, so it's a single element. So, I thought this would be zero. So, if this is zero and in this and here is plus-one and it looks like redox reaction. Because the oxidation state change [sic.]."*

In this example, Misaki explained that she noticed that the potassium was alone as a single element, which made it oxidation state zero. However, the other potassium containing compound had a plus-one oxidation state. In this way, she determined that the oxidation state changed due to the primary observation of the single element.

Similarly, Steve explained his thought process in task 1.5 by saying,

> *"This is oxidation state zero because it's elemental and I was seeing if I needed to reduce it or oxidize it. And, typically, if you're reducing something then you're gonna need a strong reducer."*

Here, Steve first noticed an oxidation state-zero first, which led him to a redox strategy. This recognition led him to assign oxidation states of the atoms in the product to determine if he required an oxidizer or reducer in order to complete the reaction. Although participants very rarely engaged in redox strategies, these types of observations have the potential to lead students towards redox-specific strategies and/or to categorize the task into the redox category and thus "rule-out" other types of strategies.

Initial steps: Discussion

Students extensively used a means-ends analysis, consisting of determining "what is missing" from the task by comparing initial and final states, which only directly linked to the heuristic strategy. However, when participants detected chemical properties, the characteristics of the property led to various inorganic-specific strategies. Students' ability to notice a property appeared to serve as a quick way to determine the task category, such as acid-base, which could function to reduce the mental load of the problem-solver.

Problem-Solving Strategy: Heuristics

The most prominent method to solve tasks was using heuristics, which often occurred after the initial step of a means-ends analysis. The definition of heuristics can be varied, as explained by Nadurak (2022) who stated, "there are several basic definitions of heuristics that differ from each other. Therefore, any study of heuristics should begin with their definition" (p. 48). As such, this section will also start with a definition.

Shah and Oppenheimer (2008) said that researchers often describe heuristics as rules of thumb or mental shortcuts, but that those terms are too vague for meaningful use. Instead, Shah and Oppenheimer (2008) described heuristics as cognitive effort reduction. They state, “heuristic behavior in the realm of judgment and decision making necessarily relaxes the difficult requirements of the weighted additive rule” and that “…heuristics predictably reduce cognitive effort” (Shah & Oppenheimer, 2008 p. 207). In this way, they described that the person could reduce the mental load of decision making or judgments using heuristics instead of some complicated algorism that considers every single aspect of the task or situation. Shah and Oppenheimer (2008) described five effort reducing behaviors including:

“1. Examining fewer cues.

2. Reducing the difficulty associated with retrieving and storing cue values.

3. Simplifying the weighting principles for cues.

4. Integrating less information.

5. Examining fewer alternatives” (Shah & Oppenheimer 2008 p. 209).

There are two identified levels of cognitive processes in which heuristics could inhabit. Kahneman and Federick (2002) described the dual process system cognitive processes, in which they defined System 1 as Intuitive (qualities included: effortless, automatic, affective, and/or prototypes) and System 2 as Reflexive, (qualities included: slow, deductive, abstract, and/or self-aware) (p. 51). In this way, the main differentiator between System 1 and System 2 was that the first requires no conscious control of the user and second required the user to gain conscious control of the decision or judgement (Nadurak 2022).

Some heuristic definitions attempt to classify heuristics only within intuitive judgements (Nadurak 2022). These would include quick and reflexive judgements made without the conscious awareness of the person using them. However, Nadurak (2022) argues that heuristics could take place on either of the dual process cognitive processes. If, for example, a person deliberately chose to examine fewer cues than are available before deciding, that person would be engaging in a system 2 heuristic response. This study focused on language that pointed towards intuitive, System 1, heuristic responses due to the initial categorization of participant heuristic responses as actions and phrases that denoted a leap in logic. The only observed participant responses that fell in this category were System 1, therefore I did not observe any deliberate uses of system 2 heuristic responses during this study. Further research would be required to determine if students also use system 2 heuristic responses for inorganic complete-the-reaction tasks.

Another point of note is that while the use of heuristics does not consider all data available in a task by the problem-solver, they often result in reasonable or correct answers. The effectiveness tends to vary based on "both on the heuristic itself and on the person, environment, and problem that needs to be solved" (Nadurak 2022 p. 55).

As there is no definitive list of descriptive heuristics for human behavior, and due to the nature of my coding process, it became difficult for me to classify the observed behavior into specific heuristic subtypes in the way that other researchers have attempted (DeCocq & Bhattacharyya, 2019; Kahneman & Frederick, 2002; Nadurak, 2022). To simplify this process for the sake of the study, I organized this section by first describing the observed behavior and then describing the mental shortcut associated with that behavior, as demonstrated below. Because heuristics are intuitive judgements where the reasoning is not necessarily conscious, it follows that participants' verbalization of heuristics may not always be straightforward. The comments I observed that resulted from a heuristic solving method often included phrases such as, "I was just guessing" or "I don't know." The notable heuristic behaviors I observed during this study included: heuristics as the foremost strategy for composition and decomposition tasks, the use of reference material, the use of underlying assumptions, and an affect response in which participants said that they were relying on a "gut feeling."

Composition and Decomposition

Heuristic use was the prevailing solving method in regard to both composition and decomposition tasks. Composition tasks are those in which the final answer consisted of multiple reactants producing a single product in the chemical reaction. In contrast, decomposition tasks are when a single reactant produces multiple products, typically with the aid of heat or electrolysis. Composition and decomposition tasks are redox tasks since both reactions contain oxidation state changes. However, participants did not typically attempt redox-related solutions with composition or decomposition tasks. The participants very rarely identified decomposition tasks as redox, and they did not appear to recognize composition tasks as redox at all. Instead, the majority problem-solving strategy was through the use of heuristics.

For composition tasks, the participants showed little chemical reasoning through the verbalization. For example, Ashley solved task 1.1 saying,

> *"So, we see that there's chlorine. So, I would just put* Cl_2 *over here. I think that's all you need to do. I don't think anything else would come out of that."*

Because she initially noticed that chlorine was missing, and then used a familiar form of chlorine to solve the task, I was able to classify this solving method as heuristics after a means-ends analysis initial step. This method is a likely heuristic because Ashley did not examine all cues in the task, and she integrated less information since there was no evidence of her examining or using chemical properties. This type of solving method was common for all participants throughout the study.

However, the participants' primary solving method could still be heuristics, even if the participant initially used chemical reasoning. For example, Misaki solved task 1.6 as follows:

> *"[Writes possible reactant]. This would be. No. [Erases possible reactant] So + 1 there. [writes in oxidation states] ... Oh, that's just its oxidation state. I'm just thinking too much here. For something else. Because this is zero so then this is the. From three [unintelligible] so this is plus or minus something. This is plus one. ...Can you change the oxidation state two from zero boron to something else? ...This is a redox reaction. Which really don't know what it goes in here [sic.]. Maybe it's just like that. Maybe is just like Mg."*

Initially it appears that Misaki performed a means-ends analysis that led her to write a possible reactant that I could not observe due to the angle of the camera, likely using heuristics. She then moved on to writing in the oxidation states, categorizing the task as redox when the states changed. This is one of the few times during the study where a participant classified a composition task as Redox. However, when she was stuck and could not determine how to change the oxidation state through the course of the reaction, it appears that she fell back on the heuristic solving method of using the remaining elements gathered from the means-ends analysis. The use of a heuristic strategy is more likely than Misaki using magnesium deliberately to change the oxidation state because her language describes affect, not properties. Her emotion-based language that she "really don't know" and that "maybe" her answer was reasonable is seen more often when a participant is using mental shortcuts and would describe their answer as a guess. Participants who attempted to use chemical reasoning but fell back on heuristics was also a common occurrence, particularly for redox tasks.

Participants solved decomposition tasks in a similar way to composition tasks, but with the inclusion of heat or electrolysis to make the chemical reaction logically follow. For example, Martha solved task P.3 saying,

> *"And of course, same with here. It's- I know this. This has some likes dissociating to CO_2. So. If I take CO_2 out of here with H_2 and then one O, So of course, water over here. The way that does that is you add heat."*

In this case, Martha considered water the obvious choice because the means-ends analysis revealed that the proposed answer must account for hydrogen and oxygen. In order to make the reaction logically follow, she added heat to the reaction. Here, the cue to heuristics would be Martha's jump to water as an answer without considering the chemical nature of the compounds involved, which resulted in a correct answer. The mental shortcut was a jump based on familiarity when examining "what is missing" after the initial step.

Similarly, Stu began task 2.1 saying,

> *"So, this is going to give off something with CO_2 because it's losing a carbon and two oxygens."*

Using a means-ends analysis and heuristics, Stu determined that carbon and two oxygens could result in the familiar product of CO_2 through the mental shortcut, familiarity.

Use of Reference Material

Another line of problem-solving that relied on heuristics was the use of reference material. While other interpretations may not consider the use of reference material a heuristic, I placed it in this section due to the lack of conscious thought, and because I observed a tendency of participants using this strategy as a mental shortcut which resulted in participants not engaging with underlying chemical properties of the tasks. During the study, I provided the participants with the class textbook and handouts in the form of packets that were available to the participants to reference, so that memorized knowledge would not be a barrier to problem-solving. However, I observed that in some cases, primarily seen through Ashley in this study, participants attempted to find exact or similar representative models in the reference material that resulted in a search-and-find methodology rather than a chemistry concept based problem-solving methodology.

For example, when looking at task 1.5, I asked Ashley what she was looking for when flipping through the book. She said,

> "*Yeah, I'm looking for any reaction that has these two components [B_2O_3 and B]. So, if I'm lucky I can find the exact same one. Um. Or two. I feel like oxygen just has to be there so. I don't know what makes it do that.*

Here, she explained that she looked through reference material for partial or, preferably, full reactions to use as a frame or example to complete the task. I classified this behavior as a heuristic, because by finding the exact answer rather than engaging in problem-solving behavior, she was integrating less chemical information into her problem-solving strategy, and her only cue was the chemical symbols rather than engaging in their underlying meanings.

Ashley solved task 3.1 while looking at the book saying,

> *"So, I see this one. I'm going to add potassium. I'm just going to put this and then put three KCl."*

When asked if she chose potassium because she noticed it in the book, she replied,

> *"Yeah, I just. I definitely wouldn't have come up with potassium by myself if I hadn't seen it, so I probably would have tried to put like hydrogen or HCl maybe?"*

In this way, she relied on an example in the book to write her own answer, even though she could have answered the task without reference material in a different way.

Use of Underlying Assumptions

Another example of heuristics was the use of underlying assumptions and associations from previous experience in order to solve tasks, rather than domain-specific solutions. This heuristic functioned to simplify the information so that information associated with a property or trend would be easier to retrieve, rather than the participant thinking about the underlying concepts of each trend each time. For example, MJ solved task 1.4 saying,

> *"OK. It's H_3BO_3 and B_2O_3. B_2O_3 looks so familiar. I know I've seen it on the slides. Yeah, but how to get there? That's the question. OK. I don't know since it gets smaller, I'm gonna say heat... And then I'm gonna put H_2. Because when in doubt, H_2."*

Here, MJ solved the task by first attempting to remember a compound from class. Her response was based on two, likely subconscious, assumptions: first that if a compound decreases in size heat is likely involved, and then that hydrogen gas is a good stand-alone compound when the answer is uncertain. Neither of these assumptions are deliberately taught in classes, so they likely arose from previous experience with these types of tasks and then became mental shortcuts through repeated observation and use.

Similarly, in task 1.7, Ashley solved the task using an association saying,

> *"And then this last one. I'm writing these ones because I feel like these two [elements Mg and Br] are always together."*

When asked if she had seen these together in tasks a lot, she responded, *"Yep."* Here, Ashley made an unconscious assumption that because she saw the two elements together frequently, that compound must be the correct answer.

The "Gut Feeling" Response

The final notable heuristic observed were related to affect comments. These were statements from participants that were related to their emotions and impacted the problem-solving process, rather than examining the chemistry involved.

When I asked Ashley, whose main strategy included the search-and-find method of using reference materials, how her strategy would change if she did not have access to materials, she responded,

> *"If it's on a test or something. Like, I would mostly rely on my gut feeling. I think I don't necessarily know why something is wrong, but sometimes I can just look at it and it just doesn't look right, and I think that's because I haven't seen it as much. So, I know that like 'I haven't seen that. Why am I writing it like that?'"*

This "gut feeling" affect language, is a result of recognizing and comparing to what she has seen before in the classroom settings. Therefore, the mental shortcut would be placing a heavy value on recognition. If she begins to write an answer that is not recognizable, she questions it.

Stu explained further on his thought process in task 2.1, where he correctly determined that the proposed decomposition reaction required heat,

> *"I want to say my gut reaction with this right here is to maybe heat it up. This is just gut reaction, so student intuition: that if you heat this up somehow, it'll give off CO_2 and O_2.*

And react with itself. That's just what- And I have no thought process behind that. That's just kind of, it's just a guess and it looks right. Or maybe it would just give off CO_2."

Here, despite claiming to have no thought process behind his decisions, ascribing his choices on a "gut reaction" and "student intuition," Stu was able to determine correctly that the reaction required heat. However, his comment on the potential products on the reaction producing CO_2 and O_2, then reacting with themselves would have been incorrect.

Heuristics: Discussion

Participants frequently used heuristic mental shortcuts, directly after a means-ends analysis. All of the observed heuristics resulted in the participants engaging with the tasks at a surface "symbol" level rather than a deeper "chemical concepts" level. I observed that participants tended to treat the chemical compounds within the tasks as symbols most often when using the heuristic approaches of obtaining recognition-based answers through the rearrangement of means-ends analysis data and through the search-and-find methodology when participants heavily used the book or class materials.

When participants relied on assumptions and associations, they depended on their own remembered experience and potentially flawed chemical representative prototypes to problem-solve rather than an inorganic theory-centered strategy that would involve consideration and proper use of the properties of the substances involved.

Nevertheless, the use of heuristics as a method generated a high rate of correctness. If students are able to use heuristics to correctly solve complete-the-reaction tasks, educators should be aware that students are likely to use them without practicing underlying concepts, which may be a detriment to learning the problem-solving process.

Problem-Solving Strategy: Categorization and Algorithm Use

The first distinct strategy of note is the categorization of compounds into acid, base, salt, or oxide then using class-taught "algorithms" to determine which type of compound is missing from the given reactant. One common example "algorithm" includes, "acid + base → salt + water." Given a task with an acidic reactant and a salt product, the student would be able to use the algorithm to determine that the other reactant is a base, and the other product is water. In that way, they could solve the task. This was the primary inorganic-specific strategy for acid-base tasks.

For example, Martha attempted to categorize LiOH on task 2.4 as follows:

"Okay, okay, Lithium to lithium hydroxide. So, we have. I don't really know if that is a base. Yeah, it does. Okay, this is a similar one to our KOH."

Martha categorized LiOH as a base because of its similarity to KOH, a base that was more familiar to her. When asked about similarities and connections later in the interview, she replied,

"*You have to kinda know on the periodic table."*

which indicates that she may be using the periodic similarity of potassium and lithium in the same column, as well as the same anion to determine the similarity between the compounds of LiOH and KOH. This is a well-worded example of deductive categorization of compounds, which could be used for the Categorization and Algorithm Use strategy. However, in this case she proceeded to use the added chemical knowledge of bases in combination with her Organic strategy and the Stability & Reactivity strategy to solve.

In another example, in task 2.6, David explained, *"And then, OK. Two different salts - probably double displacement. So, I'd guess $2SO_4$. Two plus two. HCl. So, you have basic -Or no. You just have salt plus another acid yields new acid plus new salt."*

In this example, David started by looking at the task as displacement, likely noting that switching cations and anions between reactant and product would result in the opposite salt, balanced elements, then categorized the given reactants and applied a known inorganic algorithm to answer the task.

For these exercises, I assumed that students used a Brønsted–Lowry acid–base model, as the acids were characterized by their ability to donate a proton. However, participants' comments indicated that they did not consciously use any acid-base models to answer acid-base tasks. For example, Steve said,

"So, I couldn't tell you which one is which. I know the different definitions, but I couldn't match them up. But just, what I would be most comfortable with is if you gave me a sheet of acids and bases and told me to write the products, I'd be able to write them."

Steve was highly successful in acid-base tasks at a 75% success rate, which shows that students do not need to necessarily be verbally fluent in theories in order to use them to solve inorganic tasks. Not only that, but directly before asking about the theories, Steve said that his most comfortable inorganic chemistry topic was,

"Probably just acid-base."

This strategy to solve acid-base tasks was typically effective. It also made use of class concepts. However, several participants, particularly Ashley and Daisy, relied heavily on memorization of the compounds into categories to solve them. This resulted in looking up information in the book or packets when they did not remember the properties of a compound, often looking for entire answers to the task. For example, in task 1.3, Ashley attempted to solve the task as follows:

> *"[Ashley gets out packets] … I want to look for something that [has a hydrogen] … [Continues flipping through packets. Looks at textbook] So first I'm gonna go and look up the chapter that has boron and see if it has one of those, like, flowcharts… Alright. So, I found H_3BO_3. But not anything the thing that comes- That's not helpful. Yeah. I really just hope to find something similar when I'm searching through. But I don't see anything, like, the same…Yeah, I think I'm gonna skip this one. I can't think of what I would put."*

In this example, Ashley first looked for a compound with hydrogen in it that she could use within class handouts, but then moved on to looking for the exact task (or something similar enough to replicate) within the textbook. When she could not find the reaction, she did not attempt another strategy. The use of books and packets to solve the tasks did not appear to be particularly effective for her.

Categorization and algorithm use was less effective when compounds displayed amphoteric character. For example, though Daisy's primary strategy centered around this strategy, her categorization of the boron compounds as amphoteric led to an inability to use many of the algorithms, because she was unsure whether the compound was acting as an acid or a base. For example, when trying to look for information on aluminum for reaction chain three, Daisy said,

> *"So [the inorganic textbook] says it's an amphoteric metal. Okay, so I was right, but the only problem with this is that it can go either way, so it can be either a base or an acid. So, you'd never know unless they tell you."*

In this way, she explained that amphoteric compounds were much harder to categorize for her and led to a block in the categorization and algorithm use strategy, and even that she would require instruction to determine which property the compound was displaying at any given time.

Categorization and algorithm use was the most consistent strategy that participants used. They appeared familiar with this type of problem-solving method, and it was often the first type of strategy that students tried in the absence of an obvious way forward. This may be due to the prevalence of certain acids and bases in the course from which the participants were recruited, or another reason, such as greater understanding compared to other topics. It was often effective, as it gave participants the properties of the missing compound(s). However, the strategy was only effective with acid-base tasks, participants struggled with amphoteric character at times, and the reliance on memory over pattern recognition for categorization may be hinderances to problem-solving.

Problem-Solving Strategy: Redox

Redox tasks included composition and decomposition tasks as well as more traditional redox, which I defined as those that involved oxidation and reduction but were not composition or decomposition. Redox tasks made up 12 out of the 21 tasks. One participant was very successful, in which he implemented a traditional redox solving strategy. Using this strategy, he assigned oxidation states to determine whether the chemical reaction oxidized or reduced a particular element, then deliberately used an oxidizing reagent or a reducing reagent to solve the task. However, the most common strategy in terms of traditional redox was simply recognition, where the participant would note a change in oxidation state, and then solve the task using heuristics or recall. Students also sometimes solved traditional redox tasks using Stability and

Reactivity strategies. Students treated composition and decomposition tasks very differently than traditional redox tasks. This is an important finding, as this study showed that the participants treated traditional redox, composition, and decomposition tasks very differently from each other despite all being a part of the overall Redox category of tasks. This section will discuss the traditional redox strategy and use of oxidation states without the redox strategy, as well as the unfamiliarity participants have with redox tasks.

Traditional redox – Oxidation Reduction

There was only one participant who used a traditional solving method for redox tasks, defined as using known oxidizers to oxidize compounds or known reducers to reduce compounds in order solve the task. Steve was able to identify the task as redox, then use a reducer in task 2.3, explaining,

> *"So, we've got lithium fluoride, and we need to get some lithium. So, from what it looks like, we need to get a more reactive metal to reduce that a bit more. It is reduced right? Yeah, yeah, it's giving an electron. So, I would wanna put sodium, potassium, anything under it. We could even put cesium."*

For this task, Steve read the task aloud and noticed a difference in oxidation state, which appeared to cue him to the redox strategy. Then, he chose an elemental column that he knew to have reducing properties and chose from that list.

Similarly, Steve solved task 1.5 as follows:

> "*B_3O_3. Looks like we've got a plus-two oxidation state [on Boron in the compound B_2O_3]. Since this is 1 to 1 with oxygen, so we've got to get it to zero somehow, which means uh*

we've got to reduce it with something. So why not do sodium? Since, you know it's very reactive."

Steve was able to recognize the task as redox, assign oxidation states to boron, and then choose a reducer that would react with B_2O_3.

This traditional redox method was very successful, as Steve had a success rate of 100% on redox tasks using this method. However, Steve was the only participant to successfully use this method. The other participants were largely unable to either understand the concepts fully or put them into practice in this setting.

Avoidance

Participants often avoided redox-specific strategies during the study, with several students not using redox concepts in any capacity, and others using redox as a last resort. Ashley said that she struggled with the concept. When asked what concepts in class she struggled with the most, she replied,

"Redox reactions… Yeah. I never really like clicked with those… I think it's because, well, when we first learned them and Gen Chem 2, I wasn't a chemistry major, so I wasn't, like, paying attention because I switched from biology to chemistry."

She did not attempt to use any type of redox strategies during this interview. However, she was not the only participant who avoided their use. As such, it may be that students may avoid redox strategies due to unfamiliarity. This could be because they can obtain perfectly acceptable answers in many cases without the use of any redox strategies. Ashley in particular was able to answer 50% of the traditional redox correctly, as well as 100% of the composition tasks and 75% of decomposition tasks without the use of any particular redox-specific strategy.

Instead, she focused on means-ends and heuristics while looking up exact reactions from the given materials.

Daisy, who also did not use a redox-specific strategy, stated,

"Yeah, I think it was helpful when we did our homework and stuff when he said which ones are acid-base and which ones are a redox, because I just don't immediately think about it unless he gives it to us to balance and then you can look at it and feel like 'Oh yeah this is Changing [oxidation states]'. There's just multiple parts to it that you have to think about, like everything."

When I asked if she thought it would be helpful to separate out acid-base from redox tasks, she replied,

"Yeah, definitely."

It appeared that she did not typically see cues for redox tasks and did not look for them unless the set of tasks specifically instructed her to do so.

Labeling oxidation states

The most common strategy that participants used to solve redox tasks was to first identify the task as redox, then label oxidation states or half reactions, but they ultimately relied on heuristics to generate an answer for the task. This method was partially successful in obtaining correct answers. Since the discussion of heuristics was discussed earlier, this section will focus on the problem-solving behaviors related to oxidation states and half reactions. For example, in task 1.6 Misaki started by writing in a reactant, then writing in the oxidation states. When asked about the oxidation state marking, she said, *"Oh, that's just its oxidation state. I'm just thinking too much here… Can you change the oxidation state two from zero boron to something else? So [unintelligible] this is a redox reaction. Which, I really don't know what it goes in here. Maybe it's just like that. Maybe is just like Mg."*

In this example, she correctly identified the task as redox through the oxidation state change, but she was not able to decipher how to effect that change (like using an oxidizer or reducer). Instead, she chose to use the information gathered from the means-ends analysis to answer the task using heuristics, which was successful in this case. Misaki chose Mg because it was the simple answer derived from 'what is missing.' In another example, David categorized the reaction and successfully solved task 2.4. He said,

"And then of course, for this one, this is kind of same as we did before [referencing P.2] … So, you have an aluminum with strong metallic character plus water yields hydroxide plus- That's going to be H_2*. Probably."*

Here he recognized the reaction type and used that knowledge to answer the task, but without the express use of an oxidizer or reducer.

The observed benefit of deliberately looking for oxidation states in these cases would be to identify the task as redox. Each participant who assigned oxidation states was able to tell whether the task fell into the category of redox or not based on whether the oxidation states of each element changed from the reactants to the products side of the chemical reaction. However, knowing the task-type did not guarantee a solution or even a strategy, which is why many participants likely relied on heuristics even after determining task type.

Use of Half-reactions

Another redox method was the use of half-reactions, which allowed the participant to balance electrons. Only David and Misaki used half-reactions during this study. David explained during task 1.5 that he used half reactions because,

> *"It helps you balance the reaction Because if you if you just tried to balance a Reaction - a redox reaction - just from like the molar ratios, that may or may not work because it doesn't take into account the amount of electrons that are moving between the others or between the reactants into the products. So, the. So, this sort of gives you a better idea,"*

In this way, David used half reactions as a way to balance electrons (See figure 5).

$$\left|\begin{array}{lcccl} 2B^{+3} & + & 6e^- & \rightarrow & 2B^0 \\ 3O^{-2} & - & 6e^- & \rightarrow & 3O^0 \end{array}\right.$$

Figure 5
Example of participant half-reaction: David task 1.5

Misaki, on the other hand, only used a half reaction once and it contained errors. She did so while solving task 2.3 while explaining,

> *"Yeah. I don't really do half reactions for balancing. I just kind of just figure it out"* and as she wrote the half reactions said, *"I never understood this one, but [the instructor] always puts it [half-reactions]."*

$$\left.\begin{array}{lcccl} Li^{+1} & + & e^- & \rightarrow & Li^0 \\ H_2^0 & + & (1e^-)? & \rightarrow & H^{+1} \end{array}\right| \begin{array}{l} 2 \\ 1 \end{array}$$

Figure 6
Example of participant half-reaction: Misaki task 2.3

Misaki claimed that she did not understand or need half-reactions but used them on occasion to mimic her professor.

In this way, writing the half-reactions helped reveal information about the task, but neither David nor Misaki were able to utilize that information due to their solving strategies focusing primarily on heuristics. Since students did not use half reactions effectively during this study, it is difficult to ascertain their usefulness to any overall strategy without further study.

Redox Strategy: Discussion

Traditional redox tasks were difficult for participants in this study, both due to their difficulties with underlying concepts (being able to identify redox tasks apart from acid-base tasks, establishing the transfer of electrons, as well as difficulties with identifying and explaining the use of oxidizers or reducers) and their inability to utilize these concepts within redox-specific strategies. In fact, even though composition and decomposition tasks contain oxidizers and reducers, participants did not perceive or treat them as redox tasks in this study. The single participant who deliberately used oxidizers and reducers to solve the tasks performed very well at 100% correct for the redox category of tasks.

However, the majority of participants elected to use means-ends analysis and heuristics for traditional redox tasks, sometimes with added elements such as labeling oxidation states or using half reactions. When students derived an answer this way for traditional redox, it was generally less successful, which is likely because the solving of traditional redox tasks often requires the use of an outside element (an oxidizer or reducer) that this method would not be able to generate. The method of assigning oxidation states in order to identify the task as redox was similarly unsuccessful by itself, but it could be a useful tool in identifying redox-type tasks apart from acid-base tasks.

Despite concept difficulty, all but one participant was able to solve at least 25% percent of traditional redox tasks. Stu, for example, had a success rate of 75% on redox tasks by using a combination of other strategies (including Stability and Reactivity strategies) instead. Ashley also had a 75% using heuristics as a primary strategy. These results indicate that students may be able to solve redox tasks, sometimes with a high degree of success, even without a using intended concepts or methodologies.

Problem-Solving Strategy: Stability and Reactivity

In the strategy, Stability and Reactivity, participants used elemental/compound properties and trends relating either to stability or reactivity in order to propose a task answer. The property initial step often cued this strategy from the students who noticed compounds/elements with unstable/reactive properties. Participants used this methodology for acid-base, traditional redox, and decomposition tasks, and Stu used this strategy as his primary strategy. Particularly for redox tasks, participants chose elements or compounds because they knew that the element/compound would strongly react with the given compound, not because they were reducers/oxidizers. For ionic compounds, participants attempted to use reactivity to displace a cation/anion with another cation/anion. They also analyzed compounds for stability, where an unstable compound was likely to break apart over the course of the reaction or stable compounds were likely to form. This strategy was broad and captured a wide range of inorganic topics and trends. The strategy resulted in mixed results for accuracy.

For example, in the redox task 1.5 Stu explained,

"...you could combine elemental manganese with [the given reactant], because it really wants oxygen more than boron, so that would probably make MnO_2 right there."

In this way, he used manganese because it was more reactive than elemental boron, not because it was in the class of 'reducer' substances. Nonetheless, Stu's strategy shows an understanding of periodic trends and characteristics of elements, even though the redox language was not present. On the other hand, when I asked him about trends in reactivity Stu said,

"Well, I know why [the trend] happens, but whenever I am doing the product problems, I generally think more of the trends then why there's a trend."

In this way, he explained he often used trends independently of the concepts behind them, even if he knows the chemical reasoning.

In another case, David mentioned anion displacement while solving task 2.6. When asked about why he mentioned double displacement, he explained,

"Just because lithium stays the same. I know these. And that's an anion. That's another common anion. So, they're both salts. And whatever you get. You can turn one salt into another one without changing like, the composition aside from what the anion is, we think double displacement."

In this way he demonstrated that a displacement type task was easily identifiable because of a recognizable anion. However, note that this particular anion displacement did not occur with comments on anion properties. It is unclear whether David used inorganic concepts while solving, or if he was simply "switching" the anions with no further thought.

On the other hand, Stu used displacement along with reactivity to explain task 2.3,

"My gut reaction to looking at this is that [task 2.3 is] impossible, even though I know it's not, because lithium is the most reactive of the alkaline metals. Because it's the highest

above. The only thing above it is hydrogen, so. ... my gut action would be, if this was sodium fluoride to combine it with lithium because lithium is more reactive than sodium to get sodium by itself. If sodium was the element right here. But I don't have anything that would be more reactive. Because I know hydrogen gas isn't going to react more than that. So that's really tricky for me."

Stu explained here that his typical process would be to use a more reactive alkaline metal to displace a less reactive alkaline metal, creating a single or double displacement type reaction. In this way, he combined the concepts of displacement and reactivity. However, in this case, he could not easily identify a 'more reactive' element to allow the reaction to logically proceed. This shows a fault in his logic, as reactivity actually increases for an oxidizing agent as it goes down in the Periodic Table group. In this case, correctly remembering the chemical trend had potential to result in a different outcome.

Martha took a different approach to displacement, where she used electrons in orbitals to determine if her proposed Lewis structure was stable enough to be considered as a reasonable answer. She stated as part of her problem solving in task 1.6 (see Figure 7),

"*Although, it would have four electrons. Theoretically, [boron would] have half the s orbital and then half of the p orbital and be less bad. That could work."*

B + <u>**Mg + Electrolysis**</u> → MgB_2 + **-**

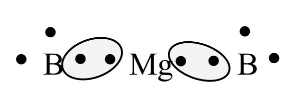

Figure 7
Task 1.6 written by Martha, using Lewis structures (reproduced in digital formatting)

Martha often used Lewis structures and orbital theory as part of her stability and reactivity strategy. In this way, she was able to determine stability and sometimes predict how the compound may react based on how electrons filled the orbitals, though the method came with some limitations due to bonding type (See Problem-Solving Strategy: Organic). In this case, while Martha was nearly correct in her chosen reactant, I determined that the incorrect use of electrolysis was enough of an error to mark as incorrect. However, her determination of MgB_2 as being stable through the use electron orbitals was correct.

In P.3, however, it was the instability of carbonic acid as a compound, which led Steve to the conclusion that it could break apart. Steve explained,

> *"So next one we got carbonic acid. Carbonic acid isn't super stable, so I don't know if I'm supposed to put anything here [points at blank on reactant side], but I know it does just decompose into carbon dioxide and water. Which I mean, is pretty intuitive considering H_2, like it's just in the formula, right?"*

In this example, Steve degraded the compound from what appears to be a cue from stability. He also mentioned the "formulas" discussed above as algorithms, but I classified the comment as a verification statement rather than a problem-solving methodology because it did not lead to a written answer.

The participants' use of this strategy also focused on the formation of stable compounds as opposed to non-stable/more reactive compounds, which would be a logical error in these tasks as taught by the class instructor. For example, when asked why an acid-base task would require a product that is a weaker acid than reactant acid in the chemical reaction, Stu explained,

> *"Stronger acids…they really want to get rid of that hydrogen if they can. And you're not gonna form something that wants to get rid of a hydrogen even more in a reaction*

because you can't form something less stable. That won't work. Every reaction is trying to become more stable somehow. So, you can't form something that would want to exist even less."

In this way, he reasoned that his task answers must go through processes in which compounds move from less to more stable substances, which accurately describes spontaneous chemical reactions.

In a similar way, participants also used the formation of products such as gases or precipitates in order to answer tasks, which has potential roots in stability. For example, MJ used the knowledge of a precipitate in task 1.7. She said,

"And then MgB_2 to give you B_2H_6, which I remember is the banana bond one, I think... Well, we're gonna make a salt, because why not? So, I'm just gonna add HCl again because it's easy and I like it... So, then I would do $MgCl_2$ as a salt. I'm just gonna draw the arrow down since it precipitates."

In this way, she solved the task through the recognition and use of a known precipitate. This was a very effective strategy, as she was the only participant able to correctly solve this task. Since precipitates leave the reaction solution, I classified this as a stability and reactivity strategy. However, more research would be needed to determine if participants chose precipitates because of their chemical properties, or because they were memorized and thus recognizable.

Stu was able to obtain answers for the majority of tasks in this manner, regardless of task category. However, his overall accuracy was 57% correct, which, though other impacting factors were likely involved, indicates that this primary strategy was possibly less successful than other strategies. Stability and reactivity concept use have great degrees of relevance to inorganic classrooms, as knowing and using elemental trends are good skills for inorganic chemists.

However, there are likely students who successfully use properties without thinking about the underlying concepts.

Problem-Solving Strategy: Organic

The organic strategy is characterized by students following electrons to determine where bonds would break and form, sometimes by using arrow-pushing mechanisms. In this research study, I only observed this strategy used by Martha. However, Calhoun (1997) also observed this type of strategy in her thesis, although her conclusions are different from the ones I formed based on this data.

As an example of the organic strategy, Martha drew the diagram illustrated in figure 8 while verbalizing her thought process for task 2.1 as shown below:

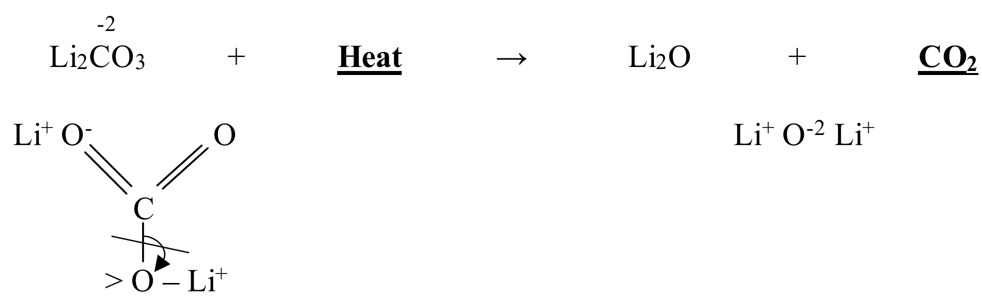

Figure 8
Task 2.1 written by Martha, using chemical structures (reproduced in digital formatting)

> *"Okay, so basically, we know that carbonate has a plus two [oxidation state] ... So, the CO_3 like as an ion- or anion. Sorry not anion - Is plus two, right? So, which is why we have the two. Minus 2. Wow I'm going crazy. okay, minus two, which is why we have two positive lithium, positive and negative…These are probably most likely like counterion kind of things. So, you have like your oxygens and then once they wander and then once these are negative and then they have the lithium. Like that and so basically either.*

Because this, we're gonna end up with an oxygen, that is minus two with two lithium counter ions… Either this or another oxygen is introduced. We end up with carbonate by itself … Or one of these is cut. Which would actually make sense, because then this would form a double bond here. Then, the lithium would leave… Heat? I mean, is it? Well, would it be aqueous, or would it just be their own separate things? Probably heat then because then you would end up with carbon dioxide. Yeah.

Martha began the task using a redox strategy by counting oxidation states of the given ions in the task. She then attempted to determine how bonds may move and break, focusing on oxygen. She finally determined that she could form a double bond which allowed "lithium to leave" (presumably Li_2O). To justify the bond movement, she determined that the reaction required heat. Finally, she found that CO_2 would be the remaining product. This answer was correct even though the Lewis structure of carbonate was incorrect.

When I asked her reasoning on why she used this strategy, Martha responded,

"*Yeah, sometimes these are, I don't know, can be a good way to think of it. I think like they are getting- the way of thinking about it that I learned in advanced organic really helped a lot because there's more of like how to think about it rather than like 'these are the reactions like memorized how it becomes a thing.'"*

When asked further about electron pushing mechanisms, she said*,*

"I would say, yeah. So, because. I mean, the main thing, because, what's causing these things to form bonds is the electrons. And so like, if you can follow the electrons, theoretically you should be able to follow what else is happening until you get to like ligands and all that stuff. That stuff is. Yeah, I mean it's- You're still following the electrons, but they do weirder things."

In this way, she explained that following the electrons and their behavior would help her predict bonding patterns and properties, at least until the tasks became more complex, and that she attributed this method to her additional experience with an advanced organic course and a desire to understand the mechanism of change rather than memorization of reactions.

For some tasks, the addition of electron configurations appeared to add an additional layer of complexity and, thus, difficulty. For example, in task 1.6, Martha attempted to solve the task (shown in Figure 9) saying,

B + **<u>Mg + Electrolysis</u>** → MgB_2 + **-**

Figure 9
Task 1.6 written by Martha, using Lewis structures (reproduced in digital formatting)

> *"Okay, so this would probably have to be with- Definitely something with magnesium. I have a feeling it's probably elemental because… boron only has three electrons. And magnesium as an ion is positive two [oxidation state]. So, magnesium would be fine, but boron would not be. But even if magnesium started as neutral [oxidation state], the boron would not be happy. Although it would have four electrons. Theoretically, [boron would have] half the S orbital and then half of the P orbital and be less bad. That could work… Can it be deficient all around? I don't know about this guy."*

In this way, the additional information that she derived for this composition task was difficult for her to follow at times. She did use chemistry-specific knowledge and strategy, but in this case, she likely did not require the additional derived knowledge in order to answer the task (as shown by the five participants who completed the task correctly using other methods. See Table 4). This is at least partially due to misconceptions, as discussed below.

Martha wrote out Lewis structures, including electrons, on the following tasks: P.2, 1.2, 1.6, 1.7, 2.1, 2.3, 2.4, and 3.2. From those, she only drew what is likely an electron-pushing arrow on task P.2. However, her verbalized thought process showed that she thought through electron-pushing mechanisms, even if she did not write them down.

In task P.2, Martha began writing the Lewis structures, and then said,

"*You have one electron, and then that would go. Hmm. I still feel like that's not right. Because it was minus… Yeah, we'll just leave it there*."

I categorized this statement as electron pushing, organic strategy because Martha verbalized that she attempted to find locations in which the electron would be able to move and bond with other elements. She drew a curved line between the hydrogen and oxygen (see Figure 10), which likely denoted electron pushing or bonding.

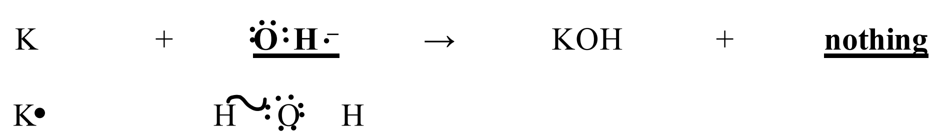

Figure 10
Task P.2 written by Martha, using Lewis structures (reproduced in digital formatting)

Martha's score of correctness decreased when using the organic strategy as opposed to other strategies. When counting tasks where she used the Organic method, her score was 40% correct. However, when Martha used any other strategy, including recognition, reactivity, and categorization, her performance was 80% correct. This method theoretically should be able to follow and count electrons, however it appeared to be a hinderance, especially in several incorrectly answered tasks where they were incorrect due to differing amounts of electrons on each side of the chemical reaction.

The application and perception of bonding theory can be different in organic chemistry compared to inorganic chemistry, which could lead to some misconceptions. This is because electron-pushing or "arrow-pushing" mechanisms function nearly solely within covalent bonding theory. Arrow pushing would not be effective for compounds that are composed of ionic bonds where elements donate electrons, and certainly not for metallic bonds where electrons have freedom of movement.

Task 1.7 demonstrates the bonding differences between the two disciplines, since it includes a compound with metallic bonding reacting with an unknown compound to produce a compound with three centered two electron bonding, B_2H_6. Martha explained her thought process as follows (see Figure 11),

MgB_2 + **H_2** → B_2H_6 + **Mg**

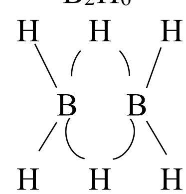

Figure 11
Task 1.7 written by Martha, using Lewis structures (reproduced in digital formatting)

"So, magnesium and Bromine. Not Bromine. Boron. Okay, so we have hydrogen here. ... Is that the weird one? Banana bonds. How do you make it? okay. okay, so we would need something with hydrogen... So basically, we need something that's reactive enough to replace the magnesium and add all of these. Because this is not like super. I don't think it's generally super, like favorable, if it doesn't have to happen. So, you either need a

highly reactive reactant or maybe like heat? Possibly right, but then it would probably just decompose. Pretty sure it's pretty easy to form hydrogen gas so. Probably not that. Maybe electrolysis. I'm not really sure, um. Okay, so we definitely need to have hydrogen. It's probably gonna need to be a good amount. And it's going to replace. Because we have an acid. Gonna have to come in. I don't think just acid would do it. But I don't really know. What else could you? I'm sure I've seen this reaction at some point. Because I think magnesium is ... pretty okay at leaving. H. I know I need at least two hydrogens? Well, not necessarily. Maybe it's just H_2*. Then how does it happen? Definitely not water. Hydrogen sulfate? okay. Well. Not oxygen. I'm not sure…Well, my initial thought was like oxygen is very good at donating electrons, and so theoretically I would think that it would be preferred over hydrogen to donate the boron because boron is so electron deficient."*

Martha's Lewis structures and her descriptions indicated that she assumed both compounds were composed of purely covalent bonding, but upon closer examination, the mechanism to break the bonds would be very different than what she attempted to do. MgB_2 has a metallic crystalline structure, but Martha's writing on task 1.6 (above) shows she was attempting to write the Lewis structure of the compound using either single or double covalent bonds. In order to use the organic arrow-pushing mechanism on this task, the student would first need an accurate Lewis structure of each compound. Additionally, the student would need to know the structure and some characteristics of three centered two electron bonding (or banana bonding) that occurs for the compound B_2H_6 (written out correctly by Martha, above in task 1.7). These bonds tend to be unfamiliar, and students may not easily recognize or manipulate them at this learning stage.

Even assuming that the student draws all structures correctly, the arrow pushing mechanism assumes that each line drawn between elements within these structures represents a two-electron covalent bond. However, with the compound B_2H_6, that is not the case. Otherwise, the hydrogen atoms between the boron atoms would be making two covalent bonds each while maintaining a neutral charge, which is not the case.

In inorganic chemistry, solid line representations for multiple bonding types are common, and changing representations can be confusing to learners at this stage. Coordination compounds, metallic bonded structures, and ionic bonding types are common in addition to typical covalent bonds. If a student wished to use arrow pushing mechanisms by incorporating the determination of bonding types into the existing strategy, they run the risk of massively increasing the mental load of a single task.

However, Calhoun (1997) described the same behavior in a more positive manner. In Calhoun's thesis, she defined the organic category of problem solving as a mechanistic approach where the student envisioned electron movement and often the drew Lewis dot structures (Calhoun, 1997, p. 60).

> *"Finally, throughout the solving tasks, the organic method was used by many of the graduate students. One in particular, Cassi (10/21, 48%), attempted the majority of the reactions using this method. She used the redox method as well, but it was always embedded in her approach to solving organic reactions… She was relatively successful in predicting the products, but had difficulty applying some of the principles she uses in organic chemistry to inorganic reactions."* (Calhoun, 1997, p. 76).

Of the 12 undergraduate students and 13 graduate students interviewed in the study, only one participant, Cassie, used the method effectively (Calhoun 1997, p. 81). Cassie performed at a 48% correct, (Calhoun, 1997, p. 40).

In her conclusion of the effectiveness of the organic method, Calhoun proposed,

"*The organic method could be an excellent way to teach predicting products of inorganic reactions, particularly to the juniors and seniors in inorganic classes who have completed a full year of organic*" (Calhoun 1997, p. 81).

In that regard, the results in this study are consistent with those from Calhoun's.

Problem-Solving Strategy: Balancing

David and Ashley exhibited a strategy, using balancing as a way to finish solving a task through obtaining more information about a missing compound. They balanced the partially completed task in order to determine the molar ratios of the final missing compound. For example, in task 1.4, David solved it saying,

"We have again an acid to an oxide. So, somewhere in here. We're losing the hydrogens to something. There has to be something with hydrogen that's being taken out. So then. Initially thinking. Just sort of had a curiosity I'll try redox… probably not redox… Again, thinking of something that would take out, take out a hydrogen. So, I guess first thing I'll do since we have B_2. Double that to balance those. So now on this side we have three. OK, so what I did is I noticed that between this and this, there's twice as many hydrogens as oxygen. So, in a two to one ratio. Let me think of what has to be kicked out. So, there's six. Three. I'll double check. Six hydrogens. Two boron, two boron. Six. Three, three, six oxygen. So, this is balanced. And usually whenever you're kicking something out - this

may or may not be in the gaseous phase, but that doesn't really matter - It's probably heat."

In this task, David started with categorization, then checked oxidation states, then balanced the task. He noticed from the balancing that there was a 2:1 ratio of missing hydrogens and oxygens in the task. He used this to write down water and accurately complete the task.

Similarly, Ashley solved the same task (1.4) saying,

"Sometimes when I see something like this I try – and, like, it's not very helpful – but I try to balance it beforehand...Actually, yeah. Then I would put H_2O over here [on the products' side of the chemical equation] because I have. Because I have six hydrogens leftover from this, I have three oxygens and so H_2O comes out. Then to get water to come out, I would probably heat it."

In the same way as David, Ashley noticed that there were twice as many hydrogen atoms as oxygen atoms and thus determined that water was the correct compound needed to complete the reaction.

However, to accurately use this method for a variety of problem types, the problem-solver must assume that only one compound is missing or that s/he had filled in all compounds correctly except for one. In this way, students would need to be able to reasonably determine at least one missing compound in a typical task before they attempt to balance.

Therefore, in cases where the student can easily deduce one reactant/product and only one other reactant/product remains, the balancing strategy would be successful (participants only attempted balancing on task 1.4 during this study). However, this strategy's use and effectiveness appears very limited, assuming that the problem solver does not need to introduce any additional elements (not deduced by a means-ends analysis/balancing), and that there is only one missing compound.

Verification Strategies

After the participants wrote down tentative answers, all but one of the participants looked back at some of those answers afterwards to verify if they believed the reactions were correct or incorrect. I categorized these verification strategies as balancing, logic scanning, and comparisons to physically observed phenomena. These strategies were generally effective in catching mistakes, particularly balancing. However, the ability to detect a mistake did not guarantee that the participant was then able to correct the mistake or even think of an alternate answer for the task.

Balancing as a Verification Strategy

Although I specifically mentioned in written and verbal instructions that they did not need to balance completed reactions, many participants decided to do so regardless. They typically balanced reactions after a tentative answer was reached, but before they decided on a final answer. The ones who chose to use this strategy were often successful in finding errors. Participants sometimes mentioned that they did the balancing in their heads rather than on paper. During the course of the study, participants also balanced electrons on a few occasions.

For example, Stu wrote down a tentative answer for task 1.2 then said,

"*I might put it down in that case. If it was, if it was homework and I had no other options, or if it was on a test, I would just write it down and attempt it. So that would also, these two would react. I know this is wrong. With the boron combined in some way. Well, it* *balances. That would balance out, so maybe… And we have three oxygen, three potassium. So, we need three of this. And we have three hydrogen and three chlorine, so they would balance out.*

In this way, Stu wrote a tentative answer that he was unsure about. However, after balancing, his confidence in the tentative answer increased.

In contrast, if the students' balancing showed an error, their confidence in the tentative answers decreased sharply. David discovered that his tentative answer for task 1.7 did not account for the law of conservation of matter by balancing, solving as follows:

> *"So then. The last one. Again, thinking so, there's borons here. There isn't a hydrogen here, so it's gotta be something with hydrogen over here. No, magnesium, so it's got to be magnesium over here. So now I'm just thinking about what could go together. So then, if that were the case, my initial sort of guess would be - just to see - maybe water. That that kind of that kind of pops up a lot. So then if I wanted to balance it. Two borons. Two and six. So three. So, it's six and six, then there's magnesium over here. So, that leaves three oxygens leftover. So, then my first thought would be: maybe it's magnesium oxide, plus two. Minus 2, so that works out. But then in doing so, there would have to be three. In order to balance three magnesium, I'll put over here. But then in doing so, now you have six. So, three times two. Three. But then in doing that, then you have a lot more hydrogens. Now you have, what, eighteen? So, then you'd have to multiply here, and then you'd be going back in a circle. So that tells me it can't be water.*

David solved the task using a means-ends analysis initial step, followed by a likely heuristic answer. He then spent time balancing the task, which revealed that his proposed answer of water would not balance within the reaction. This led him to discard his potential answer. From here, he chose to rework the task until he reached another tentative answer and balancing again, saying,

> "*I think that works out a lot better. So, if this were, I would feel relatively confident that that's at least something you could do.*"

It is worth noting here that both Stu's answer for task 1.2 and David's answer for task 1.7 are incorrect. While both answers account for the law of conservation of matter, (which the participants checked through balancing verification actions), this does not ensure that the tentative answer is the correct one.

Balancing as a verification step also functions to show an error in a means-ends analysis. For example, Steve answered the following task, 1.2, as follows (See Figure 12, where the underlined sections contain his answers).

$$BCl_3 + \underline{\mathbf{KOH}} \rightarrow K_3BO_3 + \underline{\mathbf{H2O}}$$

Figure 12
Task 1.2, as answered by Steve

Later, Steve glanced back at task 1.2 and said,

> *"Oh, I really messed something up on number 2. There's no chlorine anywhere! Yeah. So that might be a little bit of my stress."*

Here, an error in determining "what is missing" resulted in one side of the equation containing chlorine, while the other did not. Therefore, balancing can be an important part of the process because oversights like the above example often result from either an incorrect means-ends analysis and/or incorrect balancing verification step.

When I asked David if balancing helps him solve tasks, he replied, "*Yes, because. If they don't balance these, I've probably done something incorrectly. So, knowing that they balance at least shows that you've done something right."*

Similarly, when solving task 3.3, Stu explained that he balanced this task instead of the previous ones because,

"Well, I wasn't confident it would work so. I mean, I know it could work if it balances somehow. Like, maybe if you had the best chemistry rig in the world, even if this isn't something that would completely take place, You could probably put it under some extreme pressure and something like that and make it work for like a nanosecond. But this looks reasonable and balancing it just confirms that that it's somewhat reasonable to me.

These answers are interesting because while balancing functions very well to show an incorrect reaction when it comes to conservation of matter, it does not guarantee a correct reaction.

However, MJ did mention that balancing was not always worth the time it takes. When asked if she would balance a task in a testing environment, MJ replied,

"*No, absolutely not. I never do on [the professor's] tests. The extra credit portion of his tests, where it's just like writing reactions, is my worst part. Because in general, with writing reactions, like I can do the basic ones but anything that requires actual knowledge of chemical properties I struggle with quite a bit. I think I have to juggle so many [Unintelligible] I have to prioritize it."*

In this way, she explained that these types of tasks were de-prioritized compared to the rest of the test, likely especially since this question-type is restricted to the extra credit portion of the test, so balancing would likely take too much time away from other areas of the test that may be more important for her grade.

Students could use balancing electrons as a verification strategy in a similar manner, although it occurred less often in this study. Participants used electron balancing in two ways. First, they looked at each compound individually (using the orbital theory) to determine if a proposed compound was theoretically stable enough to exist. Second, they balanced to ensure conservation of electrons once the student proposes a tentative answer to a task.

When asked if Misaki had a strategy for verifying answers after solving task 2.3, she explained using the task,

$$\underline{\mathbf{2}}\ \overset{+1\ -1}{\mathrm{LiF}} \quad + \quad \underline{\mathbf{\overset{0}{H_2}}} \quad \rightarrow \quad \underline{\mathbf{2}}\ \overset{0}{\mathrm{Li}} \quad + \quad \underline{\mathbf{2HF}}^{\,+1\ -1}$$

$$\begin{array}{ccccc|c} Li^{+1} & + & e^{-} & \rightarrow & Li^{0} & 2 \\ H_2{}^{0} & + & (1\ e^{-})\ ? & \rightarrow & H^{+1} & 1 \end{array}$$

Figure 13
Task 2.3, half reaction electron balancing as answered by Misaki

> *"Oh, I don't know how to do [verify task answers]. I feel like if I just do this maybe [writes in oxidation states on question 2.3]. Everything here seems. Oxidation state may change into two, so It's a redox reaction… So, if I want to balance it, I would do the half balance reaction. Lithium, plus one. Electron. zero. And here would be H_2 zero. And it has one electron, but double so it's two. I never understood this one [likely referring to doubling a half reaction], but he always puts it.*
>
> *… This will be two. This would change. This would be two. But it still doesn't make any sense. There should be two here. There should be two here. There should be another two here and a two here and that would be balanced. Yeah. I don't really do half reactions for balancing. I just kind of just figure it out… I focus on oxidation state in case I know it's an oxidation state reaction like a redox reaction. And then I figure out if all the oxidation*

states are correct that the answer is correct. But maybe [the professor] doesn't like the reaction I use. Or maybe I made a mistake on the properties.

Misaki explained that if she needed to verify an answer to a redox task, she would most likely formally write in all oxidation states, then she would write and balance the half reactions. If the half-reactions balanced properly, she thought that the answer was more likely to be correct. However, she stated that her answer could still be wrong if she made a mistake on the properties of the compound, or if the instructor disliked the overall reaction. Because she only performed this method when I asked her about verification, it is possible that this verification strategy is not common for Misaki.

David, on the other hand, used half reactions unprompted to verify his potential answer for task 1.5 (see Figure 14). He explained,

$$\underset{+3\ -2}{B_2O_3} \quad + \quad \rightarrow \quad \underline{\mathbf{2}}\ \underset{0}{B} \quad + \quad \underline{\mathbf{3/2\ O_2}}$$

$$\left|\begin{array}{lllll} 2B^{+3} & + & 6e^{-} & \rightarrow & 2B^{0} \\ 3O^{-2} & - & 6e^{-} & \rightarrow & 3O^{0} \end{array}\right.$$

Figure 14
Task 2.3, half reaction electron balancing as answered by David (reproduced in digital formatting)

"Looking at this [reaction]. Kinda like this before. Plus three, minus 2 oxidation state [for B_2O_3]. And this [B] has zero. So first, there's a change in the electrons… I'm just setting up the half reactions over here. So, we have two borons with plus three. In order to get them to zero they have to gain six electrons. Yields two borons. This is the boron by itself. Oxygen. So, for now, we'll just say Oxygen. It would never be O by itself so. It'll probably end up being a two that may come out when I balance it here. So, we have. Three. Three oxygens. In order to get from a negative two to zero, minus. Oops. Minus

two. Minus six electrons. It's three O zero. So then to balance it, you stick the two over here. And then in order to get this? Or you just kind of cheat and say you know what? Three halves. There you go.

In this example, David was able to solve the task by first assigning oxidation states, writing in a tentative answer, then verifying his answer through balancing the half reaction. He appeared more confident in his answer after he balanced the electrons between the reactants and products. When asked if the half reactions helped his problem-solving process, he answered,

"[Writing half-reactions] helps you balance the reaction. Because if you if you just tried to balance a reaction - a redox reaction - just from like the molar ratios, that may or may not work because it doesn't take into account the amount of electrons that are moving between the others or between the reactants into the products. So, the. So, this sort of gives you a better idea.

In this way, David explained that while balancing the molar ratios of the compounds and elements is helpful, it may not be sufficient to account for changes in electron movements. Therefore, students could use half-reactions to compare the electron movements between reactants and products to ensure that their tentative answers do not gain or lose electrons.

This verification strategy was useful for determining errors when Steve looked back at task 1.7 and compared oxidation states of boron. He explained,

"So, with this one in specific, I just didn't know how I could change the oxidation state and allow hydrogen to get into boron, right? Which, I mean, and looking at this, I still don't know because. So, I know this isn't correct. I can tell you that right now, or at least I don't think it is. Because yeah… So, what's telling me it's not correct is magnesium.

Well, everything is staying the same oxidation state except for boron, unless I'm looking at this wrong right now, so that would mean that electrons just appeared out of nowhere.

In this way, Steve was able to determine that boron gained electrons during the course of the reaction by comparing the oxidation states of boron. Therefore, he was certain that his potential answer was incorrect.

The balancing verification strategy is useful in catching tentative answers that do not account for the law of conservation of matter, and it can catch errors in means-ends analysis. However, if elements are missing from both sides this strategy will not be able to catch them. Balancing of electrons appears like it could be useful, particularly for redox tasks to ensure conservation of charge and electrons between reactants and products. However, as I was not able to observe electron balancing in depth in this study, more data would be needed to determine how students use electron balancing in context and where it could be most useful to the problem-solver.

Logic Scanning

Logic scanning is a term describing the general strategy of a participant who simply looks back at a tentative answer to a task in order to search for chemical errors. The class instructor often taught these search strategies, but the students could also derive them if they deemed something within the task chemically impossible, improbable, or not recognized. Common examples of scans included the search for an acid on one side of the chemical equation with a base on the other side (or vice versa), searching for an attempt to react a weak acid to produce a strong acid, or other such logical errors in inorganic chemistry. Another example of logic scanning was when participants looked back at the finished task and searched for overall familiarity to gauge correctness.

One example of a participant scanning to look for a specific chemical error would be after Martha solved task 1.2, using Categorization and Algorithm Use (See Figure 15). After she wrote her answer, she looked back at the task saying,

"Usually, you don't get a base making an acid."

$$BCl_3 \quad \underline{\mathbf{KOH}} \quad \rightarrow \quad K_3BO_3 \quad \underline{\mathbf{HCl}}$$

Figure 15
Task 1.2, as answered by Martha

Martha proposed an answer to task 1.2 using HCl, the acid that she referenced above. However, instead of immediately moving on once she reached an answer, she looked back on it, and found an error, that bases cannot react to form acids in the way she proposed in the reaction. In this case, she did not correct the error and instead moved onto the next task. Unfortunately, she did not mention why she continued without attempting to correct her error, and more research would be needed to determine why many participants decided to continue even after identifying a likely error. In addition, Steve's scan of task 1.7 (above) could also be in this category since he scanned task, looking for a specific chemical error.

However, there were a few instances where students second-guessed or disregarded the correct answer due to a logic scan, typically due to the answer's simplicity or if they were unsure of a concept. This type of logic scanning was a search for familiarity.

For example, MJ solved task 1.6, saying, *"And then for B to MgB_2, you gotta get your magnesium from somewhere. And I lowkey just wanna write like magnesium itself, but I know that's probably wrong because that wouldn't make sense. At least to me."*

In this case, MJ actually disregarded the correct reactant in favor of a different reactant, because an element on its own appeared overly simple.

Similarly, Stu second guessed his answer for 3.5 after a logic scan, saying,

"So, that's what I would put, even though I don't think it's right, I feel like I'm still missing something… The brackets make me think that there needs to be something else besides just the base. But. Maybe. I don't know. I don't think a base would react with a base to become a complex, but it could be that I'm misremembering, and I missed the whole point. I think that's my answer."

Even though his answer was correct, due to unfamiliarity with bases reacting with other bases, as well as unfamiliarity with complexes, he was still unsure about his answer to the task.

Logic scanning was more effective when participants looked for particular errors, such as an acid with a base or changes in oxidation states. However, it appears that most participants scanned the tasks as a way to compare the reaction to ones in their memories. This approach appears to be an extension of the use of heuristics and was less effective, often resulting in students losing confidence in their correct answers.

Comparison to Physically Observed Phenomena.

The final verification strategy is "Comparison to Physically Observed Phenomena", and MJ and Stu were the only participants who demonstrated it during the course of the study. However, it is worth mentioning here for the implications to problem solving. This verification strategy is when a student compares the task to phenomena at the physically observable level of matter.

MJ solved task P.2 using stability and reactivity saying,

> *"Then the second one, you know in general in a reaction if you see K and OH you need those atoms present on the other side. K is alone. I'm assuming it's an ion in solution. It's kinda weird. In [the professor's] class you don't see it very often. And in general. I don't know… And so, in my mind I have like that thing where you switch the ions and whatever, that rule you learned. That's what I always go to. I don't know if that's correct or not. So, for me when I see KO, is when I do sodium because it has the same charge [as potassium]. So, I think about NaOH. And then it would balance so it would be KOH plus Na, which I don't know how favorable that would be. But that's the thought process for that.*

Her thought process shows a means-ends analysis followed by reactivity strategy causing the ions to "switch." Then, she used balancing as a verification strategy. However, when asked about her comment on favorability, she expanded on her thought process saying,

> *"In my mind it's just like. Like if you think of mass and stuff, some things just don't sound right. Which is a bad logic. But if you make a gas contact with a metal it's just like it, that doesn't sound like it would be right… So, I usually scratch that and try something else. For this one, in my mind, favorability-wise, K is larger than Na, I believe so deplacing [sic.], err, displacing K with Na, the odds of that, I don't how much that would work. Because the chemistry between the two might be more attracted to one than then other. That was my thinking for that, I don't know. Yeah.*

Her comment about gases contacting with metals implies that her initial logic probably was not as straightforward as her language suggested. It is very likely that she did the means ends analysis and considered the answer (or part of the answer) of $O_2 + H_2$, which are both gases, and chose to discard them since they were gases that would need to react with a metal (K) to produce KOH. While her final answer was ultimately marked correct, unfortunately her initial assertion was incorrect as metals commonly react with gasses.

Stu made a similar comment while solving task 3.2, saying,

> *"We have aluminum in its elemental form. You could probably combine that with molten sulfur. So, if I were doing it, I would just put an S there. and then a little triangle above that [denoting the use of heat]. Because I don't think that they would react if you just put them in a bowl together. I would say one of them has to be a liquid."*

In this case, he also made the assumption that the reaction would not proceed if both compounds were solids because he could not envision it happening on an observable level, therefore he decided to add heat to the chemical equation, which although not necessary, did not result in Stu losing points for the task. One interesting observation is that in many cases, solvents are used to facilitate the interaction between reactants, which could be seen by students at the observable level. However, the participants did not seem to consider this possibility when solving complete-the-reaction tasks.

If students do attempt to make assumptions about atomic properties based on preconceptions on observable phenomena, that can lead to incorrect answers. For example, if students assume that metals cannot react with gases, then they may discard correct answers that include the metal and gas reaction in favor of incorrect answers that do not. The propensity to bring misconceptions from the observable into the microscopic worlds may cause issues for problem-solvers.

Verification: Discussion

Verification of answers was often the final step in problem solving. The most significant findings regarding verification strategies during this study were balancing as a verification strategy, logic scanning, and comparison to physically observed phenomena.

A couple of participants chose not to engage in any visible verification strategy, and the remainder only chose to engage in verification on select tasks. Verification requires a complete tentative answer, and the majority of participants who engaged in a verification strategy only did so when they had low to medium confidence in their answers. However, more research would be needed to determine why participants choose to verify some tasks and not others.

Balancing the complete reaction was the most effective verification strategy in terms of catching participants' errors. Balancing revealed errors in means-ends analysis and errors in the law of conservation of matter of elements on both sides of the reaction. Balancing of electrons, while not observed frequently, appeared to function in a similar way to elemental balancing in that the problem-solver caught errors in electron counting. However, balancing would not be able to catch if elements are missing from both sides or if any other errors were present.

Logic scanning on the other hand, presents an opportunity for students to be able to determine if logical errors are present within chemical reactions. However, it functions best in a guided fashion, with participants looking for specific problems with their task such as an acid on one side of a chemical reaction and a base on the other. When not guided, participants often used familiarity to guide their choices on which tasks contained logical errors. This led to issues where participants disregarded correct answers in favor of incorrect ones that felt more familiar.

While I did not observe the verification step of "Comparison to Real Life Phenomena" frequently during this study, it was worth mentioning here due to the implications of problem solving and misconceptions that students may bring to the classroom. The characterization of the verification strategy is that the participant makes an assumption about the world at an observable level, and then applies that assumption to the microscopic level, i.e., gases do not react with metals because it wouldn't make sense. More research is needed to determine the prevalence of this strategy.

After students performed a verification strategy, they usually increased or decreased their confidence in the tentative answer. If confidence increased, they would continue on to the next task. If confidence decreased, they could then return to the strategy stage to obtain another tentative answer. It was very uncommon for a single participant to rework and reach more than two tentative answers for a single task. On the other hand, the participant could choose to move on despite low confidence in their answer. In short, just because they saw an error does not mean they could fix it. Single-strategy approaches appeared the most susceptible to this, while multi-strategy approaches were the most affected by noticing errors, as they could return to the strategy stage and try a new approach to the task.

Answer Key Analysis

The final section of the interview process was when I handed the participant an answer key and asked them to think-aloud as they compared and contrasted their answers with the key. It was stressed that the key only contained one correct answer and that others were possible. As the participants looked through the key, they largely ignored the tasks that matched the key exactly and briefly touched on those that seemed similar enough to the key. If the answer was different than the key, the participants often exhibited chemical reasoning in their comparisons. The comments that included chemical reasoning were often cues that resulted from the comparison and served to determine whether or not their proposed answer could be chemically reasonable. On the other hand, non-chemical reasoning comments were often straightforward comparisons between tasks or comments on the structure of the task format.

Answer is the Same

When participants compared their answers to the answer key, and observed that the answers were identical, they largely skipped over the task. When participants commented on these, the comments were minimal. Steve said for task 2.1,

> *"Yeah, there's that one. So, looks like that one is correct. I don't know how to annotate that."*

Here, Steve noticed that his answer matched the key, and did not have anything more to say about the task.

Similarly, Martha looked at tasks 2.2 through 2.6, which matched the key, and said,

> *"Nice. Look at that. Not that crazy. Wow, that makes me feel so much more confident in myself."*

I observed this behavior of skipping over matching answers or making a single comment to confirm a "correct" answer for all eight participants. It is worth noting that even though the student's answer for that task was correct, it does not mean that the reasoning that the student used to reach that answer was also correct. It appears that did not elicit any additional chemical reasoning or prompt any additional thought about the task. However, it may function for the participant to gain confidence in any chemical reasoning that they remember from those particular tasks, based on Martha's comment, even if that chemical reasoning was not sound.

Some comments indicated that the participants considered their answer to be similar enough to the key that participants considered their answers to be the "same" as the key. For example, Misaki solved task 3.4 by using the compound "$K(NO_3)$" when the key read "$LiNO_3$". When I asked her about the difference, and if her answer would correct, she replied,

> *"Yeah, I think mine would still work because they belong to the same group. So. So I've just used potassium because I like potassium. But I feel like it would still be the same if I used any of them, like with lithium as well."*

Similarly, David said when comparing his answer "KBr" to the key answer "KCl" in task 1.3,

> *"Yeah, they used chlorine instead of bromine, but because they didn't give you chlorine or bromine, any of the halides would have done. And I just wanted to be different."*

Both David and Misaki determined that the answers that they provided would function to solve the task in the same way as the key, since the elemental differences took place along the same column of the periodic table. Misaki correctly described the column as a "group" and provided another element within that group that would also work, and David used the descriptive category of "halide" to describe that group. In both cases it was a single elemental difference as either the anion or the cation in the task which was easily comparable.

In task 1.3, Steve compared his answer of K_3BO_3 + **$\underline{H_2SO_4}$** → H_3BO_3 + **$\underline{K_2SO_4}$**, to the key answer K_3BO_3 + **$\underline{HCl}$** → H_3BO_3 + **$\underline{KCl}$**, which I ultimately marked correct. He said,

> *"Looks like number three was fine, except we use different, you know? Acids and got different salts, so they're a little different… I don't know why it wouldn't work. It's simply*

a different acid and a different salt that's equivalent, I'd say. I mean this is a strong acid. This is a strong acid. They both produce neutral salts that are potassium salts."

Like the previous examples, the difference between the key and participant answers was in the anion. However, he compared them as categories of acids and salts, and also ranked them into strong acids and neutral salts in order to accurately compare. Unlike the answers that matched the key exactly, similar answers provided more opportunities for participants to discuss the underlying chemical concepts and trends.

Answer is Different

If the answer provided in the key was different than the answer the participant provided, the participant would either make a comment that denoted chemical reasoning to compare/contrast, or they would make non-chemical-reasoning comments. The chemical reasoning comments were often in an effort to determine whether the participant's answer would be correct despite the difference, reasoning that showed why their answer would be incorrect, or in an attempt to understand the key answer. The non-reasoning comments primarily included straight-forward observations of comparison, but also included comments on the format of the tasks and interview structure that seemed misleading.

Chemical reasoning comments.

The comments that included the most chemical reasoning when comparing answers to the answer key were when the answers did not match and the participant made the determination that either that their answer definitely would not be a correct answer, or that their answer would maybe be a correct answer.

For example, Stu compared his and the key answer for task 1.2 in which his answer was BCl_3 + **KOH** → K_3BO_3 + **HCl** and the key answer was BCl_3 + **KOH** → K_3BO_3 + **KCl + H_2O**. He said,

> "*Oh yeah, I know that makes sense. Because it wouldn't form a strong acid… Well, you can't form strong acids out of things like that. I don't know the exact reasoning, but. I know you have to do some shenanigans to form strong acids. You can't just put a strong base to get a strong acid out… So that just makes more sense. Because it does.*"

Here, Stu's comparison of the answers elicited a chemical reasoning response. He looked at his proposed compound (HCl), and because he noticed its acidic property was able to determine a reasonable response to why he thought his answer was incorrect.

For the same task, Ashley also compared her answer of BCl_3 + **KOH** → K_3BO_3 + ~~**HCl**~~ to the key. Ashley crossed out the HCl earlier during the problem-solving process, because,

> *"…this is HCl as well, but that doesn't make sense because that's like a base [KOH] and that's an acid [HCl]. Mhmm. Normally, if I was doing this on my test because the extra credit are written and they're just extra credit, I would just move on and come back. So, for now I'm just going to skip that one."*

During the task-solving portion of the interview, Ashley pointed out that her chosen answers of KOH and HCl were opposing since the strong acid and base were on opposite sides of the chemical reaction. However, she chose to move on, saying that is what she would do in a test taking environment. In looking back at the key answer later, Ashley said,

> *"I missed water. I'm trying to see. Oh no, I missed everything. Oh, Okay, Okay. So no, I didn't, this is one that I definitely like. Flipped the base and acid… So, this one, mine didn't work because it had an acid here where they shouldn't be. in my head when I'm*

looking at these, I think that I have a K over here, but it's obviously it's not balanced, but I think oh, it goes right here. So that's done. Like, it can't go anywhere else. So, I don't think about the fact that there could be another product that has like potassium. Because, like, I counted for that."

Here, the first thing she noticed was that her answer did not contain water, unlike the key answer. Noticing that water was different brought to mind the acid-base concepts that she thought about earlier in the task. She also mentally balanced the task in order to make sense of it and to continue the comparison.

In task 3.1, Martha compared her answer, $AlCl_3$ + **<u>Electrolysis</u>** → Al + **<u>Cl_2</u>**, to the key, $AlCl_3$ + **<u>Na</u>** → Al + **<u>NaCl</u>**. She said,

"Okay. Sodium. I guess sodium is pretty reactive. Well, I don't know. Yeah, that makes sense."

In this case, the difference between her answer of electrolysis and the key answer of sodium cued Martha towards the chemical concept of reactivity in order to explain why the key answer would logically follow.

While in Martha's case, she did not expand to determine whether or not her reaction would still work or not, Daisy attempted to on task P.3. Her answer was H_2CO_3 + **<u>H_2O</u>** → CO_2 + **<u>H</u>,** while the key answer was H_2CO_3 + ___ → CO_2 + **<u>H_2O</u>**. She explained,

"Okay. So, on this one [points to P.3], I was kind of right. Just put the water on this side instead of this side but then just, not maybe put this part [H product written]. I don't know… I don't know [if this answer would be correct]. Maybe? I'm just worried about this part [written product H]. Like that obviously there is this part with a new acid that's not on here."

Although final analysis determined that Daisy's final answer was incorrect, Daisy's analysis led her to be uncertain of that outcome. She was able to directly point out the main issue with her answer, the single hydrogen atom as a product. The cue from her hydrogen product appeared to be the property of acidity which was different than the key.

Steve also performed a comparison on task 1.7 in which he answered MgB_2 + **H_2O** → B_2H_6+ **MgO**, and the key answer was MgB_2 + **HCl** → B_2H_6+ **$MgCl_2$**. He attempted to determine if his answer was plausible, saying,

> *"The next one. I guess it is magnesium boride, I don't know. I remember I was really confused on this one which. That's because I looked it up afterwards and it's the electronegativity of boron and hydrogen are very similar, so I was kind of struggling to assign the oxidation states. Looks like we definitely did different stuff here. If mine'd work, I'd don't know, probably not… I don't- Well, hold on. Let me look at this… Yeah, I'd say mine probably wouldn't work. But I don't know. I mean this. This [points at key HCl] looks this looks much more valid because I mean strong acids are very prone to reacting, but not everything is prone to being hydrolyzed. And I'd say this is definitely much more likely than this [his answer]. ...I guess it could work, but. I don't. I don't think magnesium oxide would just form from hydrolysis -is my theory so that's why I think that [his answer] could be wrong."*

Since the key was not prepared before the initial interview, Steve offered to come back and compare his answers at a later date. He said that he thought about this task after the study ended to the point of looking up the electronegativities of both boron and hydrogen. While I ultimately marked the task as incorrect (balancing the proposed reaction would result in uneven hydrogens), comparing the two answers cued chemical reasoning responses. Steve mentioned strong acids and hydrolysis, forming a connection between the two and proposing that water could not react with magnesium oxide in the way he proposed in the reaction.

Non-chemical reasoning comments.

There were also many comments throughout the answer key portion of the interview that did not directly pertain to chemistry concepts or reasoning. The most common were statements that indicated an observation of the answer key and differences.

For example, in task 3.2, Ashley compared the task answers and said,

"For this one. So, I could have just added it by itself and not needed the hydrogen at all."

When asked if her answer was still plausible, she replied, "*I have no idea*." These comments indicate a straightforward comparison between the two answers, primarily as symbols on the page. Here, she attached no chemical meaning to chemical symbols beyond that the symbol "H" stood for "Hydrogen." This is similar to the means-ends analysis, where participants also compared states at a symbol level and took note of the differences.

Similarly, Stu compared task 2.1, saying,

"Heat. I was right. But it wouldn't give up oxygen."

And Martha for task 1.4 said,

"Heat and then. Hmm. Just went to water. that makes sense."

Both Stu and Martha's examples were direct comparisons that contained little to no observed chemical reasoning. Instead, they noted the differences between their answer and the key answer, and then moved on to the next task.

There were also participant comments that pertained to the formatting of the tasks rather than the tasks themselves. For instance, the participants insinuated that, had the formatting been different, they may have provided different answers.

For example, Daisy said,

> *"I think honestly just having a plus next to all of these is just like 'oh should there be something else?'"*

And in the same way, Stu said,

> *"Well, I probably wouldn't have thought of that on a test. The blank makes me think that I would need to put something there."*

These comments showed that the formatting influenced both Daisy and Stu's problem-solving, perhaps accidentally encouraging them to fill every blank space indicated by [+ _______] in the given assignment. Although I was clear in both the first given practice task and in initial instructions that tasks do not always require an additional reactant or product to obtain a correct answer, it appears that the formatting still led to confusion.

Also, when asked if having multiple (3+) total products led to additional errors (like for tasks 3.6 or 1.2), Daisy, Martha, and Ashley all replied yes.

Daisy simply replied,

> *"Yeah. I think so."*

Martha said when comparing task 3.6,

> *"Sometimes, yeah. Especially when… the situation won't like this because it's OH. It's pretty common for water to be formed because you only need to add the hydrogen."*

And Ashley said for task 1.2,

"Yes, yes. Usually. I get like two [products] its fine. But when it gets to three, that's where I get really messed up because I know usually there's one or two, but then. That there's water. It also messes me up when there's two products that have the same thing in them."

For all three participants, having three or more products was not the typical format of task reactions, which appeared to cause issues in problem-solving. Martha added that it could be especially hard to consider additional products when a single recognizable compound appears obvious to account for the known information. And Ashley added that two of the compounds could contain the same element, which can also be difficult.

One additional comment was from Daisy about separating categories of tasks. After looking at task 1.6, she said,

"Alright. Yeah I think I, it was helpful when we did our homework and stuff when he said which ones are acid-base and which ones are a redox, because I just don't immediately think about it unless he gives it to us to balance and then you can look at it and feel like 'Oh yeah this is Changing'. I mean, there's just multiple parts to it that you have to think about, like everything."

When asked if it would be helpful to separate acid-base from redox tasks, she replied,

"Yeah, definitely."

In this way, Daisy commented that this format of giving the tasks mixed up acid-base and redox tasks without labeling or differentiating in any way could be difficult. She noted that it was helpful when the inorganic class professor differentiated the two groups because it cued her to think about the different types of reactions, which was not something that she did naturally.

Another interesting comment during the answer key portion from Stu was discussing the overall strategy. As Stu looked over the answer key, he reached the end of the last task (3.6) and said,

> *"The ones I balanced, I noticed I tended to get right. So maybe I should balance more things."*

In this way, he indicated that in the process of going through the answer key, he noticed a pattern between balancing and getting answers that were the same as the key. His conclusion was that perhaps he should use balancing more in order to achieve that result. This was the only observed incident of directly taking trends to change behavior.

Answer Key Discussion

Research has been conducted in similar fields, which compares student performance with the presence or absence of examination feedback with any drawbacks associated with doing so (Lake & Chambers, 2009), and the effect of feedback on student metacognition (in which students are observed/encouraged/given the opportunity to 'think about thinking' or gain a greater understanding of their own learning and thought processes) (Sabel et al. 2017). I did not design this study to answer those questions and more research should be conducted to determine the effectiveness of an answer key, compared to any drawbacks associated with their use, on complete-the-reaction tasks in inorganic chemistry.

However, from this observation alone, it appears that participants tended to skip over answers that matched the key exactly. At most, s/he may have made a comment that the answers matched or that the answer was therefore "correct," but largely, participants skipped these tasks entirely. This indicates no additional chemical reasoning, and thus insinuates that students likely are receiving little additional educationally relevant data from looking at correct answers from a key. Answers that were similar enough to be treated the same, such as use of an element with very similar properties to another (ex. Using “Na” cation when the key used “K” as a cation), were treated in the same way with participants making few comments, although those remarks did demonstrate participants using some chemical concepts during the comparison, such as group trends.

Answers that differed often elicited responses that contained chemical reasoning, or evidence of the participant’s thinking about the chemical nature and properties of the symbols. This appeared to be largely due to the prompt, “do you think your answer would still work?” and my insistence that this key was only one correct answer and that other correct answers could exist. The elicited chemical reasoning responses were varied due to the diverse types of cues that participants saw during the comparison between their answer and the key.

There were answers that differed that did not elicit a chemical response. While many of these comments were just noting the differences and moving on, there were several critiques on the format of the tasks themselves, such as blank spaces to write may indicate that something *should* be written there (regardless of earlier directions), and that since they were not accustomed to tasks with three or more products, these tasks were more difficult to solve.

CHAPTER V: CONCLUSIONS

Distillation of Results

In this research, I studied complete-the-reaction tasks in inorganic chemistry, guided by the primary research question, "What strategies are used by students when solving complete-the-reaction tasks in inorganic chemistry?" I also attempted to make qualitative connections between strategy with task accuracy. This was done through a qualitative research study using the lens of phenomenography to explore and understand the spectrum of student problem-solving strategies. I recruited eight participants from either an Introductory to Inorganic course or an Advanced Inorganic course, who were a mix of graduate and undergraduate chemistry majors.

A flow-chart representing the students' various strategies, Figure 16 (originally shown as Figure 3), is shown here again for the readers' convenience and Table 8 provides a short descriptive definition of each classified behavior type.

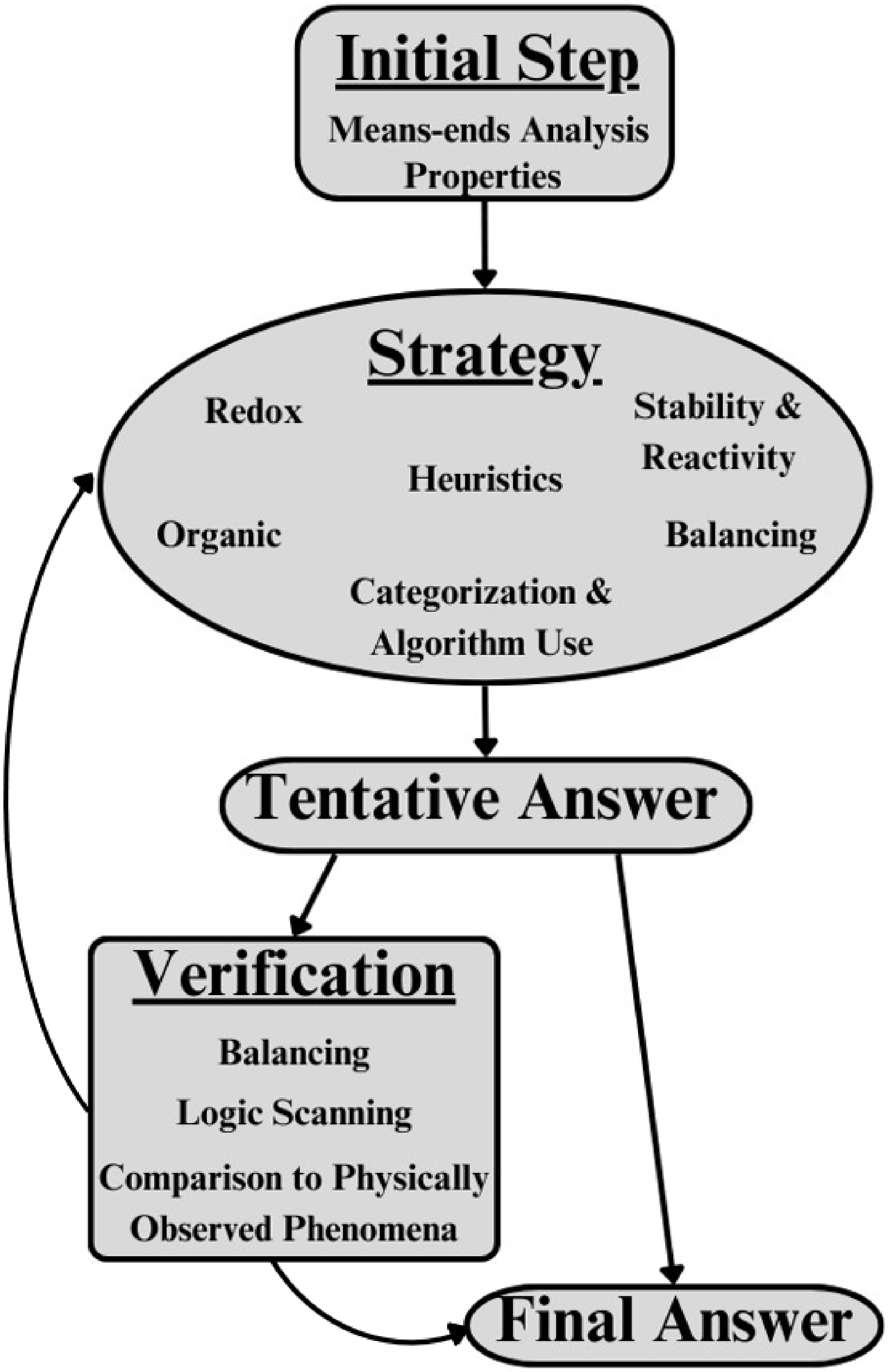

Figure 16
Flowchart describing the overall problem-solving behavior of participants (Repetition of Figure 3 for convenience)

Table 8
Descriptive classifications of participant problem-solving behavior

Name	Classification	Short Description
Means-ends Analysis	Initial Step	Students compared the reactants to the products in the given task. Most commonly led to the heuristic strategy.
Comment on Properties	Initial Step	Participants noted an inherent chemical property of an element/compound in the task. They used this information for strategy determination and use. Comments on acid-base led to the Categorization & Algorithm Use strategy. Comments on the stability or reactivity of an element/compound led to the Stability & Reactivity strategy. Comments regarding changes in oxidation state resulted in partial or full Redox strategies.
Categorization & Algorithm use	Strategy	Participants classified the given reactants and products into the categories of acid, base, salt, and/or oxide and then used class-taught algorithms in order to determine the missing elements/compounds.
Redox	Strategy	The student assigned oxidation states to elements within the given reaction, then used an oxidizing or reducing reactant as needed to oxidize or reduce the reaction, respectively. (Only used by one participant.)
Heuristics	Strategy	Students used effort reducing behaviors including recognition and affect in order to solve the task.
Balancing	Strategy	Students filled in one tentative compound and then balanced the reaction to obtain a task answer, assuming that the remaining elements formed the final compound.
Organic	Strategy	The student followed electrons, either verbally or through the use of electron-pushing mechanisms to determine where bonds would break and form, resulting in a task answer. (Only used by one participant.)
Stability & Reactivity	Strategy	Participants used elemental/compound properties and trends relating either to stability or reactivity in order to propose an answer
Balancing (Verification)	Verification	Students evaluated tentative answers, whereby they ensured that equal numbers of atoms were present on both sides of the chemical equation. If the equation did not balance, the participant assumed that an error existed in the tentative answer.
Logic Scanning	Verification	Participants looked back at the tentative answer and searched for class-taught chemical errors and unrecognizable compounds/reactions. If a class-taught error was found, or if a portion of the tentative answer appeared too unfamiliar, the participant assumed that the answer was incorrect.
Comparison to Physically Observed Phenomena	Verification	Students compared the compounds within the tentative task answer to phenomena that they could physically observe. If they could not envision the reaction occurring at the physically observable level of matter, then they assumed that the tentative answer contained an error.

Initial steps were information gathering behaviors and observations that led to further problem-solving strategies. The primary difference between the means-ends analysis and the property initial step was that the means-ends analysis resulted in the participant treating the task as symbols on the page rather than engaging with the underlying chemistry concepts. This is because determining "what was missing" from both sides of the chemical equation did not require more than knowledge of chemical mass balance and did not prompt any deeper inorganic specific properties about the "missing" elements. This is a likely reason for which means-ends analysis most frequently resulted in the use of heuristics.

On the other hand, when students did recognize a specific property, it appeared easier for students to engage with underlying concepts through more varied, inorganic-specific, strategies (such as when students noticed an acid-base property which led to Categorization & Algorithm Use strategy). Noticing a property gave students a way to "attack" the task in a way that inherently used inorganic concepts. However, students' success was dependent on the accuracy of their understanding of a property and on their ability to apply it. There were several cases where participants recalled a trend that was inconsistent with the current chemical understanding. Additionally, there were instances where the participant could recall the correct chemical concept but did not know how to apply that understanding to solving the task. In their research on problem-solving in organic chemistry, Bhattacharyya and Bodner (2005) asserted that the students' conceptual understanding was not operational, as in it could not be applied.

After these first impressions, the most common problem-solving strategy that students used was heuristics. I identified the heuristic-centered strategy as a main strategy on seventy-two separate occasions. Of those, 59.7% were correct, and the accuracy drastically increased when looking at composition reactions specifically (89.5% correct from nineteen instances). Other categories were approximately 50% each, with no direct patterns between task type and success of the heuristic strategy. It makes sense that students use this strategy, since the strategy is simple, straight-forward, and has approximately a 60% chance of resulting in a correct answer.

Table 9 shows the tasks for which heuristics were most effective.

Table 9
Tasks in which heuristics typically succeeded: Key answers bolded and underlined

Reaction Type	Task	Given Reactant		Key Reactant		Given Product		Key Product
Acid-base	3.3	Al_2S_3	+	**HNO_3**	→	$Al(NO3)_3$	+	**H_2S (gas)**
Composition	3.2	Al	+	**S**	→	Al_2S_3	+	-
Composition	3.5	$Al(OH)_3$	+	**KOH**	→	$K[Al(OH)_4]$	+	-
Redox	2.4	Li	+	**H_2O**	→	LiOH	+	**H_2 (gas)**

In contrast, Table 10 shows tasks for which heuristics were the least effective.

Table 10
Tasks in which heuristics typically failed: Key answers bolded and underlined

Reaction Type	Task	Given Reactant		Key Reactant		Given Product		Key Product
Acid-base	1.2	BCl_3	+	**KOH**	→	K_3BO_3	+	**KCl + H_2O**
Acid-base	1.7	MgB_2	+	**HCl**	→	B_2H_6	+	**$MgCl_2$**
Redox	1.5	B_2O_3	+	**Mg**	→	B	+	**MgO**

The data demonstrates that participants easily solved tasks using heuristics when the use of a means-ends analyses could determine all elements in the missing compounds, and when the participants commonly saw the missing compounds in previous chemistry classes (such as water). As such, the task category with the most success was composition. On the other hand, students particularly struggled when the task format or compounds were less common, and especially when a correct answer required an element that they could not deduce through a means-ends analysis (such as an oxidizing or reducing agent).

Additionally, though composition tasks and decomposition tasks are examples of oxidation-reduction processes, students did not make that connection. This is in spite of a typical cue to redox strategy, where participants noticed a change from (or to) oxidation state zero over the course of a reaction during the property initial step, which typically resulted in the participant categorizing these tasks as redox. This is likely because of the speed in which students solved composition reactions, which also occurred often in decomposition reactions. The means-ends initial step coupled with a heuristic methodology was faster and likely more familiar to students, resulting in an immediate answer rather than the student categorizing the task as redox and then pursuing a redox-centered strategy to obtain an answer. Participants also often solved decomposition reactions in this way, but then they would add heat or electrolysis as an extra reactant, which often resulted in them solving the task slower and more thoughtfully than composition reactions (even resulting in some Redox or Stability & Reactivity methodologies - though infrequently).

When participants attempted traditional redox methodologies, they often identified a task as redox through a change in oxidation state, assigned all oxidation states, and sometimes even wrote half reactions. However, they ultimately used heuristics to answer the task rather than choosing a compound or element for its oxidative or reductive capabilities. This is because, although students demonstrated that they were capable of pulling data from the task through redox methods, they demonstrated that they were often unable to use that data. In absence of a way forward, they fell back on heuristic methodologies, often based on recognition and memory. This resulted in a low to medium rate of accuracy that occurs with the use of heuristic methods, hindered by tasks that required the use of an oxidizing/reducing agent that the participant could not deduce through a means-ends analysis.

Steve, the single participant who assigned oxidation states to elements and then used an oxidizer reactant to oxidize the reaction or used a reducer reactant to reduce the reaction was very successful in this category of traditional redox tasks. This is likely because: first, he was able to quickly determine that the task was in the redox category of tasks, which is important as he did not attempt acid-base solutions on redox tasks (or vice versa); second, he obtained additional information about the task, determining if an element within the given reactant need to be oxidized or reduced; and finally, he was able to use that knowledge effectively to solve the task by theorizing an oxidizing or reducing agent.

When participants used the categorization and algorithm strategy, they often engaged with the task at a symbol and mathematical level. They often accomplished categorization through the memorization of compounds rather than by determining what makes something an acid, base, salt, or oxide. In the study, none of the students were able to say which acid-base model they were using, despite being generally proficient at determining which compounds were acidic or basic. However, amphoteric compound determination required deeper engagement with the inorganic material, where participants would need to look at the reaction as a whole to determine whether the compound was acting in an acidic or basic manner. If students attempted to use this strategy only as a "plug and chug" method of solving inorganic tasks, such as a math equation, it would make sense that the introduction of amphoteric compounds would drastically increase the difficulty of these tasks.

Similarly, the "algorithms" were memorized. Students memorized reactivity formula such as "acidic oxide + basic oxide → salt." Therefore, if the students could correctly identify two of the compounds in a complete-the-reaction chemical equation, they could use the algorithm to determine which compound type was missing and generate a species with those properties. However, there is a danger that students could easily memorize large lists of each type of compound, treat algorithms as math equations to be memorized and used, and then solve the task using memory, recognition, and data from the means-ends analysis. Participants who used algorithms gave no indication that they understood where the algorithms originated from, or why they worked in the manner in which they did. However, this strategy is simple to use, straightforward, and had a reasonably high rate of success compared to other strategies (varying with the use of amphoteric compounds. See Table 5). This means that, to an extent, the students were functionally using the concepts of acid-base theories without necessarily engaging with the theoretical knowledge of the same concepts. The use of algorithms as a formulaic solving mechanism is reminiscent of Calhoun's (1997) "algebraic" category of problem-solving behavior for complete-the-product reactions in inorganic chemistry. Although the algebraic methodology focused on the recombination of cations and anions to solve, both the algebraic method and the use of algorithms resulted in straightforward, mathematical interpretations of the data in which very little chemistry was required in order to solve the task.

The category of stability and reactivity encompassed any participant strategy that used either the concept of stability or the concept of reactivity in their answers, which resulted in a broad range of uses and mixed accuracy results. The main uses of the stability and reactivity were as follows. First, students used the strategy to form a precipitate or generate a known stable compound. Furthermore, students tended to use reactivity to explain and predict both the breaking apart of less stable compounds and finally, that the displacement of cations/anions with other cations/anions from other reactants in a chemical reaction. The use of this strategy assumes that the participant must keep in mind all relevant periodic trends for accurate and inorganic-based cation/anion displacement. In addition, in order for participants to determine the stability of compounds, they must either memorize the properties of major compounds, which is unsustainable, or they must deduce stability for each compound correctly using class concepts such as bonding/orbital theory. These are large categories, in which errors are likely to occur if the participant cannot think of the correct compound property, correct elemental trend, or if they are unable to accurately describe the strength of bonding or describe the electrons within orbital theory in order to deduce stability. This strategy is more complex than the other observed strategies, which leaves room for additional error. Instead, it is likely that participants often used some parts of this strategy without necessarily thinking about the underlying concepts when applying their knowledge, possibly using some portions of this theory from memorization alone. Given these complexities, it is understandable why students may frequently resort to heuristics.

The Balancing strategy and the Organic strategy were the least effective overall and the least observed. Only one participant engaged in the Organic strategy and there were only two instances of balancing as a strategy, rather than as a verification step. The Balancing strategy did result in correct answers. However, the use of this strategy relied on assumptions that are unlikely to be valid in the majority of tasks. First is the assumption that the participant can accurately deduce one of the missing reactants given limited information. Second is that there is only one other missing compound. The balancing strategy appeared to be another way to solve the task without engaging with the underlying chemistry concepts, and it has a significant potential for error.

On the other hand, parts of the Organic strategy do place a high importance on using the periodic table effectively, keeping in mind the stability of orbitals during bonding, and reasonable atom arrangements in compounds. These are all fundamental principles of inorganic classrooms, and educators could encourage students through careful consideration of parts of this strategy. Promoting the search for full and half-full orbitals may be a good method to teach students to look for stability and reactivity in compounds, as long as students are able to count electrons and orbitals correctly. However, the low success rate shown in this study, coupled with the need to correctly perceive and apply bonding theory for use with arrow-pushing mechanisms, especially when misconceptions were observed in this study, shows the disadvantages of this method. More research would need to be conducted to determine what, if any, task types that this method could be recommended for, or if it may be worth warning students to avoid the use of this particular strategy altogether.

Verification was important to the problem-solving process because the use of this step helped students to catch mistakes in tentative answers. Students were able to determine when answers were incorrect through the use of balancing and logic scanning, when used properly. However, balancing alone was not enough to determine if a tentative answer was correct, as it assumed that all species were present in the reaction. On the other hand, students often struggled to properly apply logic scanning because the list of mistakes to look for in the reaction was long, and it required the students to remember them at the right moment.

Instructional Implications

The primary outcome of this research is that students are able to solve complete-the-reaction tasks without using the underlying concepts. As such, these tasks may not adequately assess what instructors intend, especially regarding chemistry concepts. However, this is not to suggest that instructors should not use complete-the-reaction tasks; just that instructors can alert and reinforce their students of these potential pitfalls.

There are a few ways in which I would suggest interpreting this research for use in the classroom. First, if students are unable to obtain correct answers through heuristic methods, there would be an intrinsic incentive to change their problem-solving strategies. The research findings indicate that the use of heuristics tends to be most successful with tasks regarding composition reactions, tasks in which a means-ends analysis can reveal all missing elements of the chemical equation, and tasks which contain familiar compounds and formats (including tasks which contain no more than two reactants and/or products). As such, instructors might consider minimizing these types of reactions.

However, certain tasks and task types which the student can more easily solve through heuristic means, such as composition reactions, remain important to inorganic chemistry. To this end, I would recommend giving conceptual questions along with complete-the-reaction tasks to promote metacognition and connect the task to the underlying concepts that the instructor wishes to assess. For example, for a decomposition complete-the-reaction task, the instructor could write, "Describe the stability of the given reactant. Is heat required for this reaction to proceed? Argue why or why not." This phrasing would cue the student to the stability of a particular reactant when solving the task. Additionally, for a composition task, the instructor could add, "Describe the type of reaction and explain what role the given reactant performs in this reaction."

This type of question could cue students to at least consider the underlying chemical concepts in an attempt to categorize the reaction. Additionally, for any type of task, the instructor could also write, “Describe the strategies you used to solve this task and why they were/were not effective in obtaining an answer.” This question would cue students to metacognition, as well as assisting the instructor to gain insight into their students’ thought processes. Once instructors observe similar answers for these types of questions, they can transform the essay or short answer style questions into multiple-choice formatting for ease of grading, with non-concept (or incorrect concept) answers chosen as distractors.

Curating a small list of carefully chosen tasks as assessment or practice items may be beneficial for the problem-solver as well, since several of the observed concept-based strategies, verification strategies, and the act of re-working the tasks would all require additional time for the problem-solver. Also, there were instances in which students used trends and concepts without thinking about why or how they occurred, so knowing that they would have to address these types of questions could encourage students to devote more time to understanding chemical trends.

The results of this research could also be used to demonstrate benefits and limitations of some of the frequently-used strategies to students. For example, balancing equations can be a highly effective problem-solving tool, which students learn as early as high school. As such, it is expected that students would have used it as their main verification strategy. However, the data also showed that its effectiveness assumes that all the relevant species are present in the reaction. On the other hand, the logic scanning verification approach may require additional help from the instructor in order to focus onto a manageable list of common student mistakes rather than task recognition. As such, it appears that balancing and logic scanning as verification techniques could work together to effectively catch the majority of errors. While modeling successful problem-solving strategies could be an effective instructional tool, the key is to help students incorporate those lessons into their problem-solving efforts.

There are two other findings that should be considered for instruction but may not have clear solutions. First, instructors should be aware that the format of these tasks may cue students into certain strategies. For example, it is possible that the presentation of the task with one reactant and one product cued students to means-ends-analysis. DeCocq and Bhattacharyya (2019) demonstrated this phenomenon for electron-pushing tasks in organic chemistry. Furthermore, some of the participants noted that the presence of the plus signs suggested that additional species would be needed on both sides of the equation or that each side of the reaction was limited to two species total. That the students made this conclusion despite the explicit instructions and example in P.1, warrants consistent reinforcement and careful consideration of task formatting.

Another implication of this research is that students need help to better identify and understand redox processes. The research suggests that students may need additional practice in recognizing the pervasiveness of these processes, especially in the contexts of composition and decomposition tasks. In addition to recognition, students need help in the process of utilizing the knowledge they derive from the task in order to choose an appropriate, complementary oxidizer or reducer. With additional reinforcement and assistance for problem-solvers, I believe that complete-the-reaction tasks will be effective practice and assessment items for inorganic classrooms.

Research Implications

There are several ways in which further research could expand on the findings as presented. First, quantitative research could be done to determine the prevalence of the strategies and their actual success rates, since only qualitative relationships may be drawn from the current research. However, such a study would have to include many institutions since inorganic chemistry courses tend to be relatively small.

Secondly, more research needs to be done to determine why students struggle with redox concepts and strategies. This path is important because of the prevalence of redox processes in inorganic chemistry. Furthermore, redox reactions were a main stumbling block for the students in Calhoun's (1997) study.

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APPENDICES

Appendix A

Recruitment Script

Project Title: Inorganic chemical reasoning skills: An exploratory study into understanding students' choices and thought processes

Principal Investigator: Gautam Bhattacharyya

Script of Recruitment Speech

Ladies and Gentlemen,

My name is Hannah Lundien, and I am a graduate student in the Chemistry department. My research is in the field of chemical education.

I am conducting a study with Dr. Gautam Bhattacharyya on students' thought processes as they attempt to work on inorganic reactions. Gaining a better understanding of this will provide us with a greater understanding of students' problem-solving methods and strategies in inorganic chemistry. This understanding will provide us with potential methods to help students improve on their performance in their inorganic chemistry courses.

For the data collection we are requesting students to answer questions in person using the "think-aloud" method of data collection. The questions will contain reactions for which you would have to supply one or more reactants and predict one or more products, much like you may have seen on one of Dr. G.'s exams.

This is not an exam of any sort; we are not interested in your ability to get an answer. Rather, we are interested in understanding what you think about when you see the reactions. If you are able to participate, I would be happy to set up a time that works with your schedule. It should take about 45 minutes to complete. Your confidentiality will be strictly protected.

Although there are no tangible benefits for you, your perceptions will be important in helping us better deliver Inorganic Chemistry courses here and at other Universities nationwide. Any potential personal risks are minimal, and every precaution will be taken to prevent them.

Participation in this project is strictly voluntary. Not participating will in no way affect your standing in this, or any other Chemistry course, with the faculty in the Department of Chemistry, College of Natural and Applied Science or at Missouri State University. If you are interested, please complete the slip of paper that has been provided to you. Should you have questions prior to participating please feel free to contact me by email at any time. My email address is on the slip of paper provided to you.

Thank you,
Hannah Lundien

Contents of Slip of Paper:
Investigators: Hannah Lundien & Gautam Bhattacharyya (Principle Investigator), Department of Chemistry, Missouri State University
Email: Lundien97@live.missouristate.edu
PROJECT TITLE: Inorganic chemical reasoning skills: An exploratory study into understanding students' choices and thought processes

- -

___ YES, I would like to participate in this research study

- **My Name & Email Address are: ______________________________________**

___ NO, I do not wish to participate in this research study

Appendix B

Sample Open-ended Inorganic Chemistry Questions

Please write in the necessary **reactant** (if one is required) for the equation to logically proceed. If heat or electrolysis is needed for the reaction to occur, write that as well.

Then, write in any additional **products** that may occur from this chemical reaction if they exist.

Balancing is not required for this exercise.

Practice reactions:

1. Na + Cl2 $\longrightarrow$ NaCl + nothing

2. K + $\longrightarrow$ KOH +

3. H_2CO_3 + $\longrightarrow$ CO_2 +

Reaction chain 1: focusing on the element Boron

1) B + $\longrightarrow$ BCl_3 +

2) BCl_3 + $\longrightarrow$ K_3BO_3 +

3) K_3BO_3 + $\longrightarrow$ H_3BO_3 +

4) H_3BO_3 + $\longrightarrow$ B_2O_3 +

5) B_2O_3 + $\longrightarrow$ B +

6) $B +$ $\longrightarrow$ $MgB_2 +$

7) $MgB_2 +$ $\longrightarrow$ $B_2H_6 +$

Appendix C

Summary of Answer Key

Task Number	Given reactant		Key Reactant(s)		Given product		Key Product(s)
P.1 (given)	Na	+	$\mathbf{Cl_2}$	→	NaCl	+	**-**
P.2	K	+	$\mathbf{H_2O}$	→	KOH	+	$\mathbf{H_2}$ **(g)**
P.3	H_2CO_3	+	**-**	→	CO_2	+	$\mathbf{H_2O}$
1.1	B	+	$\mathbf{Cl_2}$	→	BCl_3	+	**-**
1.2	BCl_3	+	**KOH**	→	K_3BO_3	+	**KCl +** $\mathbf{H_2O}$
1.3	K_3BO_3	+	**HCl**	→	H_3BO_3	+	**KCl**
1.4	H_3BO_3	+	**Heat**	→	B_2O_3	+	$\mathbf{H_2O}$
1.5	B_2O_3	+	**Mg**	→	B	+	**MgO**
1.6	B	+	**Mg**	→	MgB_2	+	**-**
1.7	MgB_2	+	**HCl**	→	B_2H_6	+	$\mathbf{MgCl_2}$
2.1	Li_2CO_3	+	**Heat**	→	Li_2O	+	$\mathbf{CO_2}$
2.2	Li_2O	+	**HF**	→	LiF	+	$\mathbf{H_2O}$
2.3	LiF	+	**Electrolysis**	→	Li	+	$\mathbf{F_2}$
2.4	Li	+	$\mathbf{H_2O}$	→	LiOH	+	$\mathbf{H_2}$ **(gas)**
2.5	LIOH	+	**HCl**	→	LiCl	+	$\mathbf{H_2O}$
2.6	LiCl	+	$\mathbf{H_2SO_4}$	→	$LiSO_4$	+	**HCl**
3.1	$AlCl_3$	+	**Na**	→	Al	+	**NaCl**
3.2	Al	+	**S**	→	Al_2S_3	+	**-**
3.3	Al_2S_3	+	$\mathbf{HNO_3}$	→	$Al(NO_3)_3$	+	$\mathbf{H_2S}$ **(gas)**
3.4	$Al(NO_3)_3$	+	**LiOH**	→	$Al(OH)_3$	+	$\mathbf{LiNO_3}$
3.5	$Al(OH)_3$	+	**KOH**	→	$K[Al(OH)_4]$	+	**-**
3.6	$K[Al(OH)_4]$	+	**HCl**	→	$AlCl_3$	+	**KCl +** $\mathbf{H_2O}$

Appendix D

Interview Protocol

Project Title: Inorganic chemical reasoning skills: An exploratory study into understanding students' choices and thought processes

Principal Investigator: Gautam Bhattacharyya

Interview Protocol

Background Questions

- Please tell me your major and your year in school
- In addition to your inorganic chemistry course, what other chemistry courses have you taken so far? Of those which were at MSU?
- What are your overall experiences in inorganic chemistry? Which topics do you feel are the most difficult? The easiest? Why?
- What are your future career plans? How do you see the material in this course fitting in to those plans?

Tasks

Please write in the necessary **reactant** (if one is required) for the equation to logically proceed. If heat or electrolysis is needed for the reaction to occur, write that as well.

Then, write in any additional **products** that may occur from this chemical reaction if they exist.

Balancing is not required for this exercise.

Practice reactions:

4. $Na +$ Cl_2 $\longrightarrow NaCl +$ nothing

5. $K +$ $\longrightarrow$ $KOH +$

6. $H_2CO_3 +$ $\longrightarrow$ $CO_2 +$

Reaction chain 1: focusing on the element Boron

1) $B +$ $\longrightarrow$ $BCl_3 +$

2) $BCl_3 +$ $\longrightarrow$ $K_3BO_3 +$

3) $K_3BO_3 +$ $\longrightarrow$ $H_3BO_3 +$

4) $H_3BO_3 +$ $\longrightarrow$ $B_3O_3 +$

5) $B_3O_3 +$ $\longrightarrow$ $B +$

6) $B +$ $\longrightarrow$ $MgB_2 +$

7) $MgB_2 +$ $\longrightarrow$ $B_2H_6 +$

Reaction chain 2: focusing on the element Lithium

1) Li_2CO_2 + → Li_2O +

2) Li_2O + → LiF +

3) LiF + → Li +

4) Li + → $LiOH$ +

5) $LiOH$ + → $LiCl$ +

6) $LiCl$ + → Li_2SO_4 +

Appendix E

Informed Consent for Participant

Consent to Participate in a Research Study
Missouri State University – College of Natural and Applied Sciences

Inorganic chemical reasoning skills: An exploratory study into understanding students' choices and thought processes

Principal Investigator: Gautam Bhattacharyya, Department of Chemistry
Co-Investigator: Hannah Lundien, Department of Chemistry

Description of the Study and Your Part in It

The purpose of this research is to understand the thought processes of students while working reactions in the field of inorganic chemistry. This research will especially focus on the students' reasoning as they attempt the given tasks.

Your participation will involve a one-on-one interview that should last about 45 minutes. We will give you a set of tasks in which you will see parts of reaction and asked to provide the missing components. As you answer the questions, the interviewer will ask you to share your reasoning to the extent possible. The tasks are **not a test or any form of assessment** of your abilities; they are merely a way to elicit your understanding of inorganic chemistry.

Risks and Discomforts

The only risk may be in the form of some stress while working on the tasks. This risk is meant to be minimal because these tasks are ***not*** part of a test and you may ***skip*** any portion of the interview or ***terminate*** your participation at any time.

Possible Benefits

There are no tangible benefits to you by taking part in this study. However, this research may help us to understand how to better implement the curriculum of inorganic chemistry courses.

Protection of Privacy and Confidentiality

The data will be collected using video recordings, as well as the collection of the worksheet and any scrap paper used to answer the questions. In an effort to protect participants' privacy and confidentiality, only the hands and paper will be included in the video in case pointing at a particular reaction or compound may be useful in data collection. All data will be strictly protected physically and with password-protected accounts and/or files. Only pseudonyms will be used when referring to specific responses. The files will be permanently deleted upon completion of the research project and any other time period as mandated by Missouri State University and/or the Federal Government.

Voluntary Nature of Participation
Your participation in this research study is strictly voluntary. You may choose not to participate and you may withdraw your consent to participate **at any time**. You will **not be penalized** in any way should you decide not to participate or to withdraw from this study. **Your grade in CHM 375 or in any other course will not be affected whether or not you participate. Whether or not you choose to participate will also not affect your standing in the Department of Chemistry, College of Natural and Applied Sciences, and Missouri State University.**

Contact Information
If you have any questions or concerns about this study or if any problems arise, please contact Dr. Gautam Bhattacharyya at Missouri State University at 417-836-4487. If you have any questions or concerns about your rights in this research study, please contact the Missouri State University Office of Research Administration at (417) 836-5972 or researchadministration@missouristate.edu.

Please note that continuing on with the interview (beginning of data collection) will constitute your consent to participate in this research study. A copy of this document is given to you for your records. Thank You.

NOTE: Co-investigator's name changed from Hannah Lundien to Hannah Thompson over the course of this study.

Appendix F

Codes Used for Qualitative Data Analysis

Category	Code	Description	Examples
Initial Step	**Means-ends analysis**	Action at the start of task analysis which compared initial and final task states. Cues were when participants looked for "what was missing", "what was in common" and said "I have [element(s)]".	"Well, there's magnesium here [referring to the product]. There's none over here [referring to the reactant's side of the reaction]. So, this [referring to magnesium] has to come in at some point" - David 1.6
	Properties	Comment at the start of task analysis which denoted an observation of an acid, base, salt, oxide, reactivity, stability, and/or change in oxidation state. Cues were when participants immediately categorized into known categories with high certainty.	"And then this one [LiOH] is a base. 100% know that…" - Daisy 2.5
Strategy	**Heuristics**	Comments which showed a jump in logic denoting effort reduction behavior which resulted in an answer. Cues were often "I was just guessing", "I have a gut feeling" and answering immediately after a means-ends analysis without using or mentioning underlying properties.	"I want to say my gut reaction with this right here is to maybe heat it up." -Stu 2.1 "So, we see that there's chlorine. So, I would just put Cl_2 over here. I think that's all you need to do. I don't think anything else would come out of that." - Ashley 1.1
	Categorization & Algorithm Use	Comments which showed deliberate categorization of each given reactant/product into acid, base, salt and/or oxide categories. Also comments which	"And then, OK. Two different salts ...So, I'd guess $2SO_4$. Two plus two. HCl. So, you have basic -Or no. You just have salt plus another acid yields new acid plus new salt." - David 2.6

		indicated the use of taught algorithms to answer.	
	Redox	The use of labeling oxidation states, writing half-reactions, and/or deliberately using an oxidizing/reducing reactant to solve.	"So, we've got lithium fluoride, and we need to get some lithium. So, from what it looks like, we need to get a more reactive metal to reduce that a bit more. It is reduced right? Yeah, yeah, it's giving an electron. So, I would wanna put sodium, potassium, anything under it. We could even put cesium." - Steve 2.3
	Stability & Reactivity	Any actions which resulted in an answer that had to do with comments on either stability or reactivity of elements or compounds in the task.	"So next one we got carbonic acid. Carbonic acid isn't super stable, so I don't know if I'm supposed to put anything here [points at blank on reactant side], but I know it does just decompose into carbon dioxide and water. Which I mean, is pretty intuitive considering H_2, like it's just in the formula, right?" - Steve P.3
	Balancing	Comments which denoted balancing an incomplete chemical reaction.	"Sometimes when I see something like this I try – and, like, it's not very helpful – but I try to balance it beforehand…Actually, yeah. Then I would put H_2O over here [on the products' side of the chemical equation] because I have. Because I have six hydrogens leftover from this, I have three oxygens and so H2O comes out. Then to get water to come out, I would probably heat it." - Ashley 1.4

	Organic	Comments denoting electron following or written electron-pushing mechanisms often to determine bond breaking and formation.	"Okay, so this would probably have to be with- Definitely something with magnesium. I have a feeling it's probably elemental because… boron only has three electrons. And magnesium as an ion is positive two [oxidation state]. So, magnesium would be fine, but boron would not be. But even if magnesium started as neutral [oxidation state], the boron would not be happy. Although it would have four electrons. Theoretically, [boron would have] half the S orbital and then half of the P orbital and be less bad. That could work… Can it be deficient all around? I don't know about this guy." - Martha 1.6
Verification	**Balancing**	Comments or written examples of elemental or electron balancing (ensured that equal numbers of atoms/electrons were present on both sides of the chemical equation.)	"So then. The last one. Again, thinking so, there's borons here. There isn't a hydrogen here, so it's gotta be something with hydrogen over here. No, magnesium, so it's got to be magnesium over here. So now I'm just thinking about what could go together. So then, if that were the case, my initial sort of guess would be - just to see - maybe water. That that kind of that kind of pops up a lot. So then if I wanted to balance it. Two borons. Two and six. So three. So, it's six and six, then there's magnesium over here. So, that leaves three oxygens leftover. So, then my first thought would be: maybe it's magnesium oxide, plus two. Minus 2, so that works out. But then in doing so, there would have to be three. In order to balance three magnesium, I'll put

			over here. But then in doing so, now you have six. So, three times two. Three. But then in doing that, then you have a lot more hydrogens. Now you have, what, eighteen? So, then you'd have to multiply here, and then you'd be going back in a circle. So that tells me it can't be water." - David 1.7
	Logic scanning	Comments denoting that participants were looking at the whole completed reaction for class-taught or other errors.	"Usually, you don't get a base making an acid." - Martha 1.2 after tentative answer written down
	Comparison to Physically Observed Phenomena	Comments denoting a connection between the physically observable level of matter and the given task reaction	"In my mind it's just like. Like if you think of mass and stuff, some things just don't sound right. Which is a bad logic. But if you make a gas contact with a metal it's just like it, that doesn't sound like it would be right… So, I usually scratch that and try something else." - MJ P.2

Appendix G

Institutional Review Board (IRB) Approval

do-not-reply@cayuse.com
Frei 2/25/2022 4:17 PM
To: Bhattacharyya, Guatam; Lundien, Hannah P

To:
Gautam Bhattacharyya
Chemistry
Hannah Lundien

RE: Notice of IRB Approval
Submission Type: Modification
Study #: IRB-FY2022-239
Study Title: Inorganic chemical reasoning skills: An exploratory study into understanding students' choices and thought processes
Decision: Approved

Approval Date: February 25, 2022

This submission has been approved by the Missouri State University Institutional Review Board (IRB). You are required to obtain IRB approval for any changes to any aspect of this study before they can be implemented. Should any adverse event or unanticipated problem involving risks to subjects or others occur it must be reported immediately to the IRB.

This study was reviewed in accordance with federal regulations governing human subjects research, including those found at 45 CFR 46 (Common Rule), 45 CFR 164 (HIPAA), 21 CFR 50 & 56 (FDA), and 40 CFR 26 (EPA), where applicable.

Researchers Associated with this Project:
PI: Gautam Bhattacharyya
Co-PI: Hannah Lundien
Primary Contact: Gautam Bhattacharyya
Other Investigators: Hannah Lundien

Research Procedure – Annotations

Project Title: Inorganic chemical reasoning skills: An exploratory study into understanding students' choices and thought processes
Principal Investigator: Gautam Bhattacharyya

Preliminary questions

- When the participant enters, the investigator will introduce themselves and attempt to make the participant feel comfortable. The room will contain a table, the recording equipment, chairs, and additional materials from CHM 375. Then, the investigator will ask some background questions as follows:
    - "What's your major?"
    - "What chemistry classes did you take before this one?"
        - "Where did you take them? Here or somewhere else?"
    - "How does this class fit in with your plans for the future?"
    - "Of the topics covered in this class, which ones are you the most comfortable with? Which ones are you least comfortable with? Why?"

Experiment starts

- The worksheet with reactions is given to the participant. They will first do an easier sample reaction to become accustomed to the "think-aloud" data collection approach and the types of questions that will be asked of them. Then they will work through the reaction chains that make up the bulk of the experiment. Example questions are as follows:
    - "What made you choose this reactant instead of a different one?
    - "How did you know that you needed a [oxidizer/reducer/etc.] in this place?
    - "Can you explain how you came up with this product?"
    - If the participant is stuck: "Can you tell me what you would need to answer this problem?"
        - "Why that particular resource?" [At this point, the researcher would hand the participant that resource if it is available.]
- Additional responses and questions will be added as needed in order to put the participant at ease and achieve greater understanding of the participant's choices.
- After all the reaction chains have been answered, the participant will be given an answer key.
    - "Here is an answer key for the questions you just answered. Please keep in mind that there is more than one answer for every problem. I was wondering if you could compare these answers to yours."
    - Additional questions similar to the ones used in the experiment will be used to try and induce chemical reasoning responses as they perceive any differences or similarities in their responses.
- Finally, the experimenter will thank the participant for their time, reassure any privacy concerns, and escort them out of the room. That will conclude the experiment.

Appendix H

Institutional Review Board (IRB) Exemption

Do-not-reply@cayuse.com
Tue 11/16/2021 3:54 PM
To: Bhattacharyya, Gautam; Lundien, Hannah P

Missouri State
UNIVERSITY

To:
Gautam Bhattacharyya
Chemistry
Hannah Lundien

Date: Nov 16, 2021 3:53:32 PM CST

RE: Notice of IRB Exemption
Study #: IRB-FY2022-239
Study Title: Inorganic chemical reasoning skills: An exploratory study into understanding students' choices and thought processes

This submission has been reviewed by the Missouri State University Institutional Review Board (IRB) and was determined to be exempt from further review. However, any changes to any aspect of this study must be submitted, as a modification to the study, for IRB review as the changes may change this Exempt determination. Should any adverse event or unanticipated problem involving risks to subjects or others occur it must be reported immediately to the IRB.

This study was reviewed in accordance with federal regulations governing human subjects research, including those found at 45 CFR 46 (Common Rule), 45 CFR 164 (HIPAA), 21 CFR 50 & 56 (FDA), and 40 CFR 26 (EPA), where applicable.

Researchers Associated with this Project:
PI: Gautam Bhattacharyya
Co-PI: Hannah Lundien
Primary Contact: Gautam Bhattacharyya
Other Investigators: Hannah Lundien