AN IN-DEPTH INVESTIGATION INTO SCALE LITERACY: A REFINEMENT OF A SCALE – THEMED CURRICULUM INTERVENTION THROUGH SCAFFOLDING, INTERVIEWS, AND AFFECT

By

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ABSTRACT

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The University of Wisconsin-Milwaukee, 2024
Under the Supervision of Professor Kristen L. Murphy

Science educators have taken on the responsibility to incorporate essential themes into K-12 education that foster increased science literacy. One vital identified theme is related to scale, proportions, and quantity. Although, over recent decades, there is a lack of sources related to the implementation and development of scale skills. The gap related to scale-related concepts is especially apparent at the undergraduate level and in disciplines such as chemistry, where students must connect the macroscopic and microscopic levels. Past research has developed methods to measure scale literacy and integrate a scale-themed curriculum into undergraduate general chemistry. Results from this work show promising potential for scale-themed instruction overall, yet more research is needed to further hone and develop scale concepts in specific circumstances (i.e. specific chemistry courses, content areas).

The work herein expands on the existing scale-themed instruction research, focusing on improving scale instruction in general chemistry II over the course of six semesters. The scale-themed instruction was studied via a three-component approach. The first component identified areas of the curriculum to modify to better assist students with their scale and chemistry knowledge. The second component involved a quantitative and qualitative approach to assessing the success of the modified scale-themed curriculum materials. The third component

incorporated a study of student motivation, identifying key motivators of chemistry students and how motivation can impact the efficacy of the scale-themed curriculum. It was found that incorporating increased scaffolding opportunities into the course materials had a significant positive impact on students' learning gains. Additionally, qualitative interviews were utilized to identify key problem-solving behaviors, to assess content knowledge among various groups of students, and to further evaluate the effectiveness of the revised curriculum. From the motivation study, results suggest that general chemistry II students are primarily externally motivated, and students who exhibit more intrinsic motivation experienced a greater benefit from the scale-themed curriculum than those who were more extrinsically motivated. Ultimately, the three-prong approach provided an in-depth analysis of understanding the scale literacy of general chemistry students.

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A “Scaffolding” Dedication

To my parents, David and Jill Tomczyk, for the foundation you laid for me.
To my husband, Andy Schauer, for the life we will build together.

With love always,
Allison

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But as for you, be strong and have courage, for your work will be rewarded.

2 Chronicles 15:7

Chapter 1

Introduction

1.1. Revitalizing Science Education and Improving Scientific Literacy

There has been a great national concern regarding the scientific preparedness of American students and the overall scientific literacy of the American public. In 1989, the American Association for the Advancement of Science (AAAS)[1] published reports that aimed to revitalize science education in the United States stating, "*The world has changed in such a way that science literacy has become necessary for everyone, not just a privileged few; science education will have to change to make that possible."* Also in 1989, the National Center for Improving Science Education (NCISE) reported several key concepts to include in elementary science curriculum such as organization, cause and effect, systems, diversity, models, change, structure or function, discontinuous and continuous properties, and scale.[2] The AAAS report (Project 2061)[1] identified four cross-cutting themes to be incorporated into STEM education: the inclusion of systems, models, constancy and change, and scale. In 1993, the AAAS published Benchmarks for Science Literacy[3] that outlined benchmarks in science and other related fields for K-12 students to achieve by the completion of grades 2, 5, 8, and 12.

These reports provide a basis for science educators to utilize to achieve the over-arching goal of increasing scientific literacy. Science curricula should ultimately focus on a deeper understanding of science spanning one's entire education. To achieve this, the unification of these key concepts and themes is imperative. In 2012, the National Research Council (NCR) published *A Framework for K-12 Science Education*[4] which describes the vision for science education and proficiency. The framework reports three dimensions that together contribute to

the overall success of science education; the three dimensions are science practices, cross-cutting concepts, and core ideas.[4] Since 2012, the NCR's framework has been pivotal in reframing science education and spurred a body of work related to incorporating three-dimensional learning at the college level and in disciplines such as chemistry.[5-7]

Scale, which is typically defined in terms of quantity and measurement,[8] was consistently acknowledged as a vital concept. In fact, the NCR[4] and The Next Generation Science Standards (NGSS)[9] both identified scale as a key cross-cutting concept in science education. Yet, these studies and reports do not provide methodologies or standards for the integration of scale into curricula and instruction. This is especially true at the undergraduate level and in scale-laden disciplines such as chemistry.

1.2. The Role of Scale in Chemistry

Scale has a large role in chemistry. Not only is chemistry a discipline rooted in the collection of empirical data and the interpretation of quantitative measures, but it also requires a deep understanding of the subatomic world and its connections to the macroscopic world. Chemistry is historically a difficult subject for students. While many factors can contribute to this perception, it causes one to wonder if students' lack of exposure to scale in science curricula is responsible for the difficulties many chemistry students encounter.

1.3. Recent Efforts Addressing Undergraduate Chemistry Scale Instruction

To address the gap in literature related to scale education at the undergraduate level, a body of published work (2014-2019)[10-12] focused on methods to implement scale into instruction in undergraduate chemistry courses. Trate and colleagues designed and implemented a scale-themed instructional curriculum into general chemistry I (GC I) and general chemistry II (GC II).[12] The instructional materials incorporated three components: supplemental instruction

modules, scale concepts, and active learning into lecture and laboratory. The materials were employed across varying conditions over the course of eight semesters. In summary, results from this study indicated the scale – themed intervention was more successful in GC I than GC II. Based on these results, it is evident further research on scale in general chemistry II is needed.

1.4. In-depth Scale Study in General Chemistry II

The body of work presented herein will discuss a series of further studies involved in an in-depth investigation of scale in undergraduate general chemistry (primarily GC II). The investigation is comprised of three main veins (Figure 1.1): the exploration and implementation of a targeted curriculum intervention, student interviews aiming to understand students' scale skills and problem-solving behaviors spanning all general chemistry II content areas, and an inquiry into chemistry students' motivation and how motivation can impact the effectiveness of the scale curriculum.

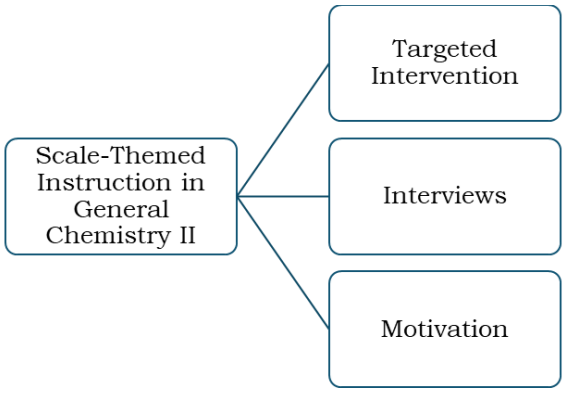


Figure 1.1. General project overview depicting the three main veins that emerged from the investigation of scale-themed instruction in general chemistry II

1.5. References

(1) American Association for the Advancement of Science, Project 2061. *Science for All Americans: A Project 2061 Report on Literacy Goals in Science, Mathematics, and Technology*; Oxford University Press: New York, NY, **1989.**

(2) National Center for Improving Science Education, *Science and Technology Education for the Elementary Years: Frameworks for Curriculum and Instruction*; Washington, DC, **1989.**

(3) American Association for the Advancement of Science, Project 2061. *Benchmarks for Science Literacy*; Oxford University Press: New York, NY, **1993.**

(4) National Research Council. *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*; National Academies Press: Washington, DC, **2012.**

(5) Bain, K.; Bender, L.; Bergeron, P.; Caballero, M. D.; Carmel, J. H.; Duffy, E. M.; Ebert-May, D.; Fata-Hartley, C. L.; Herrington, D. G.; Laverty, J. T.; Matz, R. L.; Nelson, P. C.; Posey, L. A.; Stoltzfus, J. R.; Stowe, R. L.; Sweeder, R. D.; Tessmer, S. H.; Underwood, S. M.; Urban-Lurain, M.; Cooper, M. M. Characterizing college science instruction: The three-dimensional learning observation protocol. *PLOS ONE*, **2020.** *15*(6).

(6) Cooper, M. M. Chemistry and the next generation science standards. *J. of Chem. Educ.* **2013.** *90*(6), 679–680.

(7) Laverty, J. T.; Underwood, S. M.; Matz, R. L.; Posey, L. A.; Carmel J. H.; Caballero, M. D.; Fata-Hartley, C. L. Ebert-May, D.; Jardeleza; S. E.; Cooper, M. M. Characterizing college science assessments: The three-dimensional learning assessment protocol. *PLOS ONE*, **2016.** *11*(9).

(8) Lock, G., Molyneaux, B., *Confronting Scale in Archaeology: Issues of Theory and Practice*; Springer Science & Business Media: New York, **2007.**

(9) National Research Council. *Next Generation Science Standards: For States, by States*; National Academies Press: Washington, DC, **2013.**

(10) Gerlach, K.; Trate, J.; Blecking, A.; Geissinger, P.; Murphy, K. Valid and reliable assessments to measure scale literacy of students in introductory college chemistry courses. *J. Chem. Educ.* **2014**, *91* (10), 1538–1545.

(11) Gerlach, K.; Trate, J.; Blecking, A.; Geissinger, P.; Murphy, K. Investigation of absolute and relative scaling conceptions of students in introductory college chemistry courses. *J. Chem. Educ.* **2014**, *91* (10), 1526–1537.

(12) Trate, J. M.; Geissinger, P.; Blecking, A.; Murphy, K. L. Integrating Scale-Themed Instruction across the General Chemistry Curriculum. *J. Chem. Educ.* **2019**, *96* (11), 2361–2370.

Chapter 2

Exploring Modifications to Scale-Themed Instruction in General Chemistry II: Determining Content Area and Scale Concepts Targets

"Scale is a slippery concept, one that is sometimes easy to define but often difficult to grasp,"[1]
- Gary Lock and Brian Molyneaux

2.1. What is Scale?

Scale is typically thought of in quantitative terms encompassing a variety of concepts such as quantity, measurements, distance, size, estimation, ratios, and perception.[1] Yet, scale is not limited to the quantitative. There are qualitative and abstract aspects of scale, such as understanding one's position in time and space.[1] Recognizing and experiencing scale is just one fundamental layer to understand phenomena. One with a deep understanding of scale must have the ability *to apply* and *to operate* on various scales.

2.2. Scale Literature Review

Jones and Tretter conducted many scale-related studies throughout the early 2000s. The studies contributed to the knowledge base in the following areas related to scale: concepts of scale at different grade levels, accuracy of scale concepts, conceptual boundaries, experts' concepts of scale, and the trajectory of scale development.

2.2.1. Scale Concepts and Accuracy

Early work by Jones and colleagues centered on students' understanding of scale concepts and accuracy. In a study investigating 9^{th} -11^{th} grade students' understanding of the nanoscale, the results indicated that students were experiencing challenges with the metric system.[2] Challenges with the metric system may be accounted for by the lack of exposure

American students have to the metric system. Increased exposure and instruction related to the metric system may bolster metric scale conceptions.

Jones and Tretter also conducted an in-depth study on novices (5th, 7th, and 9th graders), more experienced students (gifted 12th graders), and experts (doctoral science students) to gain insight into scale concepts and accuracy.[3] Participants were given 26 objects differing in size (e.g. an atomic nucleus and the sun) on the Scale of Objects Questionnaire to understand their perceptions of the objects' size in relation to the metric system measurements. Using the Scale Anchoring Objects, participants were then asked to sort additional objects varying in size. Results related to the conceptualization of scale show that the novice students were often off by several factors of ten when asked to name an object the size of a nanometer. Surprisingly, objects listed by participants included eyelashes (elementary student), coins (middle school student), germs, and ant legs (high school student). All doctoral students correctly ranked the sizes, and gifted seniors performed well with minimal errors. In terms of accuracy, participants were more accurate when dealing with large scales and declined in accuracy significantly with scales smaller than a milliliter. The gifted 12th graders outperformed the other novice students, aligning once again with the doctoral students. Although, the doctoral students shifted more seamlessly between scales compared to the other groups.

2.2.2. Conceptual Boundaries

Another study revealed students' conceptual boundaries when estimating measurements.[4] It was found that students use benchmarks when estimating measurements. Some benchmarks described by students included: person-sized, room-sized or field-sized. In addition, relative size was easier for students to conceptualize compared to absolute size. Alarmingly, elementary students, middle school students and high school students performed comparably.

2.2.3. Experts' Conceptions of Size and Scale

To summarize the implications from the studies described in 2.2.1 – 2.2.3, it is clear students may struggle to conceptualize size with accuracy or successfully maneuver across varying scales. After establishing how students comprehended scale, Jones and Tretter interviewed 50 experts in professions heavily rooted in scale to better understand experts' conceptions of scale and how it develops.[5] Some of the professionals interviewed included: chemists, engineers, biologists, a sculptor, a neurologist, a pilot, and an automotive mechanic. All participants noted the important role scale had in their chosen fields and reflected on informal and educational experiences that they attributed to the development of their sense of scale. Many professions described using the body as an estimation tool for distance and size (e.g. an architect uses the length of their arm to measure the functionality of the space). Professionals also described using anchors as seen with a zoologist using a red blood cell to describe a micron.

2.2.4. Trajectory of Scale Concepts Development

As an accumulation of their work on scale, Jones and Tretter created the Trajectory of Scale Concepts Development (Figure 2.1).[5] It describes three main levels of scale development (novice, developing, and experienced) and the benchmarks within each level. The trajectory can be utilized to understand and track one's relative scale development. However, the results from scale studies demonstrate students may struggle with scale concepts, and this observation can be attributed to many factors. For example, the average American student is not exposed to the metric system in everyday life, making it less familiar to utilize in science courses. Students also may lack the ability to "unitize," which is fundamentally the ability to make a new unit to understand models or values of differing scales. Understanding scale is akin to using a new language. With practice and

exposure, students can develop a high scale literacy transferable to many facets of science and beyond.

Novice • Developing measurement estimation skills • Conceptualizing relative sizes • Using measurement tools skillfully • Development of number sense
Developing • Converting measurements and scales • Surface area to volume relationship • Being aware of changing scales Using body rules for estimation and measurements • Visualizing scales • Understanding different types of scales • Development of proportional reasoning; Visual spatial skills
Experienced • Automaticity and accuracy • Creating reliable scales • Developing accuracy in using scale • Applying conceptual anchors when estimating scale

Figure 2.1. Trajectory of Scale Concepts Development by Jones and Tretter[5]

2.2.5. Scale in Chemistry

In a discipline such as chemistry, scale is an essential concept to understand. As a chemist interviewed on the role of scale in their career states, *"It's key. I mean in chemistry it is key. Again, because we are living in a macroscopic world and all the things that are composed are microscopic."* [5] Of course, scale is present in chemistry in the sense that chemistry is a discipline focused on the collection of empirical data and the interpretation of quantitative measures. Chemistry also requires a deep understanding of the molecular world and its connections to the macroscopic world. Chemistry is perceived as a difficult subject to learn. However, it can be

argued that it is not entirely the chemistry content itself that is challenging, but rather the inherent scale concepts embedded within. As illustrated in the previous sections, students can exhibit challenges in mastering these essential scale skills. Therefore, a successful chemistry course curriculum must focus on developing scale skills while simultaneously teaching chemistry content.

In traditional chemistry curricula, there tends to be more focus on the symbolic representation of chemical phenomenon rather than the microscopic level. Alex Johnstone created a model of the three main representations used in chemistry: submicroscopic (particulate), representational (symbolic), and macroscopic.[6–8] This model, coined as Johnstone's Triangle or the "chemistry triplet," focuses on students learning chemistry from the perspective of all three levels of representation and the connections linking the three together to explain chemical phenomena (Figure 2.2).[8,9] Johnstone's Triangle has been widely adapted in modern chemistry instruction and further expanded upon in chemical education.[10–12] In terms of scale, well-established scale skills are required to make connections within the three representations in Johnstone's Triangle. This is especially true when making connections between the macroscopic and submicroscopic. These tasks require visual-spatial and unitizing skills and strong number sense. Therefore, it is essential students are proficient in their scale abilities to make further connections in chemistry. This poses the question of which scale concepts are most relevant in chemistry.

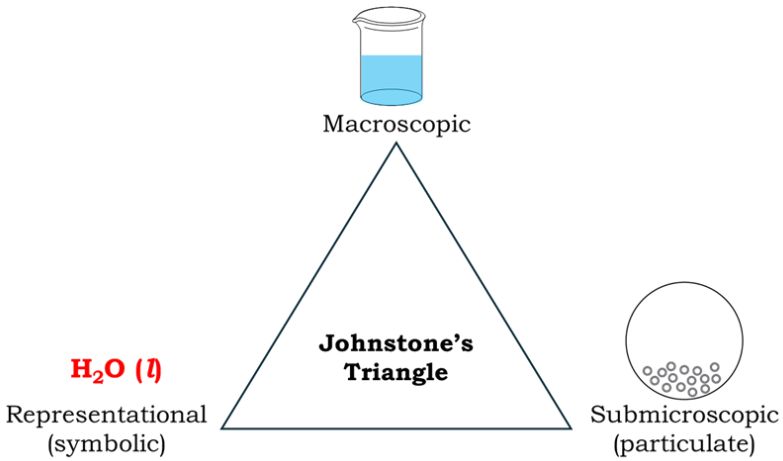


Figure 2.2. Johnstone's Triangle – the three representations in chemistry[8]

Aligning the trajectory of scale development by Jones and Lock and Molyneaux's work on scale, three categories were labeled as the most significant scaling concepts in chemistry.[13] The categories are macroscopic/particle, number sense, and scale (a combination of the former two categories). Figure 2.3 summarizes the quantitative and qualitative scale skills within each category necessary to apply when learning chemistry.

Macroscopic / Particulate • Relating one scale to another • Applying conceptual anchors when estimating scale
Number Sense • Developing measurement estimation skills • Using measurement skills skillfully • Development of number sense • Converting measurements and scales • Surface area to volume relationship • Visualizing scales • Using body rules for estimation and measurements
Scale • Development of proportional reasoning; visual spatial skills • Creating reliable scales • Understanding different types of scales • Conceptualizing relative sizes

Figure 2.3. Alignment of Trajectory of Scale Concept Development with chemistry content categories[7]

2.2.6. Recent Efforts Addressing Undergraduate Chemistry Scale Instruction

Despite scale being consistently mentioned as a cross-cutting concept by several reports on the future direction of science education,[14-16] there is a lack of literature related to the implementation of scale into curricula and instruction. Briefly introduced in Chapter 1, there have been recent efforts to address scale in undergraduate chemistry. At the University of Wisconsin – Milwaukee, an over-arching goal has been to develop, implement, and refine a scale-themed curriculum into general chemistry courses. This investigation has spanned several years, meticulously surveying each stage of the process.

In this investigation, Gerlach, et al. first performed a study adapted from the previously described work by Jones and Tretter, which sought to determine how introductory college-level chemistry students conceptualized scale.[17] Results aligned regarding conceptual boundaries of the chemistry college students to 5th, 7th, and 9th graders in Jone's and Tretter's work. However,

in Gerlach, et al., college chemistry students did not perform at the same level as the gifted seniors in Jones and Tretter's research. Next, Gerlach, et al. developed and validated two instruments to measure scale literacy of chemistry students.[18] One instrument was the Scale Concept Inventory, which targets student scale conceptions and misconceptions. The second instrument was the Scale Literacy Skills Test, which evaluates scale skills and concepts. Both instruments were designed purposefully to complement each other. By averaging the score from both assessments, an encompassing scale literacy (SL) score could be used to easily assess students' scale literacy.

In the next phase, Trate, et al. created and implemented scale-themed instruction across the general chemistry curriculum.[13] The main instructional tools and activities incorporated can be summarized in three main branches: scale-themed lectures and labs, active learning activities, and supplemental instruction (SI) activities. In lectures, instructors made increased efforts to focus on making connections across the symbolic, particulate, and macroscopic levels. Students were also encouraged to make these connections. A symbol was added consistently to lecture slides to serve as a reminder for students to think about the different representations of scale involved in a phenomenon. In the lab component, prelab and post lab questions were restructured to focus more explicitly on the particulate level.

Additionally, active learning activities were incorporated into the lecture activities booklet (a required course material). within acted as an outline for students to fill in notes and diagrams during lectures. The lecture activities booklet presented chemistry content alongside relevant scale concepts that aligned with lecture slides denoted with the scale symbol.

Twice a semester, self-paced SI activities were available for students to further develop scale skills and make connections with scale and chemistry content. Furthermore, to gain a better

sense of students' scale literacy skills and how they may develop over time, students' SL scores were measured via the two scale assessments that were both administered at the start (pre) and end (post) of the semester. Over the course of eight semesters, observations and measures related to the scale-themed curriculum were collected. Conditions varied by semester and lecture sections. This involved including various combinations of active learning activities, scale-themed lab experiments, and/or supplemental activities. For example, for one condition, only the lab experiment intervention materials were included, while in another condition, the lab experiments and SI activities were incorporated with non-scale activities (Table 2.1-Table 2.2). Some cases involved incorporating all the scale-themed intervention materials (scale-themed active learning activities, scale-themed lab experiments, and SI activities). Collecting data over a range of conditions was purposeful and meant to provide detailed insight into the most beneficial combinations of the scale intervention materials.

With any change to instruction or curricula, it is essential to evaluate the success of the modifications. From early on in this study, one aim was to develop a multiple regression model to predict final exam scores and perform a residual analysis to evaluate the success of the intervention. Initial work in the development of the model involved exploring correlations between common predictors of chemistry performance and final exam scores. In this exploration, it was revealed that the SL scores correlated with final exam scores the same or better than with ACT scores and chemistry placement test scores. In GC I, the final exam is comprised of two parts: (1) 2005 ACS Exams First Term General Chemistry Paired Questions Exam and (2) 2008 ACS Exams General Chemistry Conceptual Exam – First Term. Ultimately, the multiple regression model in GC I had three significant predictors of success for the paired final exam:

ACT composite score, diagnostic placement test score (2005 ACS Exams Toledo Exam), and SL pre score.

In analysis, the predicted paired final exam score was compared to the student's actual score, resulting in a residual value. The students' residual values (referred to as learning gains) were averaged to assess the intervention's impact on a larger breadth. A positive learning gain average was interpreted as a resulting benefit from the scale-themed intervention; a negative learning gain average was interpreted as less of a benefit from the scale-themed intervention.

In GC II, the final exam was comprised of two parts meant to address content covered in both semesters of general chemistry (GC I and GC II). Part 1 was the 2005 ACS Exams First Term General Chemistry Paired Questions Exam, and part 2 was the 2008 ACS Exams General Chemistry Conceptual Exam – Second Term. The finalized multiple regression model for GC II predicted performance on part 2 of the final exam. The three predictors of success in the model were the placement test score (2005 ACS Exams First Term General Chemistry Paired Questions Exam), ACT composite score, and pre SL score. Residual averages for GC I and GC II are reported in Tables 2.1-2.2.

Table 2.1. General chemistry I paired final exam residuals and group comparison [13]

Condition	N	Residual Avg. (%)	*p*	Effect Size
Control	143	<1.00	---	---
Lab Exp.	41	3.70	0.045	0.346
Nonscale AL + Lab Exp.(Initial)	35	1.90	0.356	---
Nonscale AL + Lab Exp. + SI (Initial)	15	6.20	0.004	0.564
AL + Lab Exp. (Repeat)	50	4.20	0.009	0.305
AL + Lab Exp. + SI (Initial)	27	6.70	0.003	0.522

Key: Lab Exp. = Lab Experiments, AL = Active Learning, SI = Supplemental Instruction

Table 2.2. General chemistry II conceptual final exam residuals and group comparisons

Condition	N	Residual Avg. (%)	*p*	Effect Size
Control	87	<1.0	0.930	---
Lab Exp.	67	4.6	<0.001	0.390
Nonscale AL + Lab Exp.	90	3.6	0.006	0.303
Nonscale AL + SI	34	1.4	0.455	---
Nonscale AL + Lab Exp. + SI	26	-1.4	0.507	---
AL + Lab Exp.	86	3.1	0.014	0.238
AL + SI	41	2.1	0.297	---
AL+ Lab Exp. +SI	20	1.0	0.644	---

Key: Lab Exp. = Lab Experiments, AL = Active Learning, SI = Supplemental Instruction

When assessing the scale intervention across general chemistry, there were positive significant average learning gains across all conditions in GC I. Surprisingly, mixed, nonsignificant results were found in general chemistry II, with the highest learning gains being in the laboratory condition. Comparatively, the scale-themed intervention was more successful in

GC I than GC II. It was hypothesized that the differing results in GC II could be a result of GC II enrollment patterns. Frequently, students do not take GC II the semester after completing GC I. It is possible a lapse in exposure to chemistry content and scale instruction may cause the lower learning gains observed in GC II. It was also found that GC II students began the course with higher scale literacy scores than GC I students. Therefore, another hypothesis is that GC II students are experiencing a ceiling effect, where scale abilities were not significantly increased further with an additional semester of scale instruction. Ultimately, based on these results, further research on scale conceptions and scale-themed instruction in GC II is needed.

2.3. Research Context

To further investigate scale instruction in GC II, modifications to the existing scale-themed curriculum were made as opposed to creating an entirely new curriculum. This was not only the most time-efficient option but also allowed what was originally successful to remain intact. However, in some ways, making modifications can be just as challenging as creating something new. Often it is not clear where or what modifications are necessary. This chapter aims to address the following central research questions related to the modifications of the GC II scale-themed curriculum:

RQ1: Using a targeted exploration, what specific aspects of the original GC II scale-themed curriculum should be modified?

RQ2: Based on the findings of RQ1, what instructional strategies should be utilized to best integrate the modifications into the course materials?

2.4. Methods

To ensure a detailed assessment of where and what modifications were needed for the GC II scale-themed curriculum, a targeted exploration of all content areas and scale skills was performed. The exploration began by using the Fall 2019 hourly exams' multiple-choice questions. Each question was categorized based on the presence and/or level for the following seven categories: complexity, type of problem (algorithmic, conceptual, recall), visual spatial, level of math, inclusion of scale, content area, and sub content area. Details related to each category are described in Figure 2.4.

The complexity of each question was determined using the methodology described in Knaus, et al.[19] The content area and sub content areas were determined by referencing the course textbook and course instructor. The other four categories were ranked using scales ranging from 0 – 5. A ranking of 0 indicated the category was not present in the question, and a ranking of 5 indicated the specific category was highly incorporated into the question. The specifics of each Likert scale varied by category, which can be found in Appendix A. All categories were first ranked by the author of this dissertation and then ranked by two other researchers. Rankings were discussed between raters until consensus was reached. Upon completion of ranking, each of the 116 multiple-choice questions had six numerical rankings, one per category. These rankings were further utilized in selected subscore calculations and internal and external correlations.

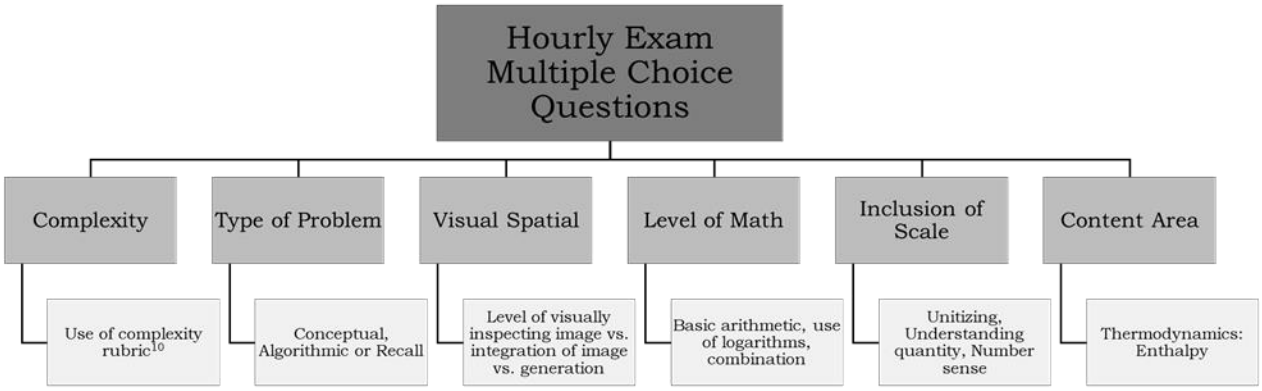


Figure 2.4. Six categories that were used to classify hourly exam multiple choice questions

2.5. Results and Discussion

The goal of the subscore correlation analysis was to identify which areas of the course were most in need of modification. Granted, there were hundreds of possible correlation combinations to examine given the varying categories included. However, with a scope that large, it would be unlikely that all correlations would provide meaningful insight into what areas to modify in the curriculum. Therefore, a great deal of effort was put into determining which correlations were most appropriate to consider. Ultimately, to narrow in on which correlations were meaningful to investigate further, a list was created detailing the top five essential scale skills for students to possess. The list (Table 2.3) involved splitting the scale category into three separate subcategories, which were listed as the top three in the following order: understanding quantity, number sense, and unitizing. The fourth and fifth elements on the list were high visual spatial skills and high math ability, respectively.

Table 2.3. The five essential scale elements

Understanding Quantity
Number Sense
Unitizing
High Visual Spatial Skills
High Math Ability

Using this list as a guide, correlations between various combinations of the five elements were examined further. (Note: Items were considered to involve high visual spatial skills or high math ability based on having a ranking of ≥ 3). It is imperative to note that even by narrowing the scope of the correlation analysis, there were still many results to interpret. Therefore, only the results that provided the most helpful insights into the modified intervention will be reported and discussed further. Yet, this does not diminish the level of detail or importance of evaluating the other correlations throughout this process.

2.5.1. Correlations

A series of internal and external correlations were executed to further determine where to focus the modifications for the intervention. Before data cleaning, there were 176 students in GC II that consented to providing their course data in Fall 2019. After cleaning the data (data cleaning process explained in more detail in Chapter 3), 52 student cases were utilized in a correlation analysis. Most correlations consisted of 52 students (unless noted otherwise in data tables). The number of exam items utilized in the correlations varied depending on which of the five essential scale elements' subscores and/or content area subscores were of focus. Item totals are reported in Table 2.4.

Table 2.4. Total number of exam multiple choice items per category

Category	Number of Items
Solutions pt.2	20
Kinetics	17
Equilibrium	14
Acid-Base Equilibrium	23
Solubility Equilibrium	6
Thermochemistry	7
Electrochemistry	5
Unitizing	12
Understanding Quantity	32
Number Sense	12
High Math Level	15
High Visual Spatial	22

2.5.1A. Internal Correlations

As a baseline, the subscores for each of the three subcomponents of scale were correlated. Any questions that had a ranking other than 0 for unitizing, number sense, or understanding quantity were included in subscore calculations. It was hypothesized subscores in one scale component would directly correlate with subscores in another scale component. Results supported this hypothesis, with positive and significant correlations between each combination (Table 2.5). This result suggested that the three scale skills work together.

Table 2.5. Correlations between scale components subscores with 52 students

	Pearson Coefficient (r)
Unitizing & Understanding Quantity	0.777
Number Sense & Unitizing	0.589
Number Sense & Understanding Quantity	0.659

All correlations significant at $p < 0.01$

Another meaningful correlation was between content area subscores and the combined scale components subscores. The subscores for any question that had one or more scale components present were correlated with subscores in each content area. Table 2.6 lists the seven main content areas covered in GC II. Note that solutions pt.2 is covered in GC II and solutions pt.1 is covered in GC I. Solutions pt.2 is comprised of concentration units, solubility, intermolecular forces, and colligative properties. Across all content areas, there were positive and significant correlations with the combined scale components (Table 2.6). Indeed, scale skills are related to performance in GC II content.

Table 2.6. Correlations between three scale component subscores and content area subscores with 52 students

General Chemistry II Content Areas	Pearson Coefficient (r)
Solutions (pt.2)	0.617^b
Kinetics	0.650^b
Equilibrium	0.658^b
Acid-Base Equilibrium	0.753^b
Solubility Equilibrium	0.487^a
Thermodynamics	0.600^b
Electrochemistry	0.480^a

$^a p < 0.01$, $^b p < 0.0001$

2.5.1B. External Correlations

Subscores from the five essential scale elements were correlated with Fall 2019 external measures such as student learning gains and SL scores. There were no significant correlations between the five essential scale element subscores with pre SL scores or post SL scores (Tables 2.7-2.8). This suggests that the SL scores alone were not an appropriate measure to understand scale literacy changes over the course of the semester. However, student learning gains proved to be a more useful measure as there were significant positive correlations between all five essential elements subscores with student learning gains (Table 2.9). This suggests that greater learning gains correlate with higher subscores in the scale elements. It also supports the idea that those with greater learning gains may differ in scale when compared to those with lesser learning gains at the end of GC II; indicating that the intervention may be more beneficial to certain groups of students than others. The learning gain measures were further explored to understand the scale literacy of those with higher learning gains compared to those with lower learning gains.

Table 2.7. Correlations between pre scale literacy (SL) scores and five essential scale elements' subscores with 52 students

	Pearson Coefficient (r)	***p***
Pre SL with Understanding Quantity	0.221	---
Pre SL with Number Sense	0.248	---
Pre SL with Unitizing	0.243	---
Pre SL with High Visual Spatial Skills	0.276	---
Pre SL with High Math Ability	0.191	---

Table 2.8. Correlations between post scale literacy (SL) scores and five essential scale elements' subscores with 51 students

	Pearson Coefficient (r)	***p***
Post SL with Understanding Quantity	0.133	---
Post SL with Number Sense	0.274	---
Post SL with Unitizing	0.171	---
Post SL with High Visual Spatial Skills	0.239	---
Post SL with High Math Ability	0.160	---

Table 2.9. Correlations with learning gains and five essential scale elements' subscores with 52 students

	Pearson Coefficient (r)	***p***
Learning Gains with Understanding Quantity	0.411	0.003
Learning Gains with Number Sense	0.443	0.001
Learning Gains with Unitizing	0.275	0.048
Learning Gains with High Visual Spatial Skills	0.359	0.009
Learning Gains with High Math Ability	0.280	0.040

The sample of 52 students was split into two groups: the high learning gains group (n = 26) and the low learning gains (n = 26) group. Students who had learning gain values above the entire sample's learning gain average (3.7%) were sorted into the high learning gains group (high group). Students who had learning gain values below the sample's average were sorted into the low learning gains group (low group). The terms "high" and "low" are not indicative of course performance or scale abilities. Rather, it is assumed that those in the high group benefited more from the scale intervention than those in the low group.

The three predictors used in the multiple regression model were compared further between the high and low groups (Table 2.10). There were no significant differences between the two groups for ACT composite scores, pre SL scores or placement test scores. All three of these measures are recorded at the start of the semester / before starting GC II. Therefore, it can be assumed that the high and low groups are entering GC II with comparable scale skills and prior knowledge. However, over the course of the semester differences in performance between the two groups emerge. Examining trends in the four hourly exam scores, the high and low group exam score averages differ more greatly. In fact, by exam 4, there is a statistically significant difference between the two groups, with the high group averaging 60.8% compared to the low group averaging 53.3%. Comparing the final exam score, there were no significant differences between the groups for the final pt. 1. Yet, on the final pt. 2, the high group scores significantly higher (62.2%) compared to the low group (43.0%).

Table 2.10. Comparisons between high and low groups for exam scores and significant predictor measures

	ACT Composite Score	Placement Test Score	Pre Scale Literacy Score	Final Pt. 1	Final Pt. 2[b]	Exam 1	Exam 2	Exam 3	Exam 4[a]
High Group (n=26)	23.4	58.7%	57.0%	73.3%	62.2%	66.3%	68.7%	66.3%	60.8%
Low Group (n=26)	24.3	60.0%	57.6%	70.4%	43.0%	63.5%	66.2%	62.8%	53.3%

ACT composite score, placement test score, and pre scale literacy scores are significant predictors in the multiple regression model
[a]$p < 0.05$, [b]$p < 0.0001$

In summary, the high and low group are comparable at the start of GC II based on the groups' similar averages on the ACT composite scores, pre SL scores, and placement test scores. Over the course of the semester, there are greater differences between exam score averages between the two groups, with the most significant differences being observed for exam 4 and the final pt. 2. These differences seen for measures at the end of the semester could be attributed to the effects of the scale-themed intervention the students were exposed to throughout the course.

With the support that the intervention is having an effect, the targeted intervention exploration shifted toward specifically identifying what content areas and scale skills to focus on for the revised materials. To achieve this aim, subscores in varying content areas and scale elements were correlated for the high and low groups. For example, subscores for questions involving a high level of math were correlated to subscores in the content area solutions pt.2. If the high group had a significant positive correlation with those parameters and the low group did not, then those content areas and scale skills should be targeted for modifications (Tables 2.11-2.15). In a few conditions, the low group had positive significant correlations while the high group did not, or the low and high group had comparable relationships for the same content area and scale skills.

Based on this observation, it was conjectured that the low group students are most likely still benefiting to some degree from the intervention material, but the model is not picking up the subtilties. Therefore, it was further hypothesized that the low group needed more support to further improve their performance in the identified content areas and scale skills. To provide more support to students, a common educational practice includes instructional scaffolding. Although it is challenging to implement scaffolding into higher education courses, scaffolding was determined to be the best approach to execute the identified changes to the GC II scale-themed curriculum. For example, using the findings summarized in Table 2.11, increased scaffolding related to math concepts in the content areas solutions pt.2, equilibria, and thermochemistry may be beneficial so that low group students have more support while learning. Scaffolding would also be beneficial for visual spatial skills, number sense, and unitizing in content areas such as solutions, equilibria, and thermochemistry (Tables 2.11-2.15).

Table 2.11. Correlations between content area subscores and high math level subscores for high and low groups

Content Area w. High Math Level	High Group (n=26)	*p*	Low Group (n=26)	*p*
Solutions pt.2	0.678	<0.01	0.257	---
Kinetics	0.647	<0.01	0.389	<0.05
Equilibrium	0.431	<0.05	0.370	---
Acid-Base Equilibrium	0.775	<0.01	0.68	<0.01
Solubility Equilibrium	0.623	<0.01	0.178	---
Thermochemistry	0.593	<0.01	0.356	---
Electrochemistry	0.520	<0.01	0.655	<0.01

Table 2.12. Correlations between content area subscores and high visual spatial subscores for high and low groups

Content Area w. High Visual Spatial	High Group (n=26)	*p*	Low Group (n=26)	*p*
Solutions pt.2	0.86	<0.01	0.205	---
Kinetics	0.665	<0.01	0.533	<0.01
Equilibrium	0.719	<0.01	0.361	---
Acid-Base Equilibrium	0.726	<0.01	0.736	<0.01
Solubility Equilibrium	0.489	<0.05	0.344	---
Thermochemistry	0.575	<0.01	0.365	---
Electrochemistry	0.55	<0.01	0.608	<0.01

Table 2.13. Correlations between content area subscores and number sense subscores for high and low groups

Content Area w. Number Sense	High Group (n=26)	*p*	Low Group (n=26)	*p*
Solutions pt.2	0.622	<0.01	0.449	---
Kinetics	0.361	---	0.36	---
Equilibrium	0.299	---	0.526	<0.01
Acid-Base Equilibrium	0.645	<0.01	0.459	---
Solubility Equilibrium	0.471	---	0.352	---
Thermochemistry	0.803	<0.01	0.64	<0.01
Electrochemistry	0.561	<0.01	0.468	---

Table 2.14. Correlations between content area subscores and understanding quantity subscores for high and low groups

Content Area w. Understanding Quantity	High Group (n=26)	*p*	Low Group (n=26)	*p*
Solutions pt.2	0.761	<0.01	0.287	---
Kinetics	0.695	<0.01	0.667	<0.01
Equilibrium	0.699	<0.01	0.735	<0.01
Acid-Base Equilibrium	0.805	<0.01	0.682	<0.01
Solubility Equilibrium	0.462	<0.05	0.331	---
Thermochemistry	0.588	<0.01	0.505	<0.01
Electrochemistry	0.512	<0.01	0.447	<0.05

Table 2.15. Correlations between content area subscores and unitizing subscores for high and low groups

Content Area w. Unitizing	High Group (n=26)	*p*	Low Group (n=26)	*p*
Solutions pt.2	0.723	<0.01	0.382	0.054
Kinetics	0.550	<0.01	0.287	---
Equilibrium	0.690	<0.01	0.429	<0.05
Acid-Base Equilibrium	0.719	<0.01	0.616	<0.01
Solubility Equilibrium	0.490	<0.05	0.551	<0.01
Thermochemistry	0.680	<0.01	0.369	---
Electrochemistry	0.460	<0.05	0.382	0.054

2.6. Limitations

In terms of limitations, this work was based on one specific GC II curriculum and its related measures. Therefore, if applied to other curricula, the same measures to identify areas of modification may not be applicable. Additionally, different areas than what were identified in this work may need to be targeted when modifying other courses' curricula.

2.7. Conclusion

In general, this chapter presents a detailed, mixed-methods methodology for identifying areas in need of modification in a course's curriculum. These methods can be adapted at varying levels to utilize in other curricula. In this context, key areas to target in the curriculum's revisions were identified using a GC II course's characteristics and related external and internal measures. Findings from this investigation suggest that providing more support in the targeted areas will benefit students. The details of the changes and scaffolding implemented will be discussed further in the next chapter.

2.8. References

(1) Lock, G., Molyneaux, B., *Confronting Scale in Archaeology: Issues of Theory and Practice*; Springer Science & Business Media: New York, **2007.**

(2) Jones, M. G.; Andre, T.; Superfine, R.; Taylor, R. Learning at the nanoscale: The impact of students' use of remote microscopy on concepts of viruses, scale, and microscopy. *J Res. Sci. Teach.* **2003**, *40* (3), 303–322.

(3) Tretter, T. R.; Jones, M. G.; Minogue, J. Accuracy of scale conceptions in science: Mental maneuverings across many orders of spatial magnitude. *J. Res. Sci. Teach*. **2006**, 43 (10), 1061−1085.

(4) Tretter, T. R.; Jones, M. G.; Andre, T.; Negishi, A.; Minogue, J. Conceptual boundaries and distances: Students' and experts' concepts of the scale of scientific phenomena. *J. Res. Sci. Teach.* **2006**, 43 (3), 282−319.

(5) Jones, M. G.; Taylor, A. R. Developing a sense of scale: Looking backward. *J. Res. Sci. Teach.* **2009**, *46* (4), 460–475.

(6) Johnstone, A. H. The development of chemistry teaching. *J. Chem. Educ.* **1993**, 70 (9), 701.

(7) Johnstone, A. H. *Some Messages for Teachers and Examiners: An Information Processing Model, in Research in Assessment VII:Assessment of Chemistry in Schools,* London: Royal Society of Chemistry Education Division, **1989**, 23-29.

(8) Johnstone A. H. Why is science difficult to learn? Things are seldom what they seem. *J. Computer Assisted Learning,* **1991**, 7, 75–83.

(9) Gilbert, J. K., Treagust, D. *Multiple Representations in Chemical Education*; Springer: Dordrecht, The Netherlands, **2009.**

(10) Taber, K. S. Revisiting the chemistry triplet: Drawing upon the nature of chemical knowledge and the psychology of learning to inform chemistry education. *Chem. Educ. Res. Pract.* **2013**, *14* (2), 156–168.

(11) Talanquer, V. Macro, submicro, and symbolic: The many faces of the chemistry "triplet." *International Journal of Science Education*, **2011**, *33* (2), 179–195.

(12) Talanquer, V. Chemistry education: Ten dichotomies we live by. *J. Chem. Educ.* **2012**, *89* (11), 1340–1344.

(13) Trate, J. M.; Geissinger, P.; Blecking, A.; Murphy, K. L. Integrating scale-themed instruction across the general chemistry curriculum. *J. Chem. Educ.* **2019**, *96* (11), 2361–2370.

(14) American Association for the Advancement of Science, *Science for All Americans: A Project 2061 Report on Literacy Goals in Science, Mathematics, and Technology*; Oxford University Press: New York, NY, **1989.**

(15) National Research Council. *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*; National Academies Press: Washington, DC, **2012.**

(16) National Research Council. N*ext Generation Science Standards: For States, by States*; National Academies Press: Washington, DC, **2013.**

(17) Gerlach, K.; Trate, J.; Blecking, A.; Geissinger, P.; Murphy, K. Investigation of absolute and relative scaling conceptions of students in introductory college chemistry courses. *J. Chem. Educ.* **2014**, *91* (10), 1526–1537.

(18) Gerlach, K.; Trate, J.; Blecking, A.; Geissinger, P.; Murphy, K. Valid and reliable assessments to measure scale literacy of students in introductory college chemistry courses. *J. Chem. Educ.* **2014**, *91* (10), 1538–1545.

(19) Knaus, K.; Murphy, K.; Blecking, A.; Holme, T. A valid and reliable instrument for cognitive complexity rating assignment of chemistry exam items. *J. Chem. Educ.* **2011**, *88* (5), 554-560.

Chapter 3

Employing Scaffolding in a Scale – Themed Curriculum

"Just as a building needs firm foundations, so does learning." [1]

– Keith Taber

3.1. What is Instructional Scaffolding?

One of the many roles of an instructor is to provide support to students as they navigate and learn new concepts and skills. Support in the classroom can take many forms, but one type is instructional scaffolding. Akin to its namesake, instructional scaffolding is often described analogously to the scaffolding used in the construction of buildings. Scaffolding, the temporary framework used during the construction, serves as the framework learners use as they "build" new knowledge. The widely used definition of scaffolding in the context of education is support given by a teacher as a student performs a task that they may have otherwise been unsuccessful in executing without the teacher's guidance (Figure 3.1).[2]

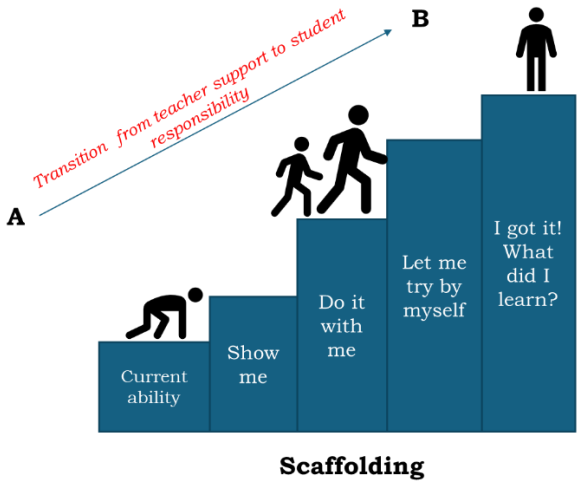


Figure 3.1. Visual representation of instructional scaffolding

Scaffolding is based on the ideas from Vygotsky's socio-cultural theory.[3] According to Vygotsky, learning is rooted in social interactions. Learning must be first achieved at the social level before it is achieved at the individual level.[4] Scaffolding practices were first introduced as a tutoring technique where experienced adults assisted children with completing a new task which otherwise may have been outside the child's preliminary learning capacity.[5] Ultimately, scaffolding centers on the importance of instructor-student interactions where both are active participants in the process.[3]

The Zone of Proximal Development (ZPD) is another component of socio-cultural theory and often associated with scaffolding. Vygotsky described the ZPD as the gap between what the learner can achieve independently and what the learner can accomplish with the aid of more experienced peers or experts (Figure 3.2A).[4] Instructors can utilize scaffolding to provide support for students as they develop new knowledge and work within their ZPD. Said another way, scaffolding is a tool to help students navigate the ZPD gap (Figure 3.2B).

When learning unfamiliar information, it is important to consider how students process information. Figure 3.3 depicts an accepted information processing model that describes how information is processed, stored, and utilized.[6] New information is filtered through sensory memory, removing any extraneous stimuli (becomes forgotten), before passing on to one's working memory. Working memory either discards information (becomes forgotten) or, via rehearsal, encodes the information in long-term memory to be retrieved for later use. Research has shown that working memory has a limited capacity; it generally can only process 5-9 pieces of information at a time.[7,8] This is the basis for Cognitive Load Theory, which explains why it is important to design curricula and teach in a way that does not result in cognitive overload, which

inhibits the learning process.[9] It is believed that scaffolding reduces students' cognitive load while learning[1,10] and assists students with internalizing the essence of the provided support.[11]

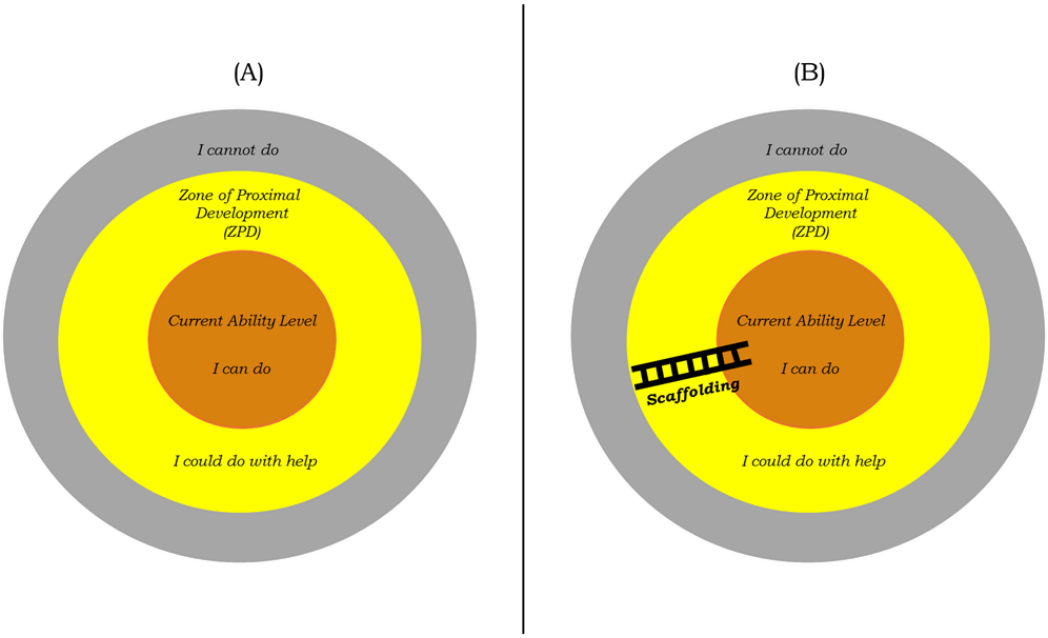


Figure 3.2. (A) Zone of Proximal Development (B) Zone of Proximal Development with scaffolding

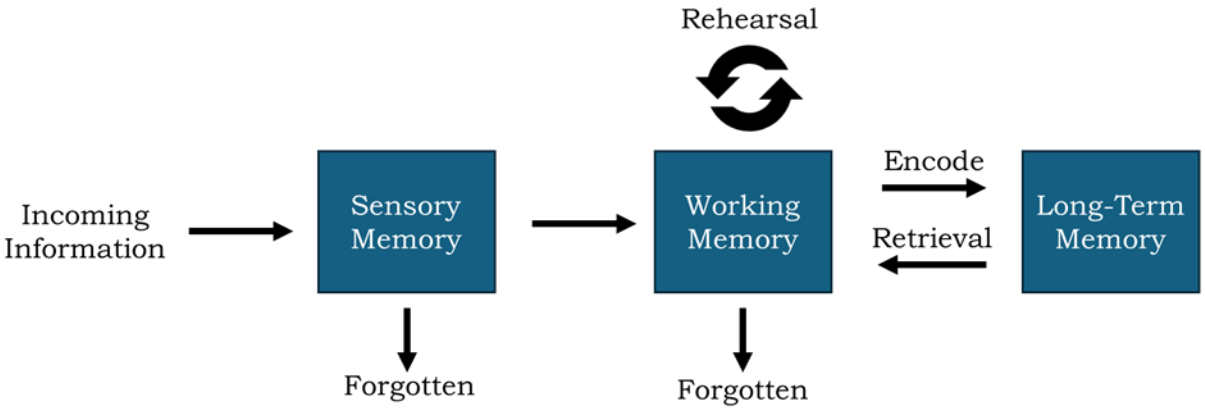


Figure 3.3. Information processing model[6]

Since scaffolding originated in tutoring, it has advanced and become a well-known educational technique to facilitate support in classrooms. In fact, there is a large body of research on the use of scaffolding in various disciplines and levels of schooling.[12-15] Additionally, open-source instructor resources are widely and easily accessible online. Yet, the ubiquity of scaffolding is a double-edged sword. While instructors have many resources on scaffolding, some authors in educational research argue that the concept of scaffolding is too broad, is becoming synonymous with any classroom support, and is lacking the essential interactive nature between students and teachers.[3,11,16–18] In fact, in 1998, Stone published work calling for the scaffolding metaphor to be "salvaged" and return to its original theoretical basis.[11,18] As a result of this, a review of a decade of scaffolding work found many inconsistencies among scaffolding literature. However, three main characteristics of scaffolding emerged: contingency, fading, and transfer of responsibility.[2] The three characteristics operate dependent on one another (Figure 3.4). Initially, when students are learning new knowledge, it is necessary for instructors to provide increased support and bear more responsibility towards learning. In the context of scaffolding, this manifests as scaffolded activities contingent on the instructor's capacity to assess their students' current abilities and adapt instruction according to the students' responses. As time progresses, the support provided is removed and responsibility of learning is transferred to the students. To this end, there is a need for a clear consensus on the introduction, design, and fading procedures of scaffolding.[2,11,16,18,19] This is especially true in science higher education, as little research on scaffolding at this level has been reported.[19]

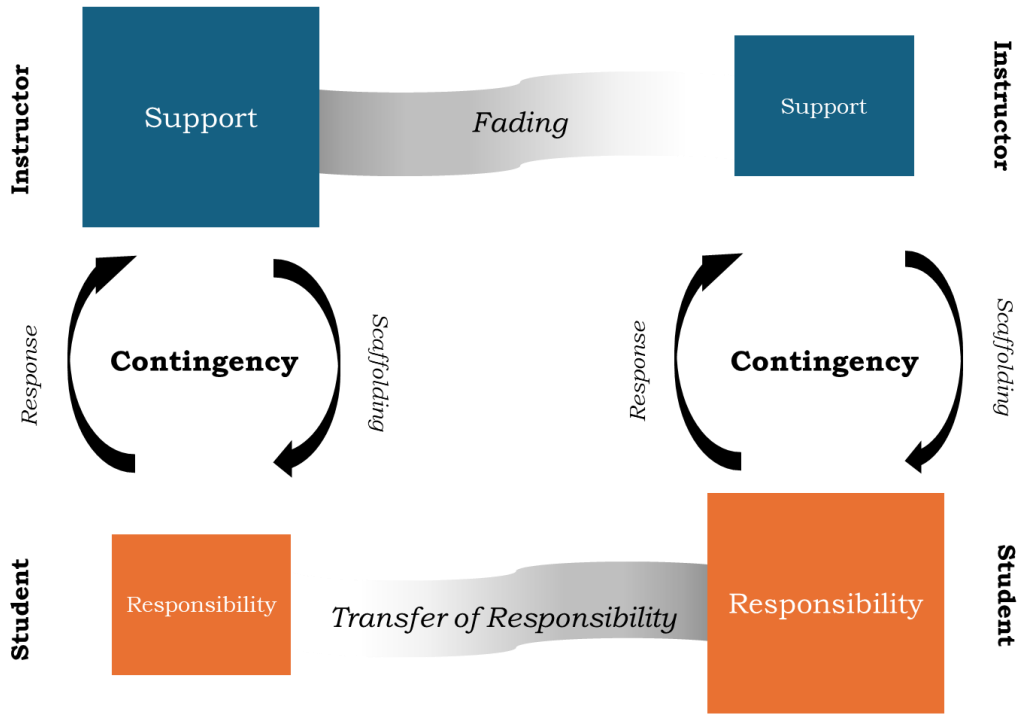


Figure 3.4. Conceptual model of scaffolding as described by van de Pol, et al[2]. The three characteristics of scaffolding are included: contingency, fading, and transfer of responsibility.

3.2. Research Context

In the context of the targeted scale – themed curriculum, a main aspect focuses on how the revisions to the curriculum were implemented via instructional scaffolding into GC II course materials. While addressing the three main characteristics of scaffolding, this chapter will discuss the methodology and strategies that were utilized when implementing scaffolding into the GC II scale - themed curriculum as well as the approaches taken to evaluate the effectiveness of the scaffolding. In this segment, the following research questions will be addressed:

RQ1: Which instructional tools and methods can be utilized to construct effective scaffolding within the identified areas of the scale – themed curriculum?

RQ2: Using quantitative measures, how effective was the implemented scaffolding in improving student learning?

3.3. Scaffolding Construction: Determining Areas to Implement Scaffolding

Before constructing scaffolded support, key elements should be considered. Keeping with the building analogy, any building's scaffolding first requires a solid foundation. For learning, that foundation is based upon prior knowledge.[1] Without a solid understanding of the prerequisite knowledge, the learning progression is compromised. Second, learning is dynamic in nature. Knowledge solidifies, and information that was once out of grasp is mastered as individuals continue to learn. Students' ZPDs are changing frequently, and for that reason, scaffolding should also be dynamic and tailored.[3] Third, each student will have a different foundation, current ability level, and ZPD, which in theory, implies each students' scaffolding would be personalized (Figure 3.5)[4] Therefore, the support provided to students is contingent on students' current abilities and will need to be adapted by the teacher depending on students' responses and as new tasks are encountered.[2,11]

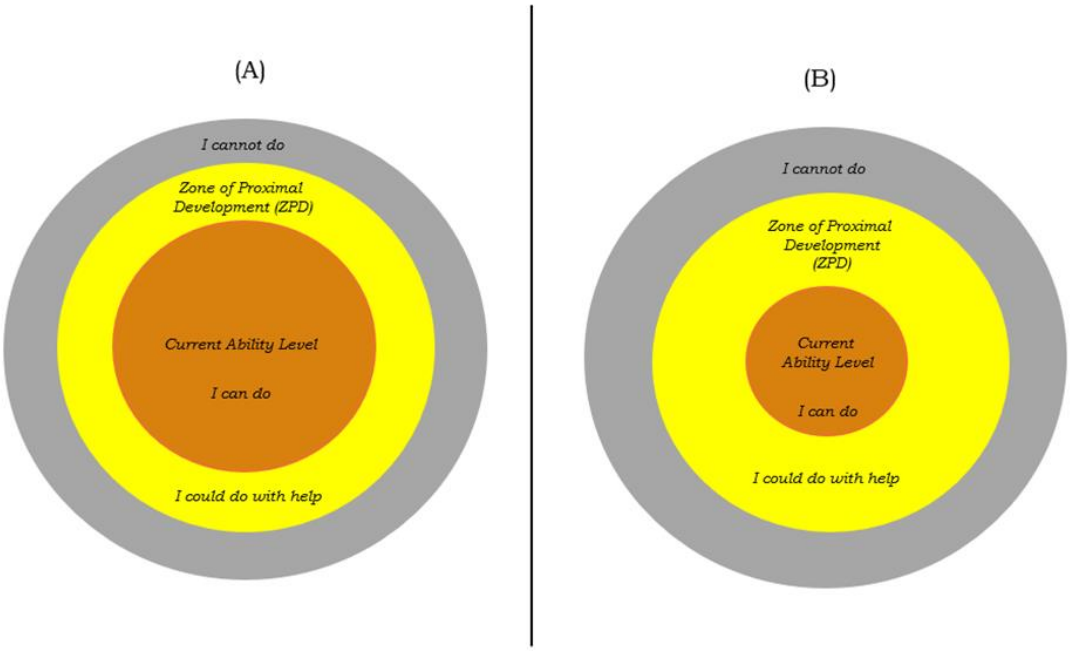


Figure 3.5. (A) Visual representation of the ZPD for a student with a higher current ability level (B) and for a student with a lower current ability level

However, it is challenging to define a student's current ability level and, consequently, implement support aligned seamlessly with traditional scaffolding practices. In practice, instructors are interacting with cohorts of students bound by the constraints of time available in a course. Additionally, the fact that a cohort of students will vary in abilities, foundational knowledge, and the type of support needed leads to more challenges when designing scaffolding. A repetitive cycle of designing and reframing scaffolding in instruction causes difficulties for instructors and a series of questions to consider. *How can scaffolding be designed? Where will scaffolding be most effective in a course? Is the scaffolded material successful, and how can that be determined?*

Studies have suggested methods to estimate the learner's existing knowledge. Some include the use of dynamic assessment and formative assessment.[20-23] In general, these methods are performed alongside the learning process. However, few of these studies occurred in higher education environments. Particularly in higher education, the ability to assess a cohort of students' abilities and having frequent individualized human-interactions is not practical in the span of a semester. In this project, information about GC II students' knowledge foundations was gathered while exploring key areas and components to target in the revision of the scale-themed curriculum.

While discussed in greater detail in Chapter 2, it was the meticulous analysis of past exam items and calculated learning gains that provided general insight into the hypothesized foundational knowledge of high- and low-learning gain students. Based on the findings related to determining the appropriate intervention method to incorporate into the scale-themed curriculum, it was hypothesized that increased scaffolding opportunities within the already established curriculum would be best suited. The exploration discussed in the previous chapter highlighted key content areas and scale – components to target. These highlighted course elements served as a "blueprint" for where scaffolding specifically needed to be incorporated. The scaffolding "blueprint" was used and aligned with a heavily utilized course material, the lecture activities booklet. Rather than create a new lecture activities booklet, the goal was to insert more scaffolding opportunities in the areas identified in the exploration phase. The lecture activities booklet is required for the course and was designed by course instructors and chemical education graduate students. It served as the best material to incorporate scaffolding due to its frequent use by the instructors and students. The lecture activities booklet contains fill-in note pages related to each section of the textbook along with practice problems, definitions, tables, diagrams, and

plots. The instructors mirror their lessons and slides to the booklet's content, and students are highly encouraged to take notes and follow along with their personal copy. The lecture activities are also meant to serve as a study tool outside of class.

3.4. Designing Scaffolding Materials

Scaffolding "building materials," or strategies, come in many forms including: providing feedback, hints, metacognition activities, redirecting, modeling, and questioning.[23] When deciding on which strategies to utilize in GC II, three points were considered in the design of the scaffolding materials. First, students may have encountered a topic previously but lack a full understanding to serve as a solid foundation. Second, students may possess the essential prior knowledge but may not be sure what to draw upon when learning new content. Third, students may feel overloaded by the presentation of material. Upon examination of the previously used lecture activities booklet, there was a lack of opportunities for students to review key previous concepts that are related to new topics. Guidance for more-involved algorithmic processes (e.g., ICE table calculations) was also needed.

Several types of scaffolding supports tend to have two elements in common: 1) channeling and focusing and 2) modeling.[16] Channeling and focusing involves controls put into place that cause the learner to focus on one piece of the task at a time rather than all at once. Modeling is when the instructor provides a model for completing the task. The scaffolding activities were designed similarly to Taber's scaffolding PLANKs (PLAtforms for New Knowledge) and POLES (Provided Outlines LEnding Support), which incorporated the two elements mentioned.[1] PLANKs present ideas already mastered or accessible to students and aid them in reorganizing thoughts to learn new knowledge. PLANKs were inserted at the beginning

of a new section in the lecture activities to review past material and reframe it for the desired learning outcome.

POLES are outlines or steps temporarily provided by the instructor to assist students until confidence with the task is developed. This is like using a GPS – the driver knows where they need to go, they just need directions to get there. In the same vein, students often approximately know how to get a final answer but are unsure of the steps to take along the way. Thus, POLES were often employed when breaking down complex algorithmic processes and had students focus on one step at a time while the instructor modeled the process in lecture. Examples of our PLANKs and POLES are shown (Figures 3.6-3.8).

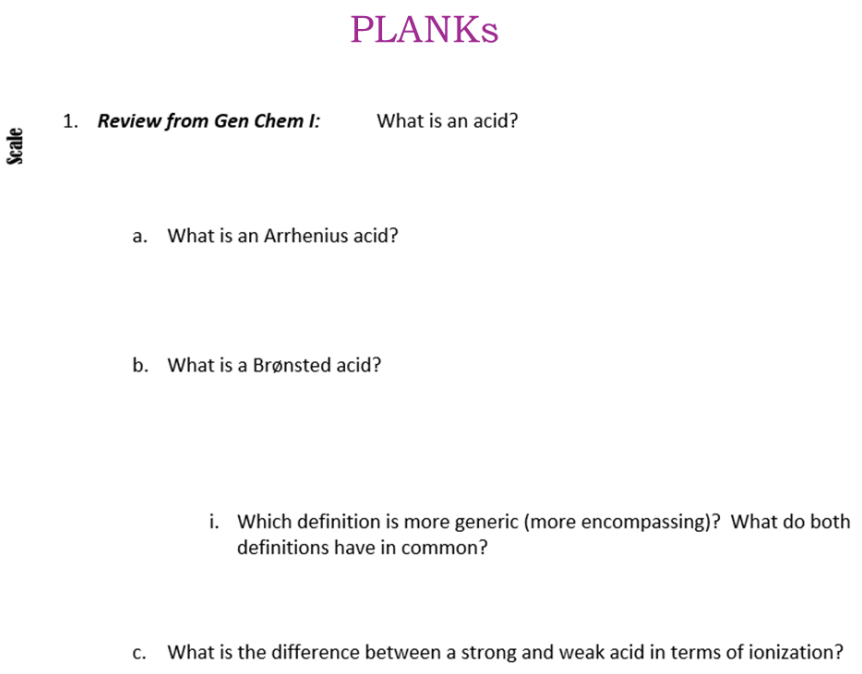


Figure 3.6. Example of PLANK reviewing key definitions related to acids

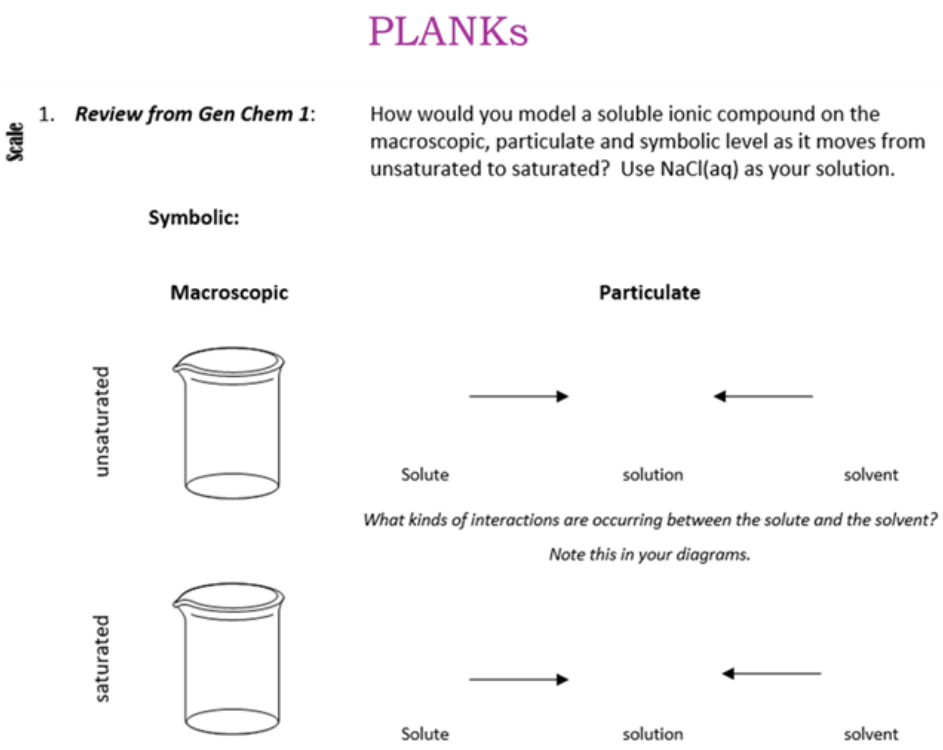


Figure 3.7. Example of PLANK with solutions at the three levels of representation in chemistry

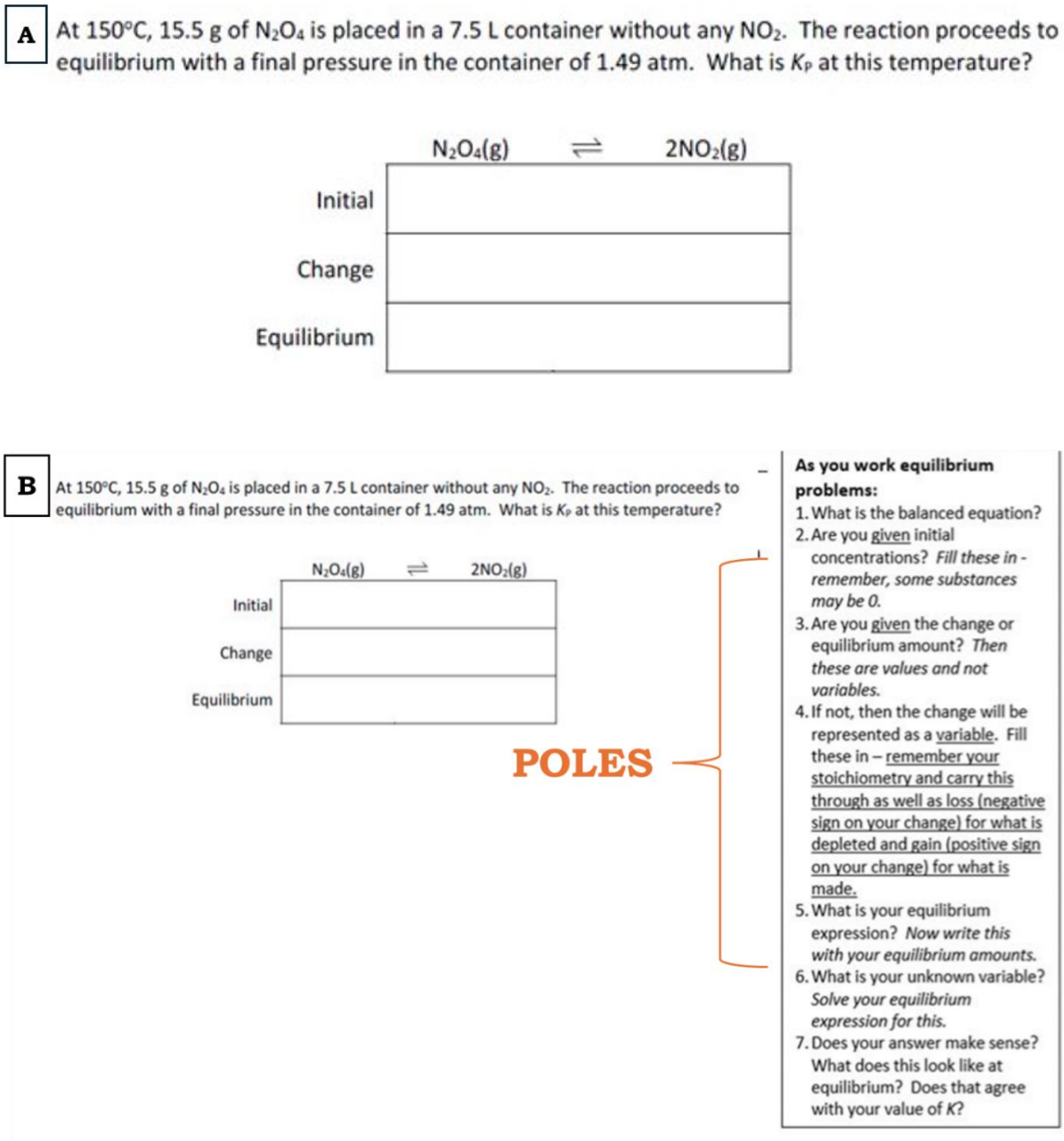


Figure 3.8. (A) Original activity before scaffolding revisions (B) Revised activity providing POLES for algorithmic process related to equilibrium

Designing scaffolding for chemistry can be particularly challenging given the task of assisting students in connecting the macroscopic and microscopic world. Alex Johnstone described that chemistry requires the consideration of the symbolic, subatomic, and macroscopic

levels.[24] Aligning with Johnstone's ideas, the scaffolding materials included activities that incorporated all three levels. In the unrevised lecture activities, there were opportunities for students to draw their own symbolic or particulate level diagrams to represent chemical phenomena. However, there was a need for building a better foundation to model how to draw these diagrams. Particulate level diagrams were scaffolded. The updated lecture activities provided partially drawn particulate diagrams for students to use as a model, and over time, the students would ideally use the partially drawn diagrams to create their own. Targeting the development of another scale component, more opportunities for students to make connections with the microscopic level and graphical representations were created to develop number sense and understanding quantity skills. For example, students had the opportunity to draw particulate level diagrams for key points on a titration curve (Figure 3.9).

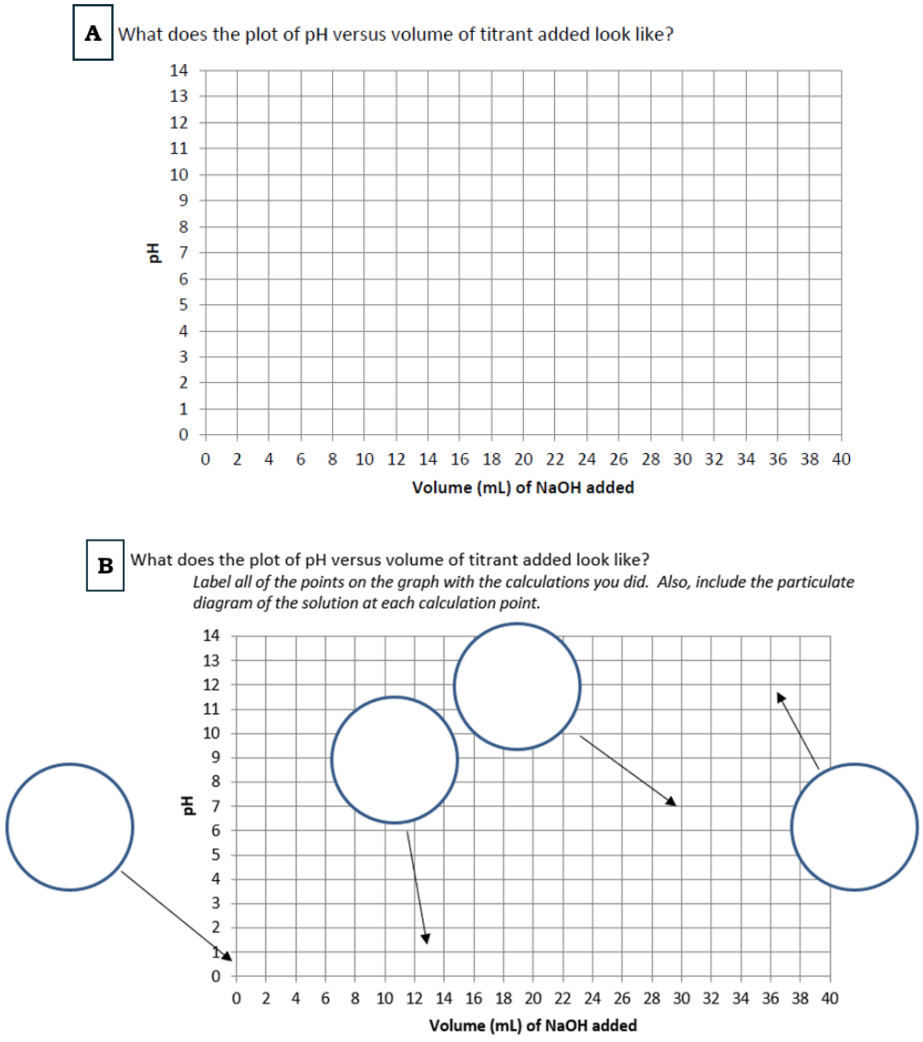


Figure 3.9. (A) Example of original activity related to pH and titrations (B) Activity in revised lecture activities with added scaffolding and scale connections

3.5. Fading Scaffolds

Two of the three main characteristics of scaffolding are fading and the transfer of responsibility.[2] Fading and the transferring of responsibility are related, as transferring the responsibility of learning to the student often takes place during the fading process.[2] Without fading, the support provided is not considered true instructional scaffolding and is more properly classified as a form of cognitive support.[16] Moreover, the scaffolding process may be

compromised if scaffolds are removed too soon or not removed at all. Considering this, it is surprising there is a lack of literature explicitly discussing fading procedures. According to an empirical literature review on scaffolding utilized in science instruction, it was found that less than 10% of their sample reported fading procedures.[19] The dynamic assessment and formative assessment techniques referred to earlier indirectly provide insight into when and where to begin fading. While ideal, these methods cannot be practiced easily in real-time, which makes reaching the fading point of the scaffolding process even more difficult. This is especially true in higher education settings, because it is difficult to tailor the fading that would result from formative or dynamics assessment due to large class sizes and the length of a semester.

In this project, immediate, real-time changes to the scaffolds and timing of fading were not realistic, because the scaffolding was incorporated in a printed lecture activities booklet purchased by students at the start of the semester. Thus, a considerable amount of work went into perfecting the timing and placement of the fading in the created POLEs and PLANKs. Definitions and concepts from GC I were only reviewed at the beginning of the relevant section of the lecture activities in the form of PLANKs. For example, the concept of polarity was relevant when discussing solubility and was reintroduced at this time. However, when polarity comes into play later when discussing acidity strength, the fundamental concepts of polarity were not reintroduced. In this way, students who still needed more support regarding topics covered in the previous course were given the opportunity for review and/or additional time to bridge their gaps in knowledge. POLEs initially consisted of a detailed outline to solve a problem, but over time, the outline was reduced or omitted. Additional practice problems later in the booklet were given hint callout boxes to assist students outside of class. Assuming the students

internalized the outlines and modeling, the practice problems would eventually appear with no outlines or hints for students to utilize directly while solving the problem.

Besides deconstructing the scaffold framework by fading the POLES and PLANKs, opportunities for metacognition were added to further promote the shift of responsibility of learning to the students. Metacognition allows the students to reflect on their own thinking and results in positive outcomes in student chemistry learning.[25,26] Also, student self-reflection has been argued to be a necessary part of the scaffolding process.[11] At the end of each section in the lecture activities, students had the opportunity to summarize and reflect on previous knowledge how it connects to what concepts they just learned (Figure 3.10).

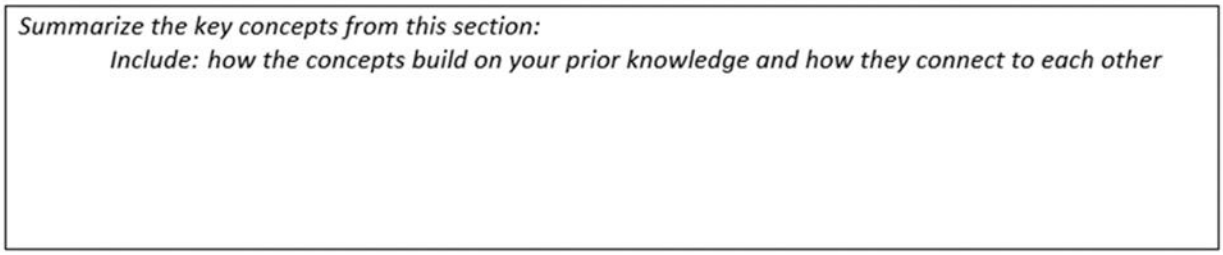


Figure 3.10. Metacognition summary activity in lecture activities booklet

3.6. Assessing the Effectiveness of Scaffolding

Upon completing the scaffolding process, it is necessary to review and assess the success of the framework in place. In this way, instructors must take on the responsibilities of an inspector – examining success of the resulting building of knowledge. As previously stated, many of the techniques provided in previous research that are used for estimating students' current abilities can be used to assess the overall effectiveness. However, methods such as dynamic assessment and formative assessment are meant to be applied in real-time and require

consistent instructor-student interaction, which is not practical in most higher education chemistry classrooms. This project presents methods to diagnosis scaffolding in higher education contexts (Figure 3.11). Quantitative and qualitative methods can be utilized to assess scaffolding. This work aims to use both quantitative and qualitative approaches to gain insight in the success of the revised scale – themed intervention. The quantitative methods employed will be described in the remainder of this chapter.

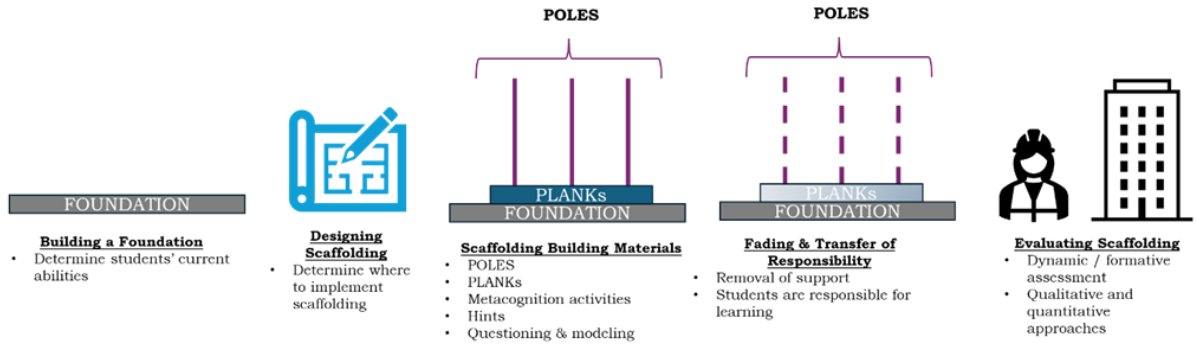


Figure 3.11. Scaffolding construction for instruction

3.7. Methods: Evaluating Scaffolding with Learning Gains

At the end of each semester, learnings gains were determined by using a multiple regression model[27] to assess the effectiveness of the implemented scaffolding materials.

3.7.1. Sample

Every fall and spring semester from Fall 2021 to Spring 2024, GC II student course data and provided institutional data were collected and utilized for this analysis. In fall semesters, there is one course of GC II by either Instructor A or Instructor B. In the spring semesters, there are two GC II courses taught by two different instructors (B and C). Instructors A and B used the scale – themed lecture activities, slides, and other created materials regularly in their instruction; however, Instructor C did not use the materials regularly in their instruction. To obtain the best

overview of the impact of the scaffolding and new scale-themed intervention materials, analysis only included data collected from the students enrolled in sections taught by Instructor A or Instructor B. The instructor assigned to each semester is detailed in Table 3.1.

Table 3.1. GC II course instructor by semester

Semester	Instructor	
	Section 1	Section 2
Fall 2021	A	----
Spring 2022	B	C
Fall 2022	A	----
Spring 2023	B	C
Fall 2023	B	----
Spring 2024	B	C

3.7.2. Data Cleaning

The data cleaning process is described below. Cases within the datasets that did not meet the following criteria were removed.

- Consented under the regulations of the IRB
- Completed all four hourly exams and the two-part final exam
- Reported ACT composite score
- Completed the placement test at the start of the semester
- Completed both scale literacy assessments at the start of the semester (Pre SCI and Pre SLST)[27]

3.7.3. Calculating Learning Gains

With the cleaned dataset, the learning gains were calculated each semester using the method described in Gerlach et al.[27]. The model uses three significant predictors of success: ACT composite score, placement test score, and scale literacy score (determined by the average score of two scale literacy assessments). The output of this model is the student's predicted final exam score on part 2 of the course's final examination. This value is compared to the student's actual final exam part 2 exam score to obtain the residual value (referred to as learning gain value herein). A positive learning gain average suggests the new targeted intervention benefited the students; a negative learning gain average suggests the new targeted intervention was not as beneficial. Using a paired t-test, the students' actual exam scores were compared to their predicted values to assess if the predicted learning gains were meaningful and significant. Learning gain averages for each semester were also reported to assess the effect of the intervention more broadly.

3.8. Results & Discussion

Table 3.2 summarizes the learning gain results. There were positive and significant learning gain averages in GC II in five out of six semesters included in this study. In Spring 2022, there was a positive learning gain average overall with no significant difference between the predicted and actual final exam part 2 scores. Given the learning gain average in Spring 2022 compared to the other semesters' learning gain averages, other factors that may have contributed to the low learning gain average were considered. Such considerations were an instructor effect, timing effect, or an anomaly. As more semester data was collected, the possibility of an instructor effect or timing effect seemed less plausible. Given that both instructors did heavily use the scale-themed intervention materials regularly in their instruction, it was expected that

learning gain averages from the semesters each taught would be similar. Aside from the high learning gain average in Fall 2022 and the nonsignificant learning gains in Spring 2022, the learning gain average is approximately 6-7% regardless of which instructor was teaching. As for the timing effect, it was possible the intervention materials may be more effective in fall or spring. However, the learning gain average remained at around 6-7% independent of when students completed the course. The strongest possibility is that the low learning gain average in Spring 2022 was an anomaly. Anecdotal evidence from this semester provides support for this claim. A few graduate students, who taught GC II regularly (including the graduate student conducting this project) noticed that this cohort of students was more expressive of their concerns regarding exams and studying compared to other semesters of GC II. While the students' behaviors are not documented with empirical evidence, it demonstrates the need to consider other affective factors that may contribute to the effectiveness of instructional interventions (see Chapter 5).

Table 3.2. Learning gain averages per semester

Semester	n	Learning Gain Average (%)	*p*	Effect Size
Fall 2021	27	6.12%	0.035	0.428
Spring 2022	22	1.84%	0.504	----
Fall 2022	32	11.23%	<0.001	1.01
Spring 2023	21	7.57%	0.001	0.863
Fall 2023	45	6.46%	<0.001	0.592
Spring 2024	27	7.42%	0.006	0.571

3.9. Conclusion & Implications

Instructional scaffolding is a beneficial tool to incorporate into any course curriculum. However, it is essential that instructors thoughtfully consider the appropriate methods and factors

to design, implement, fade, and assess scaffolding. In the context of this work, increased scaffolding opportunities were added in efforts to better revise the scale-themed curriculum in GC II. The scaffolding was carefully created, consulting literature and adapting such methodologies to best fit higher education settings while supporting scale skills development and proficiency in particular content areas. In this chapter, a quantitative approach utilized student learning gains to understand the effectiveness of the scaffolded intervention materials. Positive learning gain averages (with medium to large effect sizes) indicated the broad success of the revised materials in the context of the intervention. Yet, these results only provide a glimpse into the intervention's success overall. Qualitative and affective studies can offer additional insight into the effectiveness of the intervention.

3.10. References

(1) Taber, K. *Chemical Misconceptions - Prevention, Diagnosis, and Cure: Theoretical Background*, Vol. 1, Royal Society of Chemistry: London, **2002.**

(2) Van De Pol, J.; Volman, M.; Beishuizen, J. Scaffolding in teacher–student interaction: A decade of research. *Educ Psychol Rev.* **2010**, *22* (3), 271–296.

(3) Stone, C. A.; Forman, E. A.; Minick, N. *Contexts for Learning: Sociocultural Dynamics in Children's Development*; Oxford University Press: New York, **1993.**

(4) Vygotsky, L.S. In M. Cole, V. John-Steiner, S. Scribner and E. Souberman, *Mind in Society: The Development of Higher Psychological Processes;* Cambridge: Harvard University Press, **1978.**

(5) Wood, D.; Bruner, J. S.; Ross, G. The role of tutoring in problem solving. *Child Psychology Psychiatry*. **1976**, *17* (2), 89–100.

(6) Atkinson, R. C., & Shiffrin, R. M. Human memory: A proposed system and its control processes. In K. W. Spence & J. T. Spence, *The psychology of learning and motivation*: *II*. Academic Press, **1968.**

(7) G.A. Miller, The magical number Seven, plus or minus two: some limits on our capacity for processing information, in *Psychology of Communication: Seven Essays*, Harmondsworth: Penguin, **1968**, 21-50.

(8) Johnstone, A. H. Some messages for teachers and examiners: An information processing model, in *Research in Assessment VII: Assessment of Chemistry in Schools*, London: Royal Society of Chemistry Education Division, **1989**,23-29.

(9) Sweller, J.; van Merrienboer, J. J. G.; Paas, F. G. W. C. Cognitive architecture and instructional design. *Educational Psychology Review.* **1998**, *10* (3), 251–296.

(10) Myhill, D.; Warren, P. Scaffolds or Straitjackets? Critical Moments in Classroom Discourse. *Educational Review.* **2005**, *57* (1), 55–69.

(11) Stone, C. A. Should We Salvage the Scaffolding Metaphor? *Journal of Learning Disabilities.* **1998**, *31* (4), 409–413.

(12) Dawn, S.; Dominguez, K. D.; Troutman, W. G.; Bond, R.; Cone, C. Instructional scaffolding to improve students' skills in evaluating clinical literature. *American Journal of Pharmaceutical Education.* **2011**, *75* (4), Article 62.

(13) Joda, F. M. Effects of instructional scaffolding strategy on senior secondary biology students' academic achievement and retention in Taraba State, Nigeria. *Education Quarterly Reviews.* **2019**, *2* (2), 269–275.

(14) Kim, N. J.; Belland, B. R.; Lefler, M.; Andreasen, L.; Walker, A.; Axelrod, D. Computer-based scaffolding targeting individual versus groups in problem-centered instruction for STEM education: Meta-analysis. *Educ Psychol Rev.* **2020**, *32* (2), 415–461.

(15) Richardson, J. C.; Caskurlu, S.; Castellanos-Reyes, D.; Duan, S.; Duha, M. S. U.; Fiock, H.; Long, Y. Instructors' conceptualization and implementation of scaffolding in online higher education courses. *J Comput. High Educ.* **2022**, *34* (1), 242–279.

(16) Pea, R. D. The social and technological dimensions of scaffolding and related theoretical concepts for learning, education, and human activity. *The Journal of the Learning Sciences.* **2004**, *13* (3), 423–451.

(17) Puntambekar, S.; Hubscher, R. Tools for scaffolding students in a complex learning environment: What have we gained and what have we missed? *Educational Psychologist.* **2005**, *40* (1), 1–12.

(18) Stone, C. A. The metaphor of scaffolding: Its utility for the field of learning disabilities. *J Learn Disabilities.* **1998**, *31* (4), 344–364.

(19) Lin, T.-C.; Hsu, Y.-S.; Lin, S.-S.; Changlai, M.-L.; Yang, K.-Y.; Lai, T.-L. A review of empirical evidence on scaffolding for science education. *Int. J. of Sci and Math Educ.* **2012**, *10* (2), 437–455.

(20) Lajoie, S. P. Extending the scaffolding metaphor. *Instr. Sci.* **2005**, *33* (5–6), 541–557.

(21) Sanaeifar, S. H.; Nafari, F. N. The effects of formative and dynamic assessments of reading comprehensions on intermediate EFL learners' test anxiety. *TPLS.* **2018**, *8* (5), 533.

(22) Palincsar, A. S.; Brown, A. L. Reciprocal teaching of comprehension-fostering and comprehension-monitoring Activities. *Cognition and Instruction.* **1984**, *1* (2), 117–175.

(23) Shepard, L. A. Linking formative assessment to scaffolding. *Educational Leadership.* **2005**, *63* (3), 66–70.

(24) Johnstone, A. H. The development of chemistry teaching. *J. Chem. Educ.* **1993**, 70 (9), 701.

(25) Graham, K. J.; Bohn-Gettler, C. M.; Raigoza, A. F. Metacognitive training in chemistry tutor sessions increases first year students' self-efficacy. *J. Chem. Educ.* **2019**, *96* (8), 1539–1547.

(26) Muteti, C. Z.; Zarraga, C.; Jacob, B. I.; Mwarumba, T. M.; Nkhata, D. B.; Mwavita, M.; Mohanty, S.; Mutambuki, J. M. I realized what I was doing was not working: The influence of explicit teaching of metacognition on students' study strategies in a general chemistry I course. *Chem. Educ. Res. Pract.* **2021**, *22* (1), 122–135.

(27) Gerlach, K.; Trate, J.; Blecking, A.; Geissinger, P.; Murphy, K. Valid and reliable assessments to measure scale literacy of students in introductory college chemistry courses. *J. Chem. Educ.* **2014**, *91* (10), 1538–1545.

Chapter 4

Insight into Students' Chemistry Content Knowledge, Scale Skills, and Instructional Scaffolding via Multi-Dimensional Interviews

"We cannot observe how people have organized the world and the meanings they attach to what goes on in the world. We have to ask people questions about those things. The purpose of interviewing, then, is to allow us to enter into the other person's perspective."[1]
– M.Q. Patton

4.1. Introduction

The nature of qualitative research leads to the collection of a rich source of data to provide additional layers to support and/or clarify claims and findings resulting from quantitative approaches. So far, the quantitative methods utilized in this project have been discussed. These quantitative measures provided evidence for the targeted intervention and effectiveness of the scale-themed intervention via learning gains. Yet, especially when studying human subjects (i.e. students), quantitative methods alone cannot be expected to provide a comprehensive or an in-depth analysis. Thus, qualitative methods can be utilized to collect more data and gain insight into students' thoughts and problem-solving processes, which are not easily captured by quantitative measurements.

Qualitative research provides an opportunity for the researcher to delve deeply into the subject or phenomenon of interest. Due to the robust nature of the methodologies and data collected from qualitative research, it is important to design and carry out qualitative studies that are bound and intentional. In some cases, the use of theoretical frameworks, which are systems, goals, theories, and assumptions that can be used to guide research methodologies and analysis is often employed in qualitative studies to substantiate any claims or findings.[2,3] In terms of analysis, qualitative data is commonly analyzed using a method termed *coding*. Coding refers to assigning data with distinct designations that capture the relevant essence or observations

embedded in the dataset.[4] These codes can be analyzed further to identify emerging patterns, trends, etc. in the data.

As in quantitative research, it is necessary to demonstrate the validity and reliability of research findings, especially with codes. There are different methods to employ to demonstrate the rigor and trustworthiness of qualitative research findings.[5] One method common method is inter-rater reliability (IRR). IRR is when the coder/rater and other colleagues compare, discuss, and reach consensus on the codes or findings. IRR demonstrates the validity and reliability of findings and minimizes any bias that may influence the interpretation of results.[6]

4.2. Research Context

Student interviews were employed to further support findings related to the overall investigation of scale and to gain deeper insight into student problem-solving and chemistry knowledge. In this way, a set of three robust student semi-structured, think-a-loud interviews were employed to serve the following goals: (1) to gain insight into student content area knowledge in GC II (2) to understand students' learning gains and scale knowledge in the context of chemistry and (3) to further assess the power of the instructional scaffolding implemented into the course. Due to the nature of these aims, a theoretical framework was not utilized in the methodology, as the interviews were mainly intended to supplement the investigation of the intervention's effectiveness.

In this chapter, the creation of the interview sets will be discussed along with the methods of data collection and transcription. The following research question will be addressed:

How do the responses to the interview prompts reflect students' scale literacy and scale skills?

4.3. Creation of Interview Sets

Considering the three goals previously stated, interview sets and prompts were designed based off a multi-dimensional model (Figure 4.1) to collect meaningful, rich data that simultaneously fulfilled the purpose of the interviews. This included collecting student data related to GC II content area knowledge, scale concepts, and the level of complexity at which tasks were presented and completed. The final interview sets were separated by the content areas covered in GC II. The interview decks will be referred to by the titles "solutions and kinetics," "equilibria," and "thermodynamics and electrochemistry" for ease and clarity throughout this chapter. Once all interview sets were created, the prompts were mapped alongside the topics covered in the course by a course instructor to ensure there were no major oversights in covering all the subcontent areas and/or scale elements embedded.

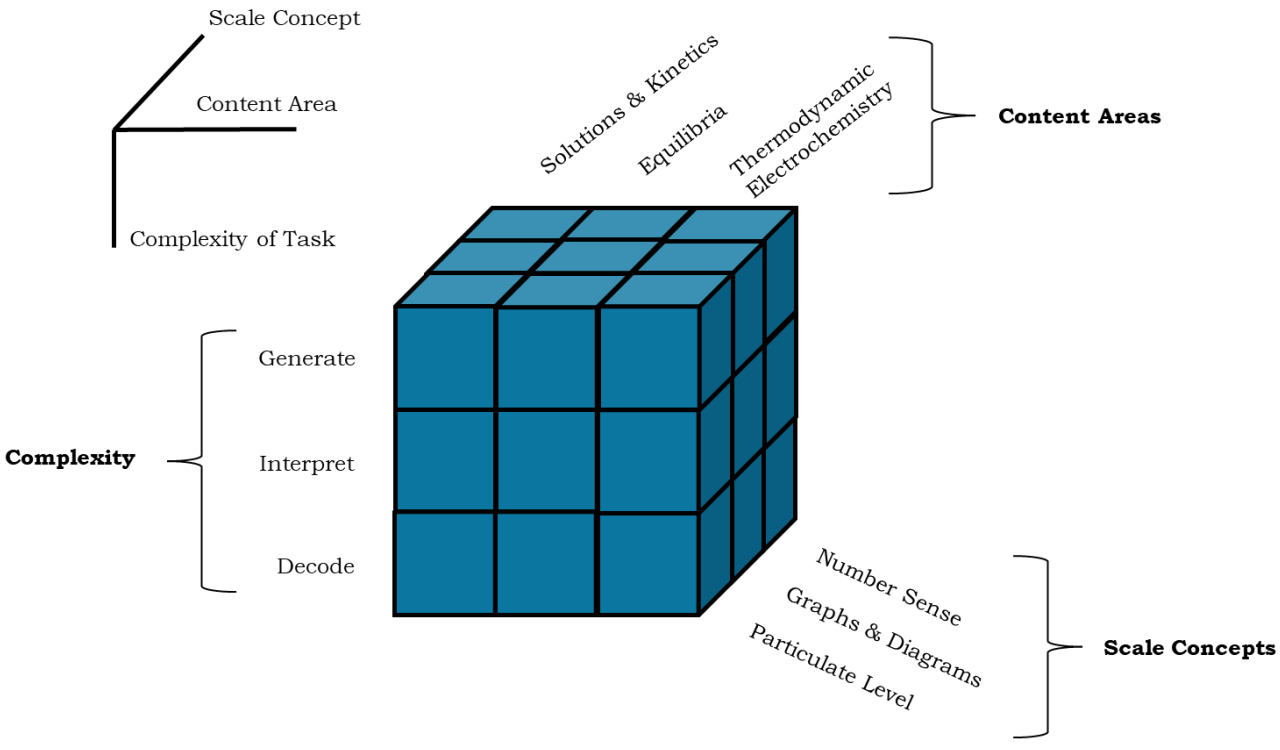


Figure 4.1. Representation of multi-dimensional interview protocol

Dimension 1: Content Areas

As one goal was to gain insight into student problem-solving and understanding of the content areas covered in GC II, three interview sets were created. Each set focused on specific content areas covered in the course, and the breakdown of topics covered in each set naturally aligned with the content covered on each of the three exams. The first interview covered topics related to solutions and kinetics (exams 1-2). The second interview set covered all topics related to equilibria, including general, acid-base, and solubility (exams 2-3). The third interview covered thermodynamics and electrochemistry (exams 3-4). All interview sets can be found in Appendix C.

Dimension 2: Complexity

Another goal was to further assess the efficacy of the scaffolding implemented into the course. One way to do this is by creating linked interview prompts that range in complexity. Linked prompts refer to two or three prompts covering the same sub content area or concept but differ in the difficulty of the prompt.

By analyzing the responses to the linked prompts, it can highlight areas where students may benefit from more support and lead to even more increased instructional scaffolding in that content area or scale concept. There were three levels of complexity incorporated into the prompts: decode, interpret, and generate (Figure 4.2). Broadly, the three levels of complexity align with the idea of providing more support at the start of scaffolding (decode) and providing less support at the completion of scaffolding (generate). The three levels also align with the Trajectory of Scale Development,[7] where a decode prompt aligns with novice type abilities in the trajectory and a generate prompt aligns with developing/expert abilities. In summary, a decode prompt broadly prompted students to describe scenarios depicted using explicit features.

Interpret style prompts were not as broad and prompted students to incorporate both explicit and implicit features or make connections. A generate style prompt asked students to generate their own diagrams, graphs, or values based on information that can be implicitly gathered from the information provided.

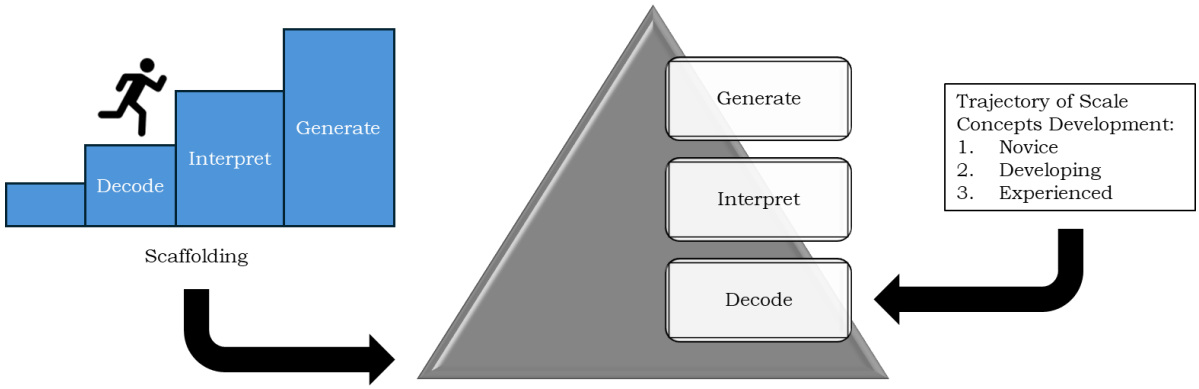


Figure 4.2. Complexity of interview prompts – alignment with scaffolding and Trajectory of Scale Concepts Development (Tretter, et al.)[7]

Dimension 3: Scale Concepts

To gain insight into students' scale abilities in the context of chemistry, the third dimension of the interview sets focused on various scenarios where the scale concepts embedded in chemistry are needed to fully understand and successfully complete the prompt. Aligning the Johnstone's Triangle[8] (macroscopic, symbolic, and subatomic levels) and the targeted scale concepts (unitizing, number sense, and understanding quantity) mentioned previously in Chapter 2, the three scale elements integrated into the prompts were related to particulate diagrams, number sense, and graphs and diagrams (Figure 4.3). At least one of the three scale elements was incorporated into each prompt.

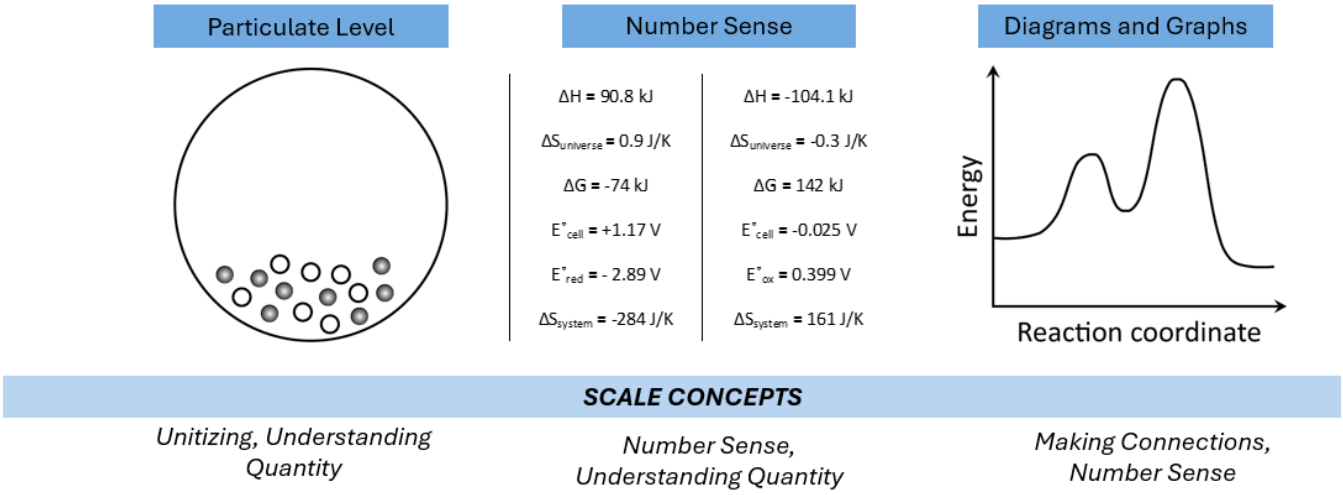


Figure 4.3. Scale concepts incorporated into interview prompts

4.4. Interview Sample and Matrix

Recruitment involved in-class announcements and email to all GC II students. Participants were selected / sorted based off the following matrix where the sample was split by sex and performance on the exam relevant to the topics covered in the interview sets. Exam scores and/or relevant content specific subscores were used to determine the performance assignment.

The interviews took place in an approximately 90 minute – 120 minute (depending on the interview set) timeframe. Students were encouraged to write on the provided paper copies of the prompts and share any thoughts they had aloud. Before beginning, students completed a training activity with the author which demonstrated the level of verbal articulation expected for the think-a-loud interviews. The training activity consisted of the author describing features of campus maps and generating maps from memory (Appendix C). Audio and video data of the students' verbal and written responses were captured. All participants provided signed consent under the Institutional Review Board (IRB #14.404). Upon completion of each interview, to

address misconceptions, the researcher went over all the answers to the prompts in varying levels of detail based on the students' performance. Participants were given a free ACS General Chemistry study guide for participating.

In Fall 2021 and Fall 2022, Solutions and Kinetics interviews were conducted until the data collection reached saturation[4] and/or the matrix requirements were satisfied. Starting in Spring 2022 and ending in Fall 2023, Equilibria and Thermodynamics & Electrochemistry interviews were conducted. Given the vast amount of data available through the interviews, it was determined to focus on one content area / interview set, for one scale component across all three stages of complexity. Given the newly modified curriculum and solutions and kinetics interview sets started at the same time and the importance of particulate diagrams in chemistry, prompts from the solutions and kinetics set involving particulate diagrams across all complexity levels were studied and analyzed. Note that while not every individual prompt incorporated a particulate diagram, it may have been included in analysis because the prompt was linked to another prompt that did include a particulate diagram directly.

Table 4.1. Interview matrix for solutions and kinetics interviews

Solutions and Kinetics Interview Set		
Performance Group	**Males**	**Females**
High	4	4
Middle	5	6
Low	4	4

The interview matrix for the solution and kinetics interviews is reported in Table 4.1. Every interview participant completed all twenty prompts in the solutions and kinetics deck except for three individuals who had to stop the interview early due to overlap in their personal

schedules. Only the complete responses from these three students (Miguel, Vera, and Krista) were coded and analyzed.

4.5. Data Analysis

Figure 4.4 depicts the overall workflow of the data analysis. Each segment will be discussed in further detail.

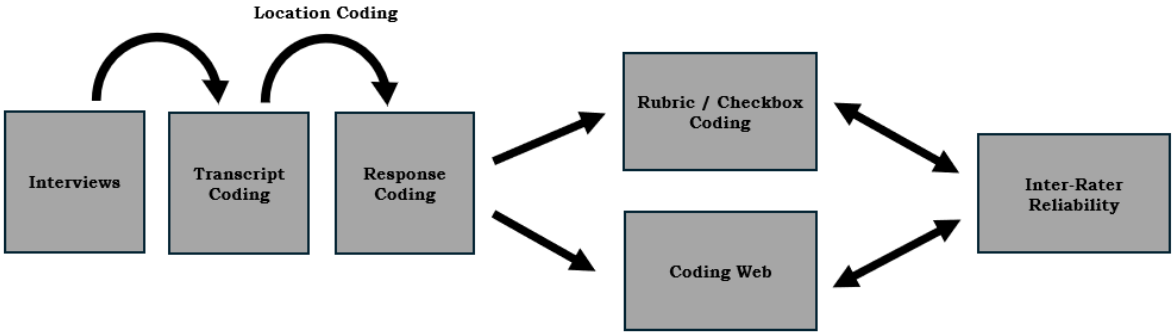


Figure 4.4. Interview data analysis workflow

4.5.1. Data Transcription

All interviews were transcribed via the transcription service, Otter.Ai, and further edited by the author. Due to the nature of the interview, many students used nondescriptive words or generic pronouns to describe the features of the prompts and their drawings and responses. This became challenging when evaluating the audio transcription as it was unclear what the students were specifically referring to. Location coding was added within the transcripts to clarify the ambiguous words, phrases, and hand gestures. This was done by the researcher reviewing the audio and video recordings simultaneously throughout the transcription process. A summary of the location codes inserted into the transcriptions is reported in Appendix D.

4.5.2. Coding and Inter-Rater Reliability

Coding was a very involved process due to the number and variety of unique responses for each interview prompt. While coding, two different types of coding schemes were employed to best represent the patterns within the data. The coding scheme styles were termed (1) the coding web and (2) the checkbox rubric. Each individual prompt only involved the use of one of the coding scheme styles. Selecting the appropriate coding scheme for a particular prompt was dependent on the complexity of the prompt and the nature of the responses. Responses for decode prompts and some interpret prompts were best captured with the use of coding webs due to their more open-ended nature. As the level of complexity and involvement of the prompts increased, coding webs were no longer the most suitable method of coding. Instead, rubric checkbox coding schemes were utilized for some interpret and all generate prompts. Using the generate prompts as a general example, students were required to draw diagrams that connected to provided values/plots. The large variation and level of detail students provided not only in their explanations, but also in the depiction of their generated images, required a set of guidelines much like a rubric. All coding schemes are reported in Appendix D.

Initially, the author inductively created the resulting coding schemes. After which, a semi-randomized sample of codes was given to a team of 3-5 chemical education researchers for inter-rater reliability (IRR). The first round of IRR involved the author providing the selected sample's transcripts, written responses (if applicable), and the utilized coding scheme. The members of the IRR group were asked to use the given coding scheme and assign codes. After, the entire group met to discuss the level of agreement between members. Often in this process, the author received feedback that warranted revisions on the initial coding schemes. If that

occurred, the researcher would make the necessary revisions and perform another round of IRR until consensus of the codes were reached.

While IRR was imperative in building the reliability of the codes, in certain cases, IRR was essential in the creation of the coding schemes. For example, for Prompt 15, the robust response data collected led to challenges in narrowing the focus and capturing the essence of the data. In this case, a coding rubric checkbox was created collaboratively. The IRR members each created their own coding rubric. Then, the group met to compare each other's coding schemes, and, ultimately, the final coding scheme was created using a combination of each researcher's contributions. By comparing similarities in the coding schemes, key areas within the prompt's responses were identified and refined the focus of the analysis of that prompt.

4.6 Results and Discussion

In the first portion of the results section, key findings from the analyzed prompts will be summarized. There were no observable differences in responses or problem-solving behaviors by sex, so results will be discussed as a whole group or by performance. Location codes and coding schemes (Appendix D) can be used for reference to aid in understanding the codes and parentheticals used in the results and discussion section. A total of 12 prompts were analyzed; Table 4.2 summarizes the characteristics of each prompt studied in terms of the content area, scale connection and level of complexity. Note that all students' names within are pseudonyms.

Table 4.2. Characteristics of the solutions and kinetics prompts analyzed

Prompt	Content Area	Scale Connection	Complexity Level
1	Solutions	Particulate Diagram	Decode
2	Solutions	Particulate Diagram	Decode
3	Solutions	Particulate Diagram	Decode
4	Kinetics	Particulate Diagram	Decode
8	Kinetics	Graph	Decode
9	Solutions	Particulate Diagram Graph	Interpret
10	Solutions	Number Sense	Interpret
12	Kinetics	Particulate Diagram Graph	Interpret
14	Solutions	Particulate Diagram	Generate
15	Solutions	Particulate Diagram Graph	Generate
16	Solutions	Particulate Diagram Number Sense	Generate
17	Kinetics	Particulate Diagram Graph	Generate

4.6.1. Prompt 1 (Solutions: Decode)

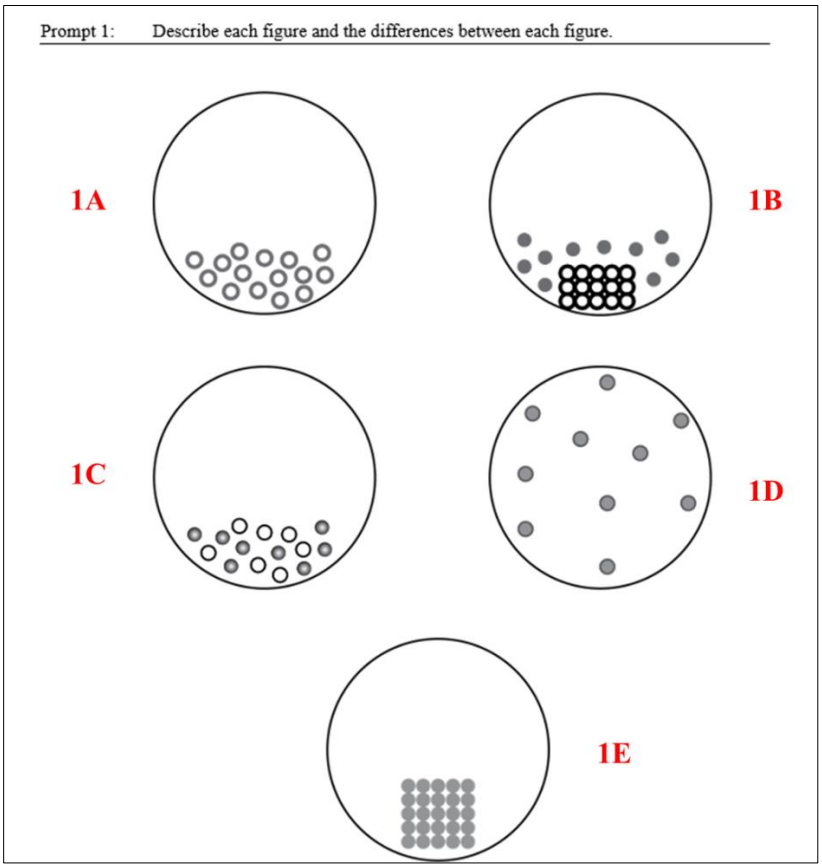


Figure 4.5. Prompt 1 with relevant location codes

The students were asked to describe the particulate diagrams provided in prompt 1 (Figure 4.5). While the prompt was open-ended intentionally, it was expected that students would describe the states of matter of the diagrams (1A = liquid, 1B = heterogenous mixture, 1C = homogenous mixture, 1D = gas, 1E = solid). Indeed, for diagrams 1D and 1E, all 27 students identified the correct state of matters, and most students identified correctly in 1A, 1B, and 1C (Table 4.3). All students who identified the states of matter incorrectly were part of the low performance group and classified 1A and 1C as gases and 1B as gas and liquid. An unanticipated finding was students mentioning the saturation of the liquids provided in 1A-1C at

this stage of the interview. Six students (Nadja, Marshall, Robyn, Maddie, Andrew, and Arthur) across all three performance groups discussed saturation. Another unanticipated finding was a high performing student discussing Ksp correctly in the context of 1B.

"This (1B) looks like a saturated solution of sort, or potentially just a solid and a solution, because I don't see any particles of this solid (1B_p2) floating in it. So, it might not be dissolved at all, or it might have an extremely low KSP, for example. This one (1C) here is different from this one (1B), but the same as these (1A)(1B) because it's also a liquid. But it looks like a solution that is not saturated yet, because there's different types of particles in it. And you don't see a solid at the bottom. So, it's hasn't met its maximum solubility, or everything can dissolve at least." ***– Marshall (high performance group)***

Table 4.3. Code counts for prompt 1 responses

Prompt	States of Matter (Correct)	States of Matter (Incorrect)	Saturation (Correct)	Saturation (Incorrect)
1A	26	1	5	1
1B	25	2		
1C	26	1		
1D	27	0	----	----
1E	27	0	----	----

4.6.2. Prompt 2 (Solutions: Decode)

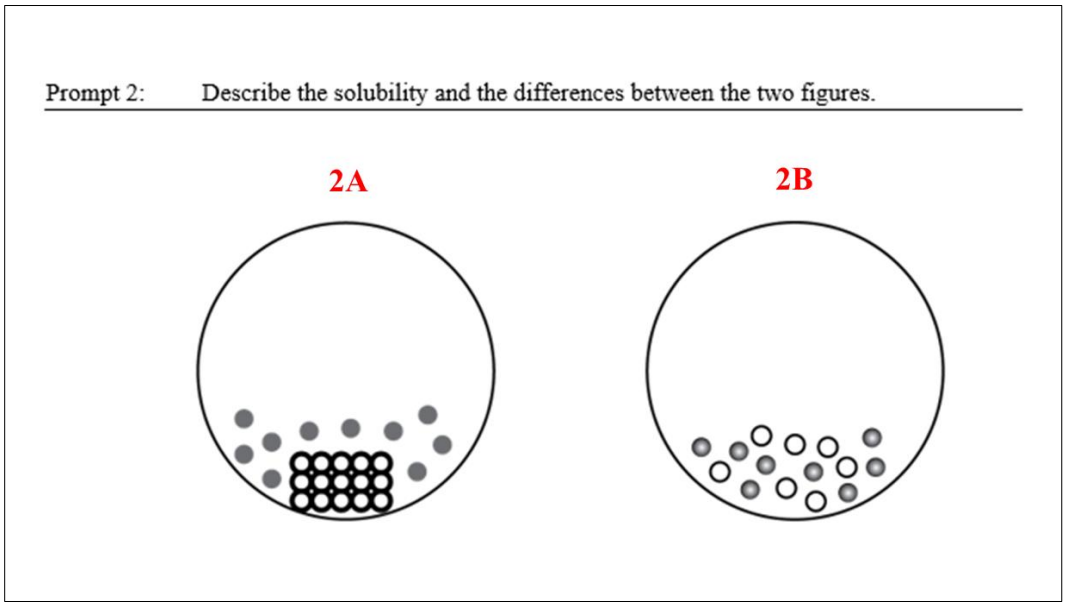


Figure 4.6. Prompt 2 with relevant location codes

In prompt 2 (Figure 4.6), students were asked to describe the solubility differences between two particle diagrams (2B depicts greater solubility than 2A). All 27 participants identified the solubility differences correctly. Again, the concept of saturation was discussed across all performance groups. Nadja, Andrew, and Arthur all discussed saturation correctly in prompt 1 and again in prompt 2. It is a promising finding that GC II students are considering the saturation of solutions when provided with solutions with and without precipitation, as this requires a deeper level of understanding embedded within the images than simply identifying the surface features or states of matter.

4.6.3. Prompt 3 (Solutions: Decode)

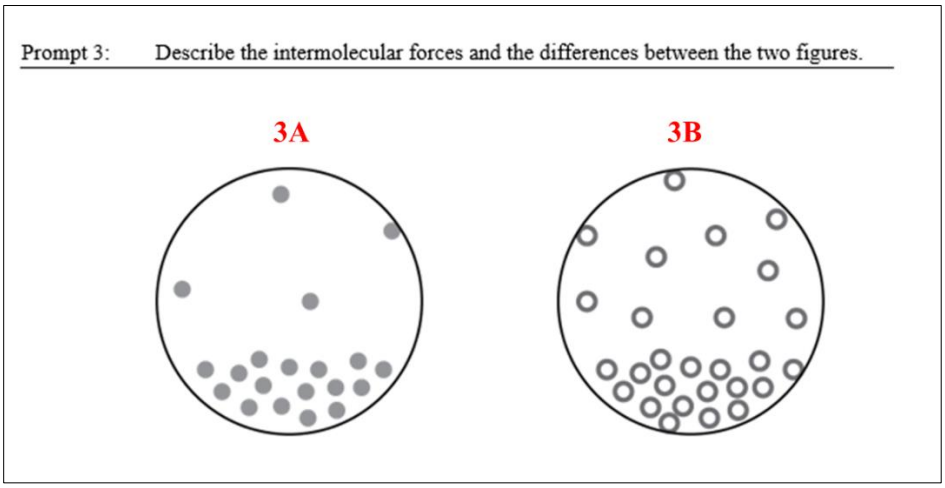


Figure 4.7. Prompt 3 with relevant location codes

In prompt 3 (Figure 4.7), students were asked to identify which particulate diagram depicted a substance with stronger intermolecular forces (IMFs). There were no observable differences between performance groups for identification of the IMFs. Seventeen students correctly identified 3A as having stronger intermolecular forces (Table 4.4). All 17 participants employed the strategy of comparing the number of gas particles between the two images, reasoning fewer gas particles are associated with stronger IMFs. Of the 17 students, 5 students discussed volatility, and six students discussed vapor pressure while determining their answer. A few students (4) also discussed how 3A would require more energy / a higher temperature to become a gas than 3B. Ten students who did not select or incorrectly selected the image with stronger IMFs also employed the strategy of counting and comparing the number of gas particles in the images; however, their reasoning was reversed, stating that more gas particles are associated with stronger IMFs.

Table 4.4. Code counts for prompt 3 responses

3A Stronger IMPs	3B Stronger IMFs	Not determined	Compared Number of Gas Particles	Volatility	Vapor Pressure	Energy / Higher Temperature
17	5	5	26	5	6	4

4.6.4. Prompt 4 (Kinetics: Decode)

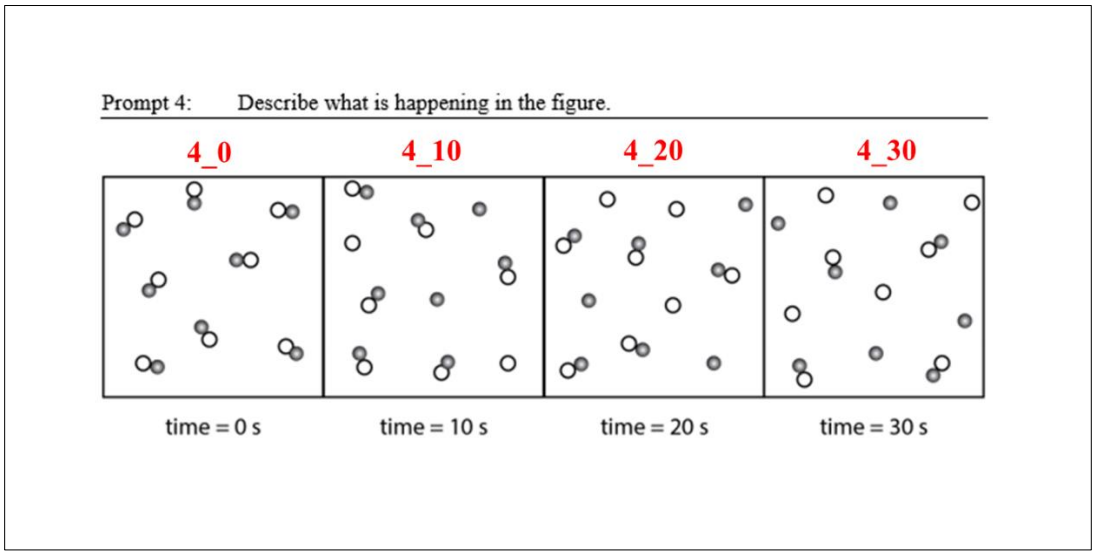


Figure 4.8. Prompt 4 with relevant location codes

In prompt 4, the students were asked to describe the decomposition of a substance over time. Ideally, students would make connections to concepts related to kinetics, such as half-life or rate. For prompt 4 (Figure 4.8), twenty students described the diagram as depicting molecules breaking / decomposing over time, as explicitly shown. Of the 8 students in the low performance group, only Andrew described and identified half-life correctly; the other low performance students only described the colors and time component of the diagrams or stated that the molecules were breaking/decomposing over time with no reference to half-life.

Andrew: "*So, looking at the figure we have looks like a complete molecule for all the particles in the first one (4_0), and then it looks like they're kind of splitting up as the figures go along. This is a half-life I believe, and so as the time elapses more of the molecules are breaking apart."*

Interviewer: "*So, you mentioned half-life, are you able to identify the half-life at all?"*

Andrew: **counting* "It would be 30 seconds."*

Fifteen students discussed half-life. Five (4 middle performers and 1 high performer) of the fifteen students articulated a misconception related to half-life related to the definition or identifying the point on the diagram. Ten students identified the half-life of the sample correctly (at t = 30 s) with no misconceptions. In summary, as seen in the former prompts, the low performance group students did not expand or describe the scenarios beyond what features are explicitly shown in the diagrams in comparison to the middle and high performing students. Table 4.5 shows the counts for the most frequently used codes.

Table 4.5. Code counts for prompt 4 responses

Code	Number of Students
Molecules breaking/decomposing	20
Discusses half-life	15
Half-life misconception	5
Half-life correctly identified	10

4.6.5. Prompt 8 (Kinetics: Decode)

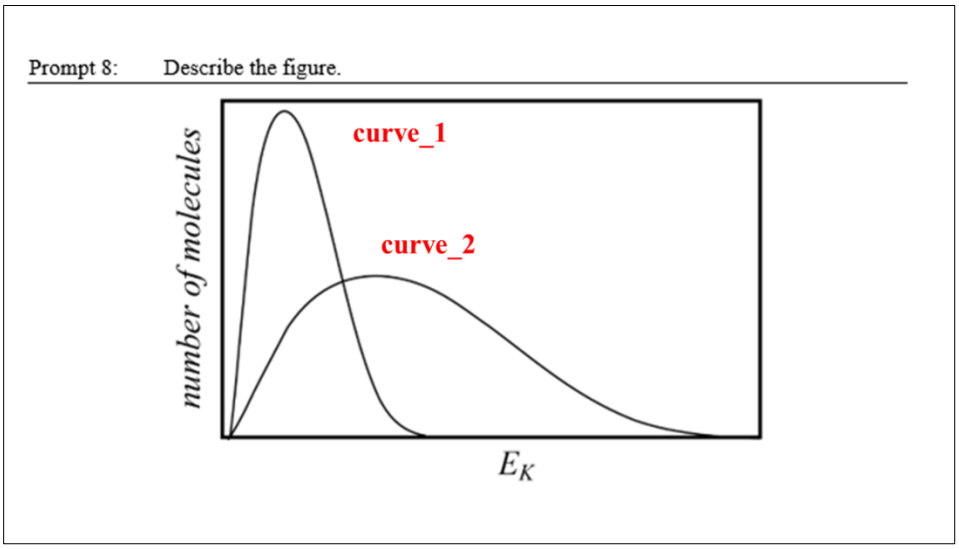


Figure 4.9. Prompt 8 with relevant location codes

Prompt 8 (Figure 4.9) provided students with the opportunity to discuss a Maxwell-Boltzmann distribution. Temperature, average kinetic energy, number of molecules, and speed are all important aspects to consider when interpreting a Maxwell-Boltzmann distribution. However, most of the student responses were lacking at least one or more of these aspects. Additionally, upon the initial presentation of the prompt, most students needed probing before providing any response. A common prompt by the author during interviews was asking students to describe the x-axis. Responses ranged from unsure, kinetic energy, energy (general), rate, or activation energy.

There were several misconceptions observed; one frequent misconception was treating the distribution as an energy diagram by interpreting the two curves in relation to faster or slower steps/reactions, energy needed to react, and rates. Even in one case, the x-axis was treated as time. Counts for ideas about energy diagrams being applied to the Maxwell-Boltzmann distribution are reported in Table 4.6.

Table 4.6. Code counts for prompt 8 responses related to energy diagram and MBD misconceptions

Graph Interpretation		**Curve 1**		**Curve 2**	
Energy Diagram	3	Slower rate	2	Slower rate	3
X-axis as time	1	Faster rate	5	Faster rate	3
		Lower activation energy	0	Lower activation energy	4
		Higher activation energy	3	Higher activation energy	2

"So, on the y axis, we have number of molecules, and on the x axis we have um Ek, I'm trying to remember what that symbol is. But this one (prompt 8) looks a little similar to the last diagram [prompt 7, energy diagrams] where we have a higher peak on the left side, and we have a kind of a lower peak on this side. So again, I think this one would be the one (8_pk1) with the higher activation energy, and this one (8_pk2) will be the one with a smaller activation energy. But still this one (8_pk2) is the faster reaction. It's happening a lot faster, and the reaction in this peak (8_pk1) is happening a lot slower." ***– Brooke (low performance group)***

Five students correctly mentioned temperature in relation to the distribution, and one student recalled it was a distribution plot. However, these students seemed to rely on recalling this information rather than truly understanding and explaining the concepts further in connection with the plot.

"Yeah, like a different temperature because I just remember that these two (curves) are like different temperatures just because of how high and how long it will be." ***– Nathan (low performance group)***

"I'm not even sure what Ek means when I think about it. But I can see that something or no, you know what this is distribution of? This is like the Multi... Max Boltzmann something like that distribution graph. So I think I would at least know where to go from here. I'd like to look up what I needed to look up." ***– Nicole (middle performance group)***

The three students who explicitly classified the plot as an energy diagram were low performers. However, overall, across all performance groups, students struggled to interpret the surface features of the plot. No student was able to provide a fully correct response. This indicates that students may need more explicit instruction on the concepts and features of a Maxwell-Boltzmann. In Rodriguez et al.,[9] it was found that students who view a Maxwell-Boltzmann distribution as a distribution rather than a process exhibited better understanding and predicting behaviors. While in this sample most students did not recognize the distribution, efforts in instruction to emphasize how distributions can be interpreted may improve understanding.

4.6.6. Prompt 9 (Solutions: Interpret)

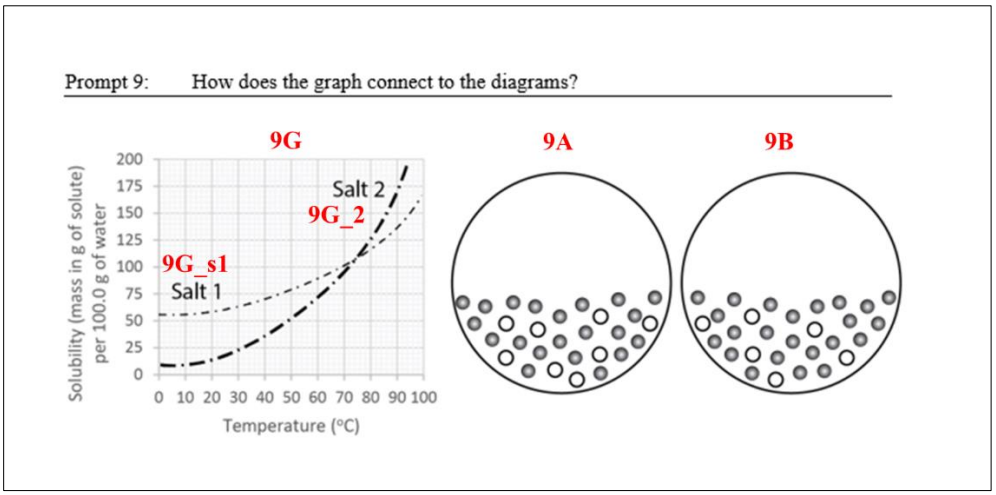


Figure 4.10. Prompt 9 with relevant location codes

In prompt 9 (Figure 4.10), students were asked to make connections to the particulate diagrams and the solubility curve provided. Some examples of possible connections that could be drawn include comparing the relative solubility between the two salts at a given temperature or discussing how the solubility of a particular salt changes with temperature or solute added.

The interpretation of the provided graph and the particulate diagrams were coded independently. In terms of the solubility curve, 24 participants correctly identified the overall concept that the solubility of two salts were increasing with increasing temperature (Table 4.7). Of the three students (middle and low performers) who incorrectly interpreted the graph, there was a common misconception about the amount of water as not constant.

"Well, they're almost... the difference is that the grams of water are there when they're applied at same temperature. I think they increase and the same, the same grams water that it's added, so I don't think I can tell the difference between those two. The only difference is the amount of water that it's added. Yeah. That's why I can't tell the difference. Now that I look here when they reach the 75 degrees they're the same amount of water but the difference is that this one (9G_s1) needed a little bit of water more. Little bit more of water. The salt number 1. And yeah, two. Yeah, as the temperature increased, it just needed a little bit more water. But compared to the salt number two, it (9G_s2) needed way more water than the salt number 1." ***-Miguel (low performance group)***

For connecting the particulate diagrams to the solubility curve salts, a common strategy (21 students) involved counting and comparing the number of solute and solvent particles. Three low performance group students did not count the particles, and they all determined that both particle diagrams were demonstrating the same solubility at 80°C. Thirteen students connected the diagrams to the solubility curve using a specific temperature.

Table 4.7. Code counts for prompt 9 responses

Code	Number of Students
Correct graph interpretation	24
Incorrect graph interpretation – water is not constant	3
Counting and comparing solvent and solute particles	21
Diagrams represent same solubility at ~80-90°C	3
Correct solubility connection at a specific temperature	13
Saturation – correct	4
Saturation – incorrect	2

Interestingly, more students discussed saturation correctly in earlier prompts (1 and 2) where the saturation of the diagrams was not as relevant. Yet, in this prompt, where saturation of solutions is more relevant and embedded within the interpretation of the solubility curve, fewer students (4) discuss saturation at all, let alone correctly (2).

This suggests that students may be better at connecting more advanced topics, such as saturation, with more simplified drawings and fewer information sources to incorporate; or students may be experiencing stress on their cognitive load by presenting the particulate diagrams and solubility curve together. Also, the method of scaffolding used for the solution diagrams and incorporating particulate diagrams may not be sufficient. Therefore, in practice, it may be beneficial for students to introduce these elements in a scaffolded manner.

4.6.7. Prompt 10 (Solutions: Interpret)

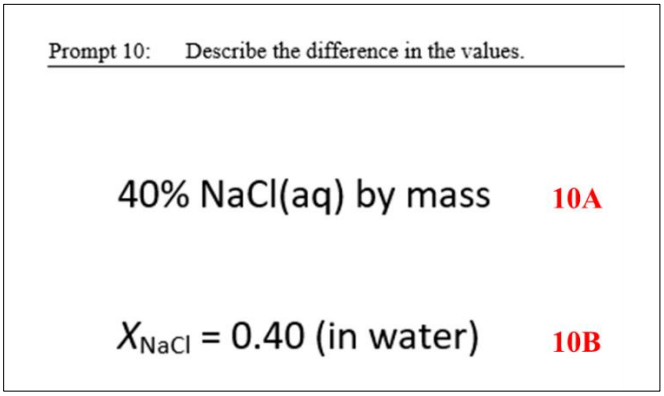


Figure 4.11. Prompt 10 with relevant location codes

The key differences for students to discuss in prompt 10 involve the interpretation between two values used to describe concentration (percent mass (10A) vs. mole fraction (10B)). In prompt 10 (Figure 4.11), the mass percent value was coded independently of the mole fraction value. In general, there were meaningful correct interpretations for the mass percentage than the

mole fraction (Table 4.8). All students that provided a meaningful interpretation for the mole fraction value were from the high-performance group. Ten students provided an ambiguous (7) or incorrect (3) interpretation mass percentage. When an ambiguous interpretation was given, students understood the solution to be made up of a solute and solvent and provided a general ratio in terms of percentages (i.e. 40% solute, 60% solvent). All three of the incorrect interpretations were linked with the misconception that the mass percentage was determined based on the amount of water present (i.e. the denominator of the mole fraction is in terms of the solvent, not total solution mass).

For the mole fraction value, 14 students provided an ambiguous (7) or incorrect (7) interpretation. Most of the incorrect interpretations (7) were linked with misconceptions about the mole fraction being out of total moles of solvent rather than total moles of solution. Interestingly, ten students believed the two values to be the same despite the use of different symbols and language between the mass percent and mole fractions presented in the prompt. Also, the eight students to provide meaningful interpretations about the mass percent value were not the same four students who provided a meaningful interpretation about the mole fraction value. All four students to provide a meaningful mole fraction interpretation were high performing students.

Table 4.8. Counts for codes related to value interpretation in prompt 10

	Mass Percent	Mole Fraction
Meaningful Interpretation	8	4
Surface Level Interpretation	3	2
Incorrect Interpretation	3	7
Ambiguous Interpretation	7	7
Same Value	10	

This prompt was created to probe further into number sense skills associated with solutions. Comparing the findings in this prompt to the other prompts related to solubility with particulate diagrams present, it is evident that students have weaker number sense when provided with values instead of solubility diagrams.

4.6.8. Prompt 12 (Kinetics: Interpret)

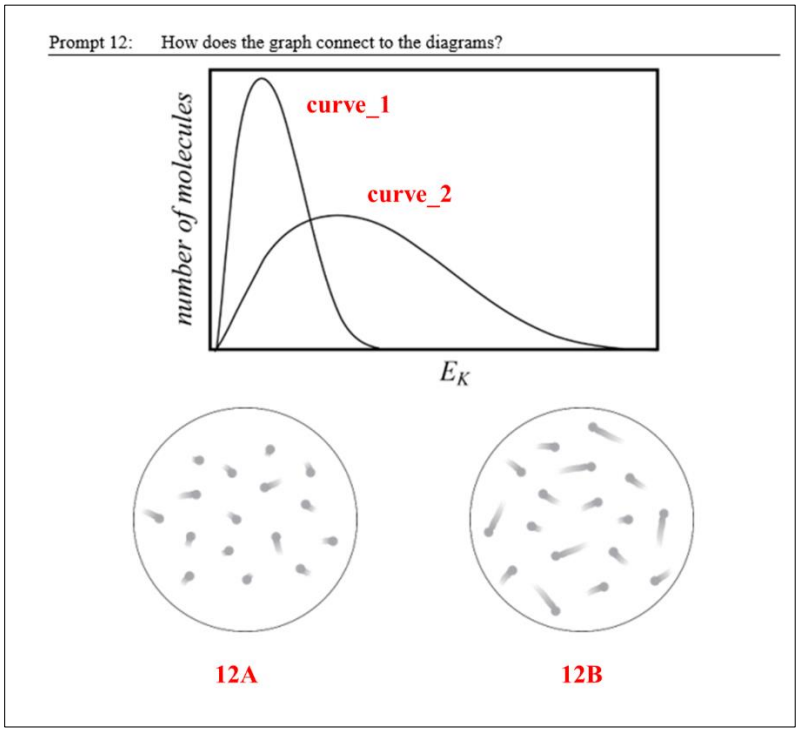


Figure 4.12. Prompt 12 with relevant location codes

Prompt 12 (Figure 4.12) was linked to prompt 8 with the main difference being the addition of particle diagrams being presented with a Maxwell-Boltzmann distribution. Interestingly, it appeared that the particle diagrams being present helped students better understand aspects of the MBD that they did not know earlier in Prompt 8.

"Um I know it's [x-axis] something to do with energy. I think its energy potential? ...But the diagram definitely helped like understand that graph more than without the diagram." – ***Andrew, low performance group***

Furthermore, one high performing student showed misconceptions in prompt 8, but in prompt 12, with the use of the particle diagrams, was able to provide the most correct response out of all participants (Table 4.9). Overall, students were able to describe the particle diagrams' explicit features of the motion and speed of the particles. Despite the support the particle diagrams seemed to provide students, there was still a wide range of responses with many misconceptions when connecting the particle diagrams to the curves. One such misconception, as observed in prompt 8, was treating the provided distribution as an energy diagram. Even when describing the Maxwell-Boltzmann distribution as an energy diagram, misconceptions emerged related to treating the x-axis as time, which has been observed in previous work.[10]

By assessing prompt 8 and prompt 12 together, there was gained insight into what type of support students may need when learning about MBD and other graphs. Observations suggest particulate diagrams would be one type of support. Additionally, it may be beneficial to scaffold the introduction of the MBD plot and related particulate diagrams to prevent cognitive overload.

Table 4.9. Comparison of Marshall's responses between prompt 8 and prompt 12

Marshall's Response (Prompt 8)	Marshall's Response (Prompt 12)
This is a Maxwell Boltzmann distribution, I believe. And you see that the number of molecules at a certain energy levels, primarily what we're thinking about. So if I look at this bottom curve (8_pk2), primarily, you can see that they have... it has a higher number of molecules at a higher energy level, as opposed to this taller graph (8_pk1) where the energy is overall pretty low. Most of the molecules are sitting at this low energy level. And that would make them well, I guess. I think this can depend on temperature. So this (8_pk2) would be at a higher temperature, these molecules overhead overall have more energy, whereas there's more molecules (8_pk1) in that lower energy level.	*Um, in these particle diagrams, the streaks or lines (tails) behind them are commonly used to represent the kinetic energy. So at least, I can't exactly say what counts is low and high. But I can tell that this one on the right (12B) has higher kinetic energy, or average higher kinetic energy. Average, because say this particle right here (12B_p_short), doesn't have higher kinetic energy than this one here (12A_p_long). But overall, with all these really long streaks (12B_tails), the particles moving faster, say overall, this one (12B) has a higher average kinetic energy, which is fitting to this portion of the distribution right here (12_pk2), whereas this one's (12A) fitting to this (12_pk1) and when I say that portion, I mean the entire slope. And that's because kinetic energy is lower in this slope (12_pk1), and we see a lot of them [molecules] with a lower kinetic energy. Whereas here (12_pk2), our average kinetic energy is towards the higher end in comparison to this (12_pk1). So I matched up this image (12B) with this plot right here (12_pk2), because there's a higher percentage of the particles in this diagram at a higher kinetic energy compared to the one on the left (12A).*

4.6.9. Prompt 14 (Solutions: Generate)

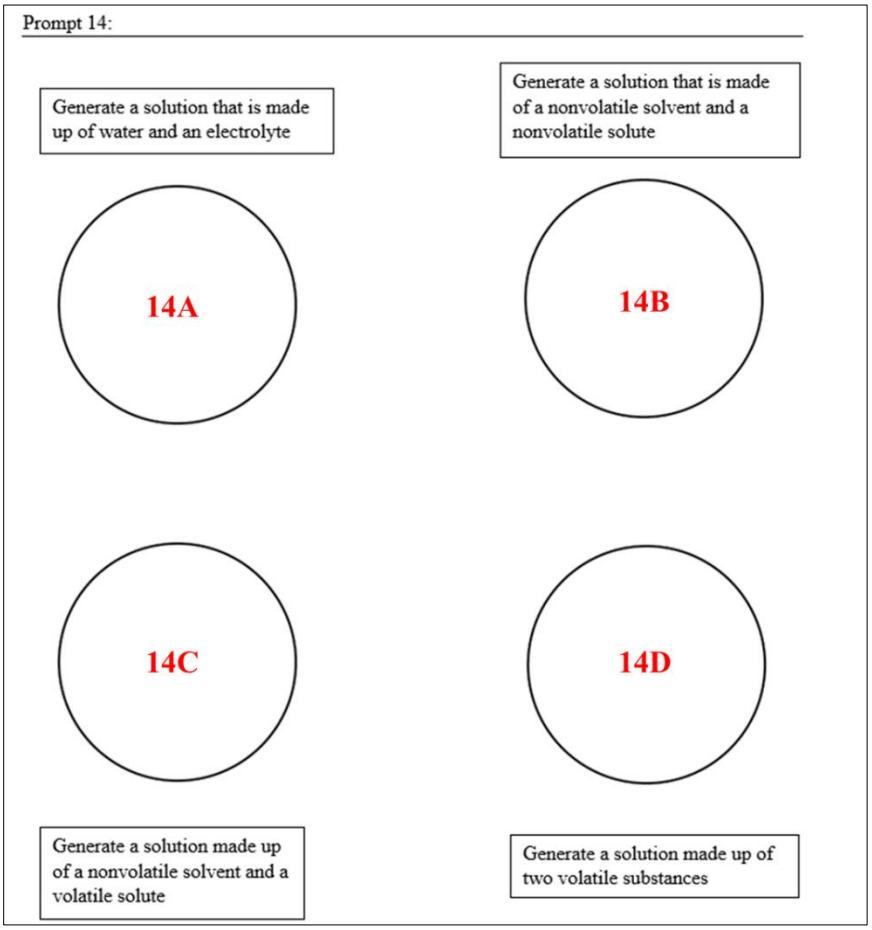


Figure 4.13. Prompt 14 with relevant location codes

Prompt 14 (Figure 4.13) was targeting students' abilities to draw their own particulate diagrams and connect knowledge of electrolytes and volatile solutions. 14A was coded separately from 14B-D as it was the only image focused on electrolytic solutions. There were some variations in how the electrolytic solutions were depicted (Table 4.10). Variations included using a generic species to represent the electrolyte with no dissociation or using a generic charged, dissociated species. Thirteen students gave NaCl as an example of an electrolyte, showing NaCl in both undissociated and dissociated forms, or drawing just one of the ions. One

plausible reason for NaCl being identified frequently as an electrolyte is due to that example being used often in lectures and the lecture activity booklet. The depiction of one of the ions suggests that students may think only one ion has electrolytic properties. Overall, there were no observable differences between the performance groups for the chosen method of depiction.

Table 4.10. Counts for codes related to drawings in prompt 14A

Drawing Code	Number of students
Generic particles, no dissociation	4
Generic particles, dissociation	4
NaCl, dissociation	7
NaCl, no dissociation	3
Sodium ion only	5
Chloride ion only	1

For 14B-D, volatility was described by 14 students as a substance that evaporates or changes phase readily. Twelve of the students who used that definition for volatility depicted all images correctly. Four students described volatility as reactivity, stating volatile solutions will react quickly, rather than changing physical state. All four of those students did not draw all the images correctly.

"So gut reaction is saying that it's not a substance that will quickly like react. [researcher interjects with "Okay."] And volatile is one that will quickly react, that's how I would separate the two. [researcher interjects with "Okay."] That's about those, that's the best I got. ***-Xavier (middle performance group)***

Further to note, vapor pressure and boiling point were infrequently discussed by the students, yet that did not seem to impact students' drawings. Notably, students from the high and middle performance groups were the only students to connect volatility with high vapor pressure

or provided examples of volatile and nonvolatile substances (Table 4.11). No students made apparent connections to the drawings with IMFs.

Table 4.11. Counts for codes related to drawings in prompt 14B-D

Volatile Concepts Code	Number of students
Volatile relates to high vapor pressure	2
Correct examples of volatile/nonvolatile substances	5
Volatile relates to low vapor pressure	3
Incorrect examples of volatile/nonvolatile substances	2
Volatile relates to boiling point	1

4.6.10. Prompt 15 (Solutions: Generate)

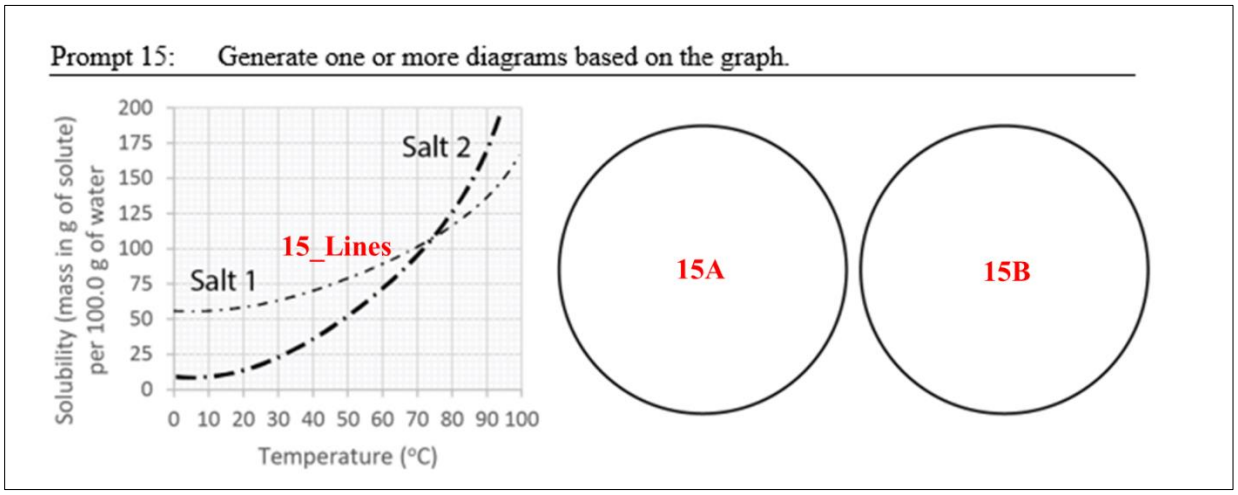


Figure 4.14. Prompt 15 with relevant location codes

Prompt 15 (Figure 4.14) was designed to probe students' ability to depict solutions using a solubility curve, which would require students to understand the solubility trends of the salts, saturation, and the effect of temperature. Four main levels of students' understanding of solubility emerged when coding. A relative understanding involved students' identifying

solubility trends with temperature and comparing the salts' solubilities at specific temperature points. A basic understanding involved identifying solubility trends with temperature along with concepts of saturation. An advanced understanding entailed students' correctly depicting saturation of the solutions at a specific temperature and considering the masses of solute. All other interpretations were coded as unclear.

Most students demonstrated a relative understanding of solubility and depicted solutions at the saturation point. Examples for each level of understanding with drawings are reported in Tables 4.12-4.14.

Table 4.12. Nadja's response and drawings for prompt 15

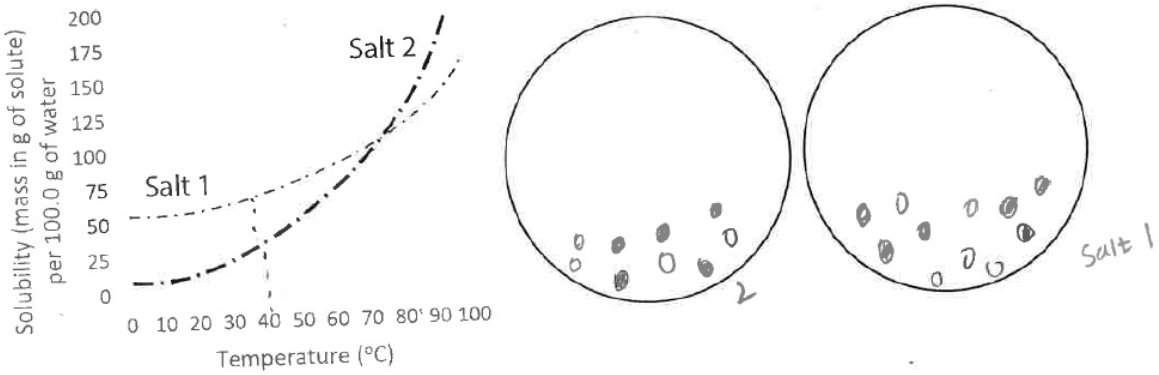
Nadja (middle performance group) – Relative Understanding

"…okay, at 40 degrees there's about 50 grams of about 50 grams of the salt (salt 1) is soluble in water so there's more more salt in the solution at 40 degree of salt one and there's less of salt 2 at 25 grams."

Table 4.13. Isaac's response and drawings for prompt 15

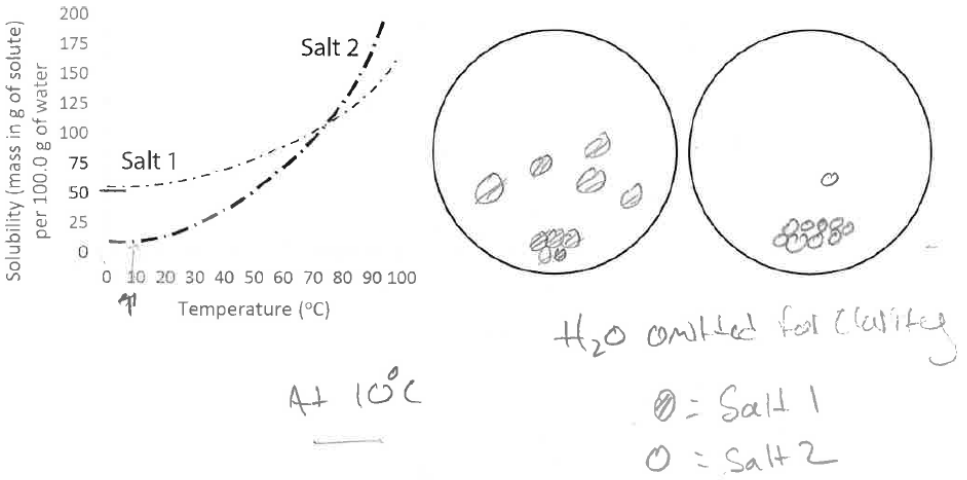
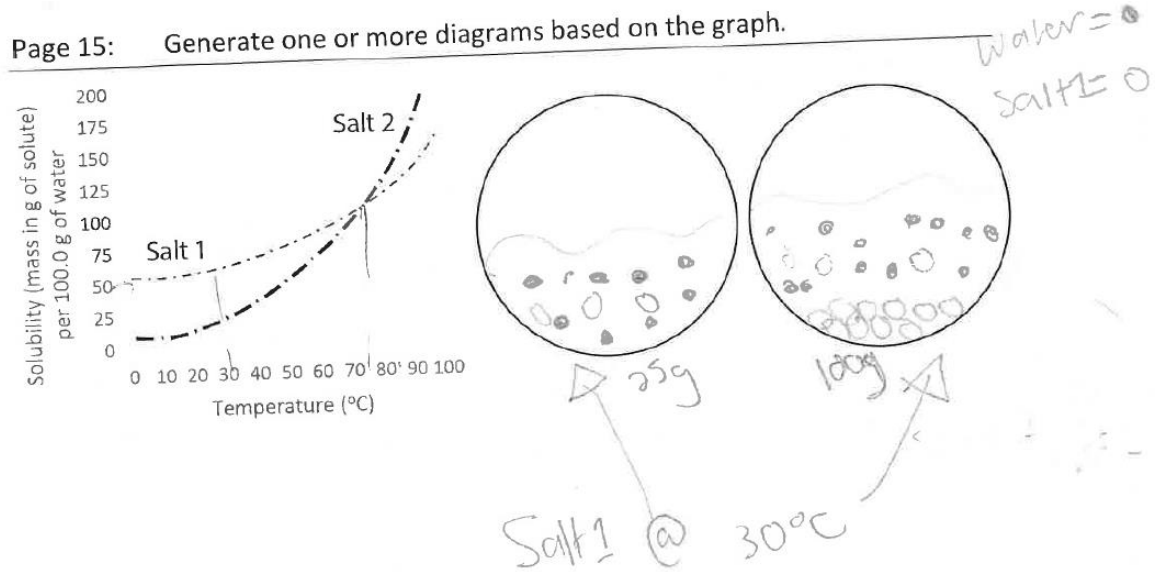
Isaac (low performance group) – Basic Understanding

"Uh, because I know that this one (15_lines) is more soluble at the lower temperature of 10 degrees Celsius, which is what I set this (15A) to. So, I know that more of it (15A) is in solution and not solid, like this should be something like this. That makes it kind of look clearer. And it's not at zero (15_lines) for a salt two (15B) at 10 degrees Celsius,(15_lines) so there is a little bit of it (15B) dissolved, but not a whole lot, so that's why I only put one. I mean, it's probably not, like proportional, but that's, that's my thought process."

Table 4.14. Willow's response and drawings for prompt 15

Willow (middle performance group) – Advanced Understanding

*"So, they're both 30 degrees, but this one (15B) is like, at like 100 grams of the solute instead. So, in this one (15A) Yeah. This is like water. And this is salt 1, as an open circle. *Writes key* And then there would be in this one (15A), because this (15_lines) is soluble, in there first graph I would like a bunch of water. *Draws several closed circles in 15A* Usually, she leaves water molecules out, but I'm just going to put them in. And then there's salt chilling in there. *Draws several open circles in 15A* And then the second one (15B), it's not, so there would be a bunch of salt at the bottom as a solid, and then some of it in there, and then a bunch of water. *Draws several open and closed circles in 15B*. So. This is a liquid. *Draws horizontal line in 15A and 15B to signify liquid**

4.6.11. Prompt 16 (Solutions: Generate)

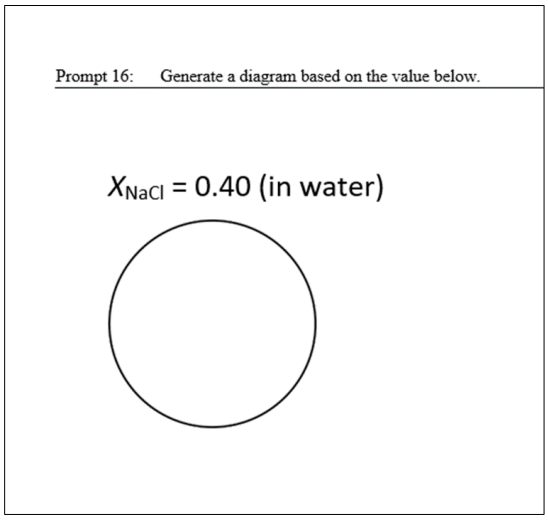
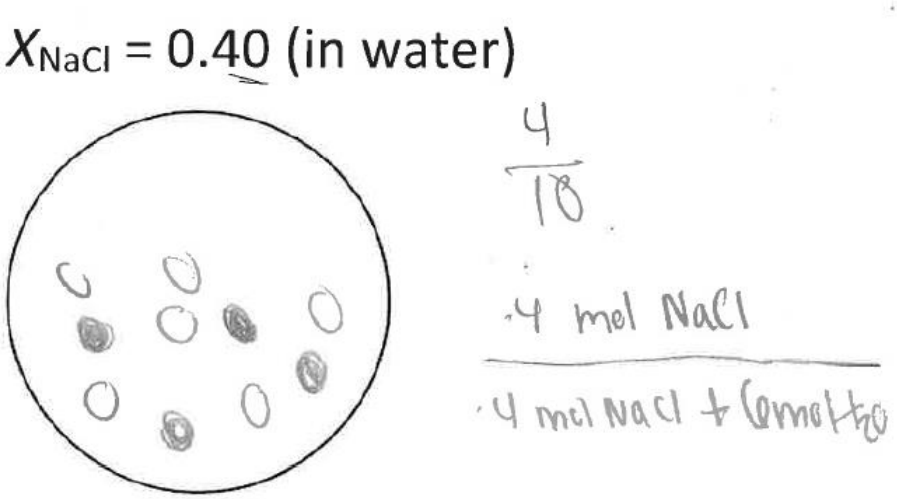
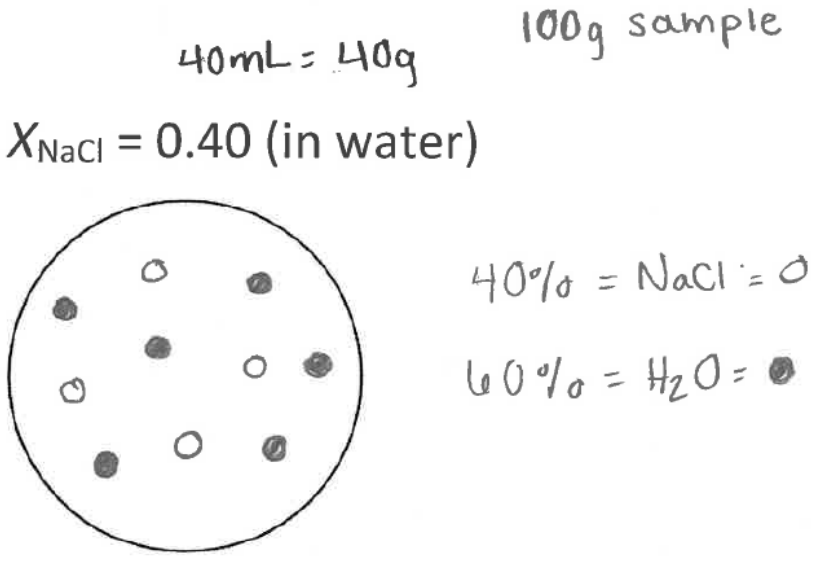


Figure 4.15. Prompt 16 with relevant location codes

Linked to prompt 10, prompt 16 (Figure 4.15) had students draw a solution when provided with a mole fraction value. Twenty-one students did not show dissociation of NaCl in solution; however, 15 students depicted the correct ratio of NaCl to water despite not showing dissociation. In prompt 10, students had challenges describing the mole fraction value. However, 10 of the 15 students provided an accurate drawing based on the value itself even when exhibiting misconceptions about the mole fraction (i.e. unit misconceptions). For example, as shown in Table 4.15, Paige (high performance group) correctly described mole fraction and depicted a correct representation (without dissociation). Andrew (low performance group) did not provide a correct explanation of mole fraction yet provides a correct drawing similar to Paige.

Table 4.15. Student responses and drawings for prompt 16

Paige (high performance group)

"So I would do four of those (dark circles). And then six of the white ones (open circles) are going to be water. Each one of these [particles] represents one mole of it. So if there's like four moles out of the 10 total is the NaCl. Then six would be white for water because mole fraction is like the whole part of our whole thing. So if it's four moles of NaCl And then you would do it over four moles of NaCl plus, and then I would do six mole of water, because we need it to equal at point four. So it's that part over the whole again."
Andrew (low performance group)

*"Generate a diagram based on the value below. So, we'll say that this is a 100 gram sample *Writes "100g sample to the right of 16* And we decided in the last one [page*

*15] that this was, 0.4 liters is zero point 40 milliliters, or, what the heck *Begins erasing what was previously written* It's 40 milliliters which is equal to 40 grams. *Writes 40 mL = 40g above 16* And of our 100 gram sample, that's 40 percent of what will be in the diagram and water will be 60 percent. *Writes key next to 16* So we'll do 1, 2, 3, 4" *Draws 4 open circles in 16* "1, 2, 3, 5, 6" *Draws 6 closed circled**

Comparing student responses from prompt 10 to their drawings in prompt 16 (Table 4.16), it was surprising to see that 6 of the 7 students who provided an incorrect interpretation of the mole fraction originally in prompt 10 generated a diagram correctly (with no dissociation) in prompt 16. This observation was also seen in 3 of the 7 students who gave an ambiguous interpretation in prompt 10. Providing a correct drawing in prompt 16 does not mean that the students' interpretations of the mole fraction improved, but rather that students with varying degrees of understanding can provide correct diagrams by interpreting 0.4 as a fraction and not connecting the value further to its context in concentration units.

Table 4.16. Comparison of responses for mole fraction in prompts 10 and 16

Mole Fraction Interpretation in Prompt 10	**# of students with mole fraction interpretation in Prompt 10**	**# of students with correct drawing in Prompt 16 (no dissociation)**
Meaningful Interpretation	4	3
Surface Level Interpretation	2	1
Incorrect Interpretation	7	6
Ambiguous Interpretation	7	3

If this prompt were an exam question graded solely on the drawn image, both students would have received the same score based on their depiction; however, as seen with their explanations, the two students have a different understanding of mole fraction that is not captured in the drawing of the diagram itself. Additionally, this observation suggests that students have a general sense of the value 0.4 and how to depict that value in a drawing; however, students demonstrate difficulties when connecting chemistry concepts (mole fraction, dissociation) to their number sense skills.

4.6.12. Prompt 17 (Kinetics: Generate)

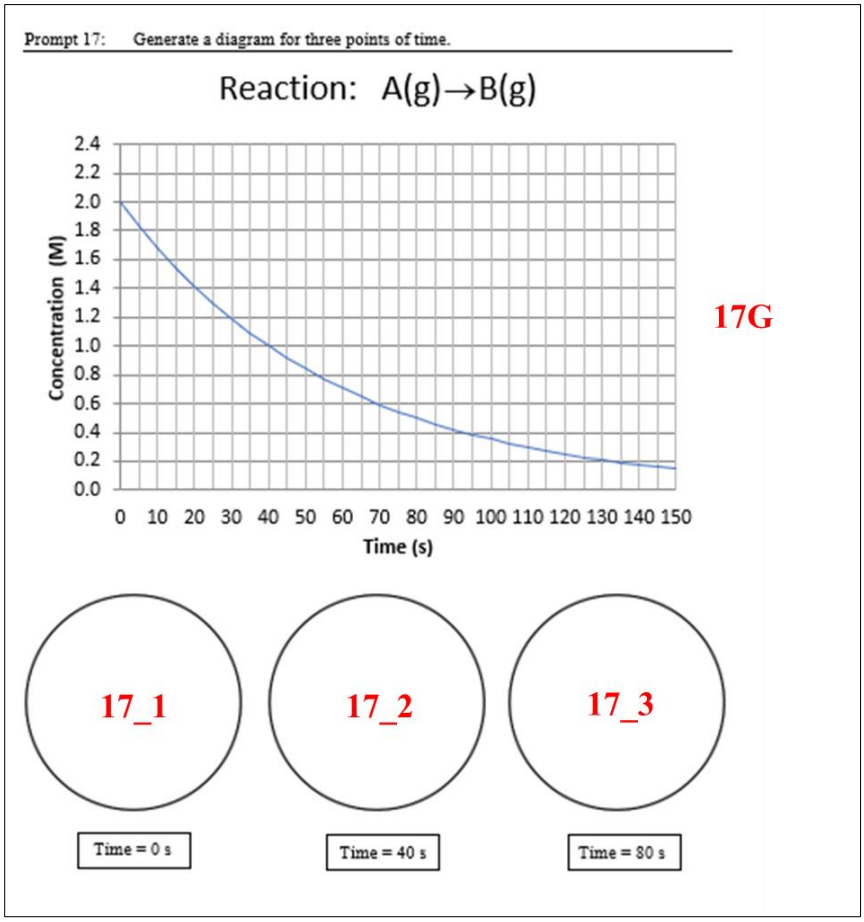


Figure 4.16. Prompt 17 with relevant location codes

In prompt 17 (Figure 4.16), students were asked to draw a diagram of the reaction at three points of time based on the provided graph. Nine students provided an accurate definition of half-life along with a correct drawing, depicting the concentration of A decreasing by half and the concentration of B doubling over time. Again, as in prompt 4, Andrew was the only low performing student to provide an accurate depiction and explanation about half-life (Figure 4.17).

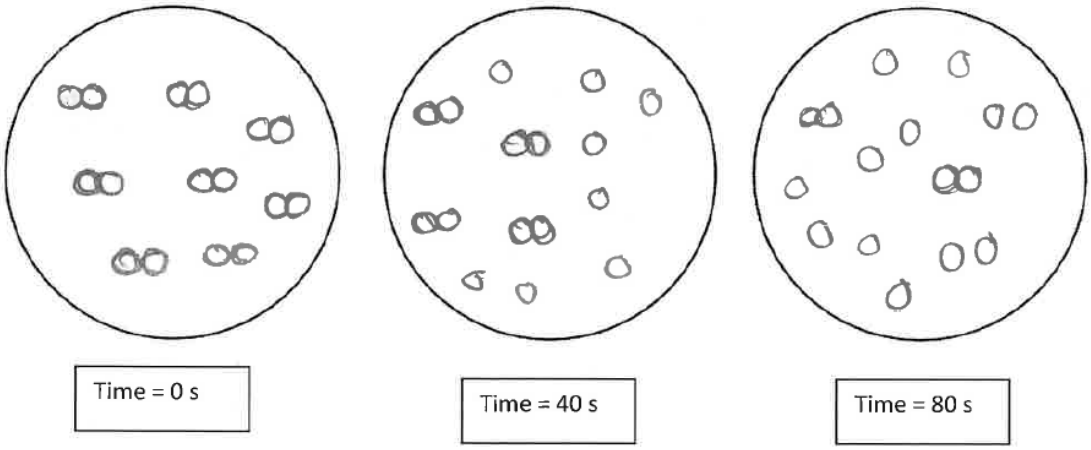


Figure 4.17. Andrew's drawing to prompt 17 depicting half-life

An unanticipated finding was that 9 students encountered an odd number of particles when halving their sample. Instead of adjusting the number of particles to an even number, students either rounded the number of particles or drew "half" of a particle / symbol (Figure 4.18).

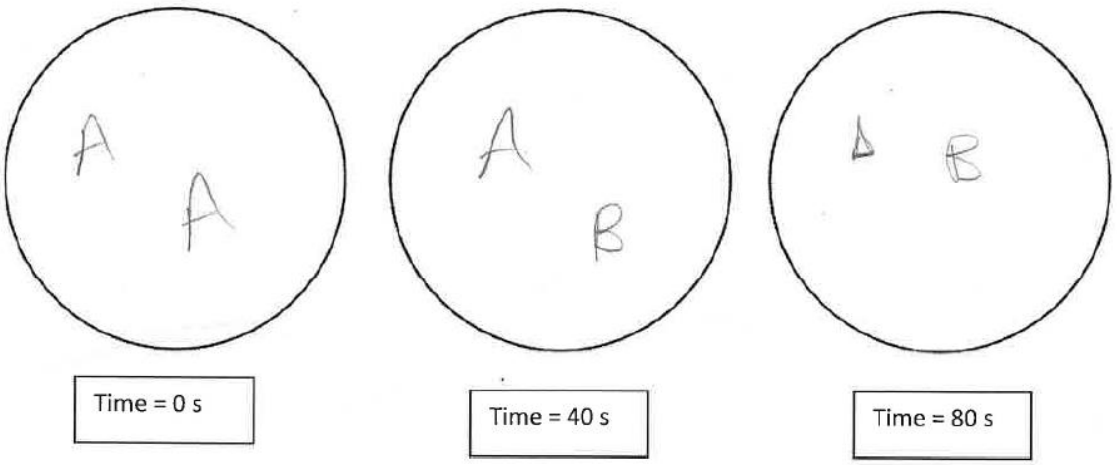


Figure 4.18. Student's drawing depicting half of the letter "A" to demonstrate the concentration of A being reduced by half.

4.6.13. Using Interviews to Assess Scaffolding

As mentioned previously, interview prompts were designed in a linked manner (Figure 4.19). By analyzing the linked prompts as a progression, there can be information gleaned about instructional scaffolding and if any student groups (i.e. performance group) need more support in particular course aspects. Select student responses for the linked prompts 2,9, and 15 will be discussed in detail to demonstrate this investigation (Figure 4.20). Nicole (middle performance group) and Eve (high performance group) were two student participants whose responses were used to evaluate scaffolding. In prompt 2, both students successfully identified which image was depicting greater solubility, and both students similarly described the images, using vocabulary such as "homogenous mixture."

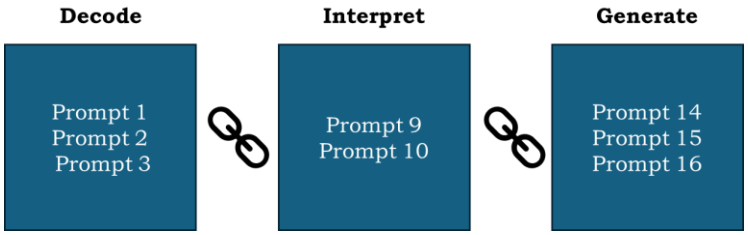


Figure 4.19. Linked prompts covering solutions concepts

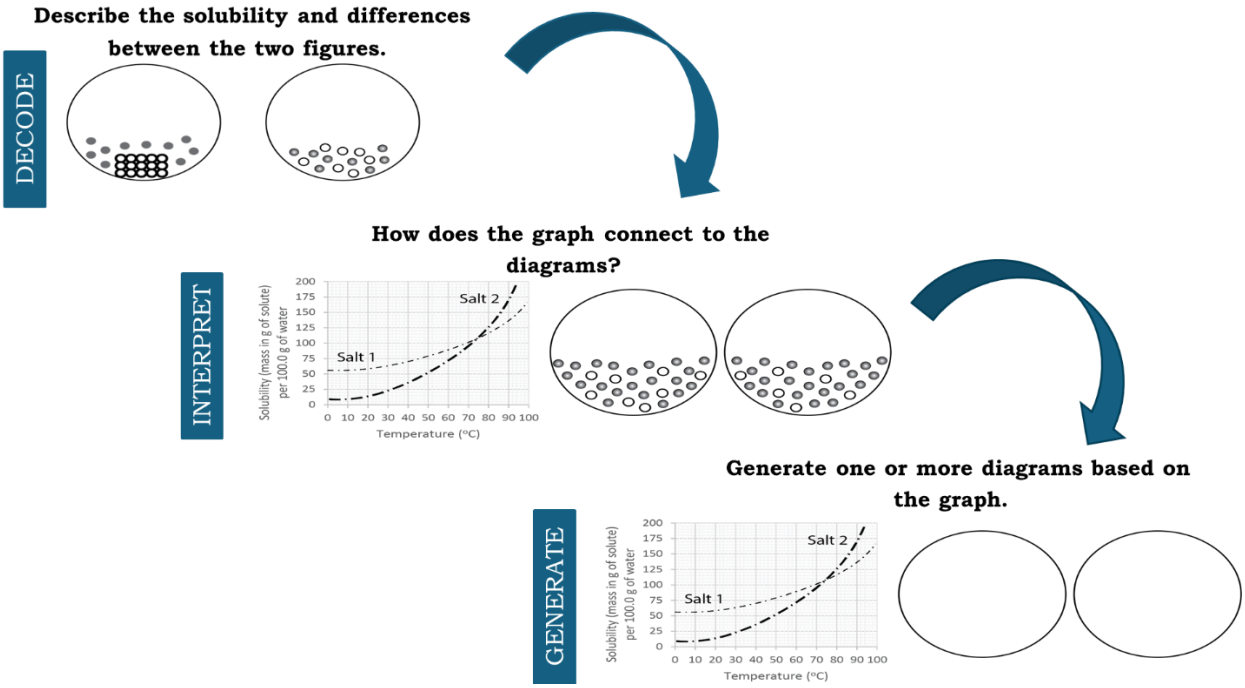


Figure 4.20. Linked prompts 2, 9, and 15

Table 4.17. Nicole and Eve's verbal responses to Prompt 2

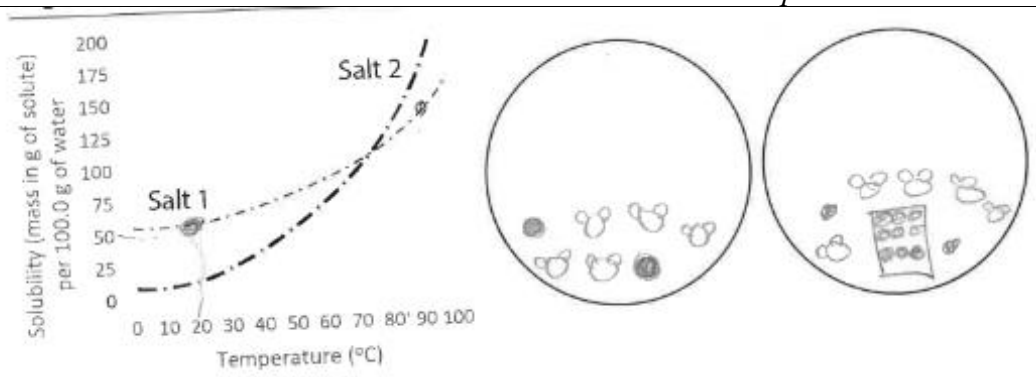
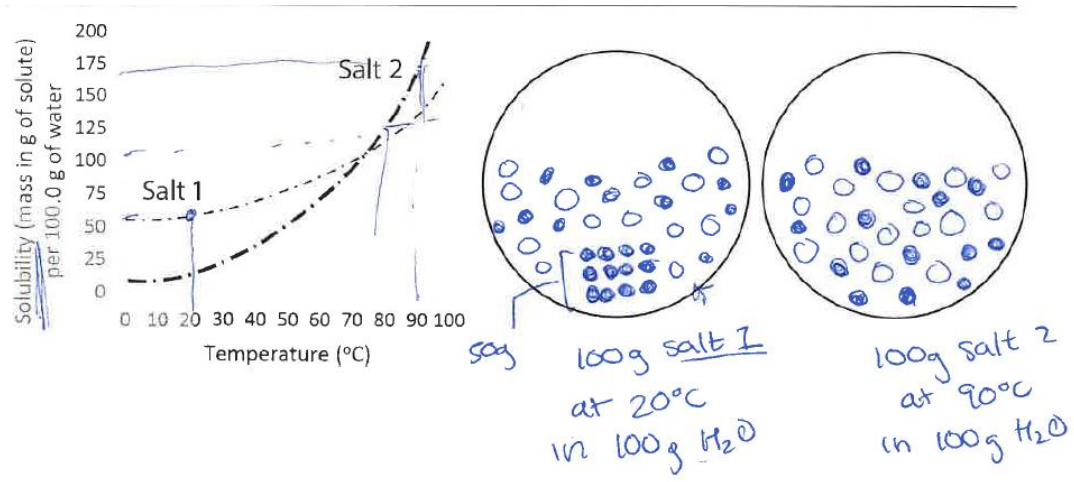
Nicole	Eve
But this one (2B), you wouldn't necessarily see the differences in these two liquids, it would just be all one homogeneous mixture. And this one (2A) would be heterogeneous. And this one (2A) is, it's got different solubility, because this one precipitates out. But this one (2B) doesn't…"	*"This one (2A) looks like it's less soluble substance because it's still on a solid phase (2A_p2). So, and it's got liquid (2A_p1) around it, because this isn't up in the air like a gas would be. And it looks like it's more organized than a gas would be. So, this (2A_p2) is in a solution. And it's got a solid, so that's less soluble. Well, this one (2B), they're mixed in and it's kind of randomly organized. So, it's got to be a solution, homogeneous solution, because they're all mixed in two different colors and under two different elements."*

In prompt 9, differences emerge in the students' responses (Table 4.18). Nicole understands the overall concept of solubility increasing with temperature. However, she articulates a misconception about the solubility curve regarding saturation and does not expand on the effects of temperature or mass of solute. She is unable to recall how the graph can be used to determine the saturation of the solutions at various temperatures, which leads her to not being able to determine a specific point of the curve to connect the particulate diagrams. This misconception about saturation carries through into prompt 15. Nicole indicates that a solution made up of 50 grams at 20°C would be unsaturated, yet she correctly depicts an unsaturated solution in the particulate diagram. At 90°C, using 125 grams of solute, Nicole does determine the solution to be saturated, yet depicts a particulate diagram with precipitate (Table 4.19).

Table 4.18. Nicole and Eve's verbal responses to prompt 9

Nicole	Eve
"So, this (9G) is a solubility curve. And you're comparing the two salts to each other. So one of the salts is more soluble at different temperatures than the other. And based on where they are like on the curve, it would be like different types of mixtures, or you would have like a saturated solution and an unsaturated solution, or a supersaturated solution. I'm pretty sure, unsaturated is up here (9G_above). And saturated is down here (9G_below), but I'm not positive. I need to think about that again."	*"Then, if it was at like 30 degrees Celsius, then salt 1 has a higher solubility. So, there could be more of salt one in solution. There could be more salt particles in the water (9A) than solution 2 (9B) could fit. So this would be solution of salt 1 because there's more salt in the water than in here (9B). Yes. but if it was at 30 degrees, but it was at 90 degrees, then salt 2 has more opportunity to dissolve in water (9B). Higher capability of dissolving and water. this (9A) will be salt 2 at 90 degrees and salt 2 at 30 degrees (9B), salt 1 (9B) at ninety degrees."*

Table 4.19. Nicole and Eve's verbal responses and drawing for prompt 15

Nicole
*"…So, I'll go with like, at 50 grams of salt one at 20 degrees. It would be an unsaturated solution. So, it would be, like all of the solute going into the water would get dissolved. *draws open and closed circles at bottom of 15A* So it would look like that and there would be no precipitate in it. But then, for (15_lines) something that would precipitate would be like over here, maybe (15_lines). It's looking like 25 grams [says 25 but points to 125 on Y axis] of solute at 90 degrees. So then, *draws a solid in 15B* there would be some of the solute particles in the water. But then there would also be like a solid precipitate forming because it's a saturated solution at that temperature."*

Eve
"Because if I put 100 grams of salt one into a solution of water at 20 degrees Celsius, then 50 grams of it will be solid and 50 grams will be in solution." *… "And then with salt 2 (15_lines), we can put 100 grams, make it soluble at 90 degrees. So, 100 grams of salt 2 at 90 degrees in 100 grams of water (15B). At that point (15_lines), salt 2 is soluble up to 175 grams."*


In prompts 9 and 15, Eve is one of two students to demonstrate a full understanding of the role of temperature and mass of solute in connecting the diagrams to the curve. She articulates how the particulate diagram that depicts greater solubility (9A) can be either salt 1 or salt 2 depending on the temperature. In prompt 15, Eve uses 100 grams of salt 1 at 20 °C to demonstrate that 50 grams will precipitate, and 50 grams will remain in solution. Using 100 grams of salt 2 at 90°C, Eve draws all 100 grams in solution, creating a saturated solution. Comparing Nicole and Eve's responses, both students demonstrate an understanding of using particulate diagrams to depict solubility. However, Nicole demonstrates a weaker understanding of the solubility curve, connecting particulate diagrams to the plot, and the number sense embedded within the plot. In this way, Nicole's response provides insight into the use of scaffolding in instruction of solubility. Increased scaffolding in this topic may better assist students.

4.7. Limitations

A limitation of this work is generalizability. The extent to which the student participants interview responses are representative of all GC II students cannot be determined. Furthermore, the classification of the sample based on performance group was determined via relevant exams measures. The extent to which the exam scores reflect the students' overall course performance cannot were not investigated in the scope of this work.

Analysis of data from this work suggests the possibility of introducing new topics to students with a particular focus on either number sense, graphs, or particulate diagrams depending on the topic. However, from this data set, the best approach cannot be identified without a more elaborate exploration. Lastly, more evidence is needed regarding which areas of

the course, and to which level, the scaffolded materials would need to be further modified in the intervention.

4.8. Conclusions

A series of interview sets were created and utilized to gain insight into GC II students' content area knowledge and scale skills related to solutions, kinetics, and particulate diagrams. Findings suggest that particulate diagrams are a useful tool for students to utilize when deciphering or demonstrating phase changes and solubility concepts. Overall, students across all performance groups successfully decoded the particulate diagrams' surface features throughout the interview. As the complexity of the prompts increased and additional values and/or plots were incorporated, a greater disparity between performance groups emerged. For example, low performance group students tended to rely on the explicit surface features of particulate diagrams and plots compared to the other performance groups where more interpretation and connection behaviors were observed. Also, students demonstrated a higher number sense when dealing with particulate diagrams versus when dealing with numerical values or graphs. Findings from this study also highlighted common areas of misconception related to saturation, solubility curves, a Maxwell-Boltzmann distribution, and half-life. These misconceptions were particularly observed in scenarios where graphs and values were given without or in conjunction with particulate diagrams. Thus, instructional practices should focus efforts on using particulate diagrams. These findings also suggest presenting particulate diagrams and graphs from the same content area in a scaffolded fashion so as not to cognitively overload the students when learning.

Interview responses also provided insight into the effect of the scaffolding implemented into the scale-themed curriculum. By recognizing misconceptions and areas where students

exhibited challenges, the level of scaffolding needed to better support students can be assessed and adjusted in future revisions to the curriculum.

4.9. References

(1) Patton, M. Q. *Qualitative Research and Evalulation Methods*, 4th ed.; Sage: Thousand Oaks, CA, **2015.**

(2) Rodriguez, J.-M. G.; Nardo, J. E.; Finkenstaedt-Quinn, S. A.; Watts, F. M. The use of frameworks in chemistry education research. *Chem. Educ. Res. Pract.* **2023**, *24* (4), 1109–1126.

(3) Bodner G. M. and Orgill M., *Theoretical Frameworks for Research in Chemistry/Science Education;* Pearson: Boston, MA, **2007.**

(4) Merriam, S. B.; Tisdell, E. J. *Qualitative Research: A Guide to Design and Implementation*, 4th ed.; Jossey-Bass: San Francisco, CA, **2016.**

(5) Watts, F. M.; Finkenstaedt-Quinn, S. A. The current state of methods for establishing reliability in qualitative chemistry education research articles. *Chem. Educ. Res. Pract.* **2021**, *22* (3), 565–578.

(6) Lombard M.; Snyder-Duch J., Campanella Bracken C.; Content analysis in mass communication: Assessment and reporting of intercoder reliability." *Human Communication Research.* **2002,** *28*(4), 587-604.

(7) Jones, M. G.; Taylor, A. R. Developing a sense of scale: Looking backward. *J Res Sci Teach.* **2009**, *46* (4), 460–475.

(8) Johnstone, A. H. The development of chemistry teaching. *J. Chem. Educ.* **1993,** *70* (9), 701.

(9) Rodriguez, J.-M. G.; Stricker, A. R.; Becker, N. M. Students' interpretation and use of graphical representations: Insights afforded by modeling the varied population schema as a coordination class. *Chem. Educ. Res. Pract.* **2020**, *21* (2), 536–560.

(10) Rodriguez, J.-M. G.; Stricker, A. R.; Becker, N. M. Exploring the productive use of metonymy: Applying coordination class theory to investigate student conceptions of rate in relation to reaction coordinate diagrams. *J. Chem. Educ.* **2020**, *97* (8), 2065–2077.

Chapter 5

Accounting for Affect: Investigating the Motivation of General Chemistry Students

"Motivation and learning can affect one another. Students' motivations can influence what and how they learn. In turn, as students learn and perceive that they are becoming more skillful, they are motivated to continue to learn." [1]

- Dale Schunk

5.1. Introduction

There has been a call-to-action to increase scientific literacy and the number of Americans with STEM-related college degrees.[2-4] Consequently, science educators need to foster more interest in the sciences among young Americans. In tandem with *interest* in science is the *motivation* to learn science. Motivation is the internal state that initiates and supports goal-oriented behaviors.[5] Humans motivate themselves in several facets of life; they form beliefs about what they can do, set goals, and plan courses of action to achieve those goals.[6] These behaviors are observed in educational environments and can affect academic outcomes as well. Therefore, it is necessary for science instructors and researchers to delve deeply into science students' motivation.

5.2. Theoretical Perspective

Motivation is a complex construct that has been discussed through different theoretical perspectives. Albert Bandura described motivation through the lens of social cognitive theory.[7,8] Social cognitive theory expands beyond a strict focus on the mind's inner cognitive processes; it encapsulates the idea that learning is self-regulatory and is influenced by social, motivational, and affective factors.[7-9] Some examples of affective factors include self-efficacy, anxiety, and motivation. A large body of Bandura's social cognitive theory centers on self-efficacy, or the belief in one's own capabilities. Self-efficacy also plays a large role in students' motivation.[10,11]

Self-determination theory (SDT) is another framework that is utilized to understand motivation. In SDT, a human's psychological well-being or individual self-determination is based on the degree of fulfillment and satisfaction of three basic needs: autonomy, competence, and relatedness. [12-15] Satisfaction of these needs is affected by several factors including anxiety, self-efficacy, and motivation. According to SDT, motivation is viewed as multi-faceted, and people are motivated by one or more factors at varying degrees. [12-15] Rooted in self-determination theory, Deci and Ryan constructed a motivation continuum with different types of motivators (Figure 5.1).[14,15]

One end of the continuum describes internally regulated, self-determined behaviors. This includes intrinsic motivation, encompassing the innate inclination people possess within to explore and grow one's capabilities with a sense of personal satisfaction and autonomy.[12] The other end of the continuum describes amotivation, which is the lack of desire or interest in performing a task and exemplifies nonregulated and nonself-determined behavior. The middle of Deci and Ryan's continuum includes external motivation. There are four subscales of external motivation regulation (external, introjected, identified and integrated) ranging in the degree of self-determined behaviors.[13,16] External regulation is the least self-determined of the four, and tasks are performed to fulfill external demands or to be rewarded. Tasks performed with introjected regulation are influenced by personal fear, anxiety, social acceptance, and/or ego. Identified regulation reflects when a task is recognized consciously with some degree of personal importance. Integrated regulation is when identified regulations are fully incorporated within oneself and align with one's personal values. Ultimately, motivation is multi-layered because humans are complex, multi-dimensional beings.

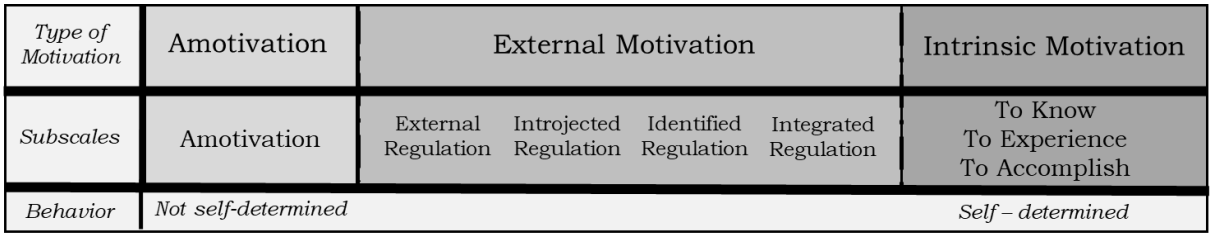


Figure 5.1. Motivation continuum by Deci and Ryan[14,15]

Considering past research, students may exhibit differing interest[17] or motivation[18] depending on the subject domain, and science encompasses several specific disciplines. While one may be motivated to learn physics, feelings toward another adjacent subject, such as chemistry, may be quite different. Moreover, a motivation continuum, in the context of learning, suggests that students may fall into one position on the continuum or straddle two positions. Chemical education researchers are aiming to shed light on these perceptions by understanding and measuring the motivation of chemistry students, especially at the undergraduate level.

However, this pursuit poses challenges, as motivation cannot be directly measured. In statistics, motivation is considered a latent variable. Latent variables are measured indirectly through techniques such as structural equation modeling (SEM).[19,20] Surveys are instruments commonly used in studies with latent variables. It is assumed the latent variable of interest influences the responses to the developed survey items.[21] Within all research pursuits, it is imperative that any instruments used to obtain the data are established as reliable and trustworthy.[22] This is especially true with surveys, as one cannot assume the survey will perform the same across all populations.[22] Thus, validation for survey items, scales, and the interpretation of responses is essential to provide trustworthy and meaningful results.[23] There are quantitative and qualitative methods to establish validity and reliability of surveys. Exploratory Factor Analysis (EFA) and Confirmatory Factor Analysis (CFA) are complementary types of SEM

often employed in survey validation.[24,25] EFA is used to determine the relationship and underlying factor structure of variables. CFA is then employed to further verify the validity of the determined factor structure and generate a model. Qualitatively, reliability and validity can be established using participant interviews, test/retest models, and interrater reliability.[26] The use of multiple techniques increases the evidence of claims.

5.3. Motivation Surveys

The Science Motivation Questionnaire (SMQ) is a survey that measures the motivation of science majors and nonscience majors.[27] More well-known is the second version of this instrument, the SMQ II.[28] The SMQ II has been validated for science and nonscience major samples via EFA and CFA. The SMQ II survey (Appendix E) has students consider the prompt "*when I am in a college science course*…" for 25 items measuring five types of motivation: intrinsic motivation, self-efficacy, self-determination, grade motivation, and career motivation.[28] Students select their responses to the prompt and items using a five-point Likert scale, where (0) = never, (1) = rarely, (2) = sometimes, (3) = usually, and (4) = always. A benefit of the SMQ II is that it is easily adaptable by replacing the word "science" with another science discipline. The SMQ II has also been adapted for chemistry in various contexts such as in undergraduate general chemistry students[29], Greek secondary students[30] and Spanish secondary students.[31]

The Academic Motivation Survey (AMS) measures the motivation of college students and employs self-determination theory to measure seven subscales of motivation on the motivation continuum (Figure 5.2).[32] The survey includes items related to amotivation, external motivation (external regulation, introjected regulation, and identified regulation), and intrinsic motivation (subclassified into "to experience," "to accomplish," and "to know"). Integrated regulation was omitted from the AMS due to its similar nature to identified regulation. The

further classification of intrinsic motivation was based on studies indicating that people may possess different types of intrinsic motivation, but no one motivator is more self-determined than the other.[33]

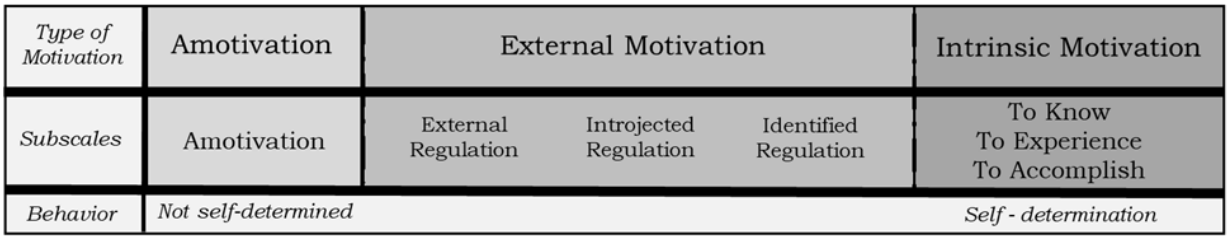


Figure 5.2. Motivation continuum for AMS-Chemistry as presented in Liu, et al.[34]

The original AMS consists of 28 statements reflecting the seven motivation subscales with a seven-point scale to answer the prompt *"why do you go to college?"* The AMS has been adapted for use in chemistry (AMS – Chemistry) and was validated undergraduate general chemistry students via CFA and student interviews.[34] To adapt for use in chemistry, the prompt was modified to "*why are you enrolled in this chemistry course?*" and substituting the word "college" to "chemistry" within the items. The AMS-Chemistry has since been utilized in a variety of chemistry courses including general chemistry[34] and organic chemistry.[35,36] The full AMS-Chemistry can be found in Appendix E.

5.4. Motivation of Differing Groups

Motivation studies have revealed that students may differ in motivation based on sex, time, academic achievement, or major. Past research results vary when it comes to motivation differences based on sex. In a few studies, female college students exhibited higher motivation overall.[32,37] Academic achievement in chemistry has been linked to higher intrinsic

motivation.[34,36] Female chemistry students exhibit higher self-determination[34,36] than male chemistry students. In another study, most chemistry students were extrinsically motivated, with female students having less amotivation.[34] Alternatively, there were no major motivation differences between sex in a study with organic chemistry students.[36] Overall, more research is needed based on the mixed results observed when studying the motivation of males and females. Motivation also has been observed to change over time[34] and age group;[30] concerningly, college students' motivation decreases with increasing time in school.[37]

As mentioned previously, student motivation is also impacted by career goals. Since 2015, there are approximately 52,000 – 53,000 medical school applicants a year.[38] This estimate is only accounting for those applying to medical school, but there are also other pre-professional (pre-dentistry, pre-pharmacy, pre-veterinary) students to account for. Many of these applicants will be required to take introductory and/or higher-level chemistry courses for their desired major or post-undergraduate goals. Thus, there is a need to understand the motivations of these groups to better support them while learning. There have been efforts to research motivation of pre-med students,[39,40] but literature is limited when it comes to investigating pre-professionals' motivation in undergraduate chemistry courses.

5.5. Motivation and Instruction

It is important to recognize that students' motivations may be influenced by their instructors or the type of instruction they receive.[41] There is research related to how instructors' own motivations can impact their students' motivations and academic achievements in a course.[42,43] In fact, in one study, when instructors reported more intrinsic motivation for teaching a particular program, students also reported higher intrinsic motivation and experienced better

support and more positive learning experience.[42] If students perceive their instructor with negative attributes (ex. angry), it can increase extrinsic motivation over intrinsic motivation.[44]

Additionally, there is research that suggests the type of instruction utilized can impact students' motivations in learning.[41,45] Aligning with SDT, several studies found that instruction that fosters autonomy and a sense of competence among students results in increased self-determination and intrinsic motivation.[46-48] In one study, dual-approach instruction was utilized for middle school science; and results showed that the instructional method had a significant increase in several aspects of motivation.[49] Seeing as instructional practices can impact motivation, it causes one to wonder if the motivation of students impacts their receptibility to certain instructional practices and/or curricula interventions. In science, literature is limited regarding the effect of instructors and instructional practices on student motivation, especially in higher education and chemistry. Therefore, it is important to explore this area of research further.

5.6. Research Context

This portion of the project has an overarching goal of understanding the motivation profile of general chemistry students at a research-intensive, Midwestern public university. There was interest to understand what one motivation subscale was most prevalent among students (single categorical assignment) and if student motivation differs by sex, major, or over the semester. Because a major component of this project centers on the evaluation of the revised scale-themed curriculum in general chemistry II, we sought to understand the degree to which motivation influences students' responsiveness to interventions. Additionally, past research shows motivation is key in the development of scientific literacy.[28,50] Because this project is focused on scale, a vital component of scientific literacy,[28] we were interested in investigating this facet as well. This study aims to address the following research questions:

RQ1: Are there significant differences in motivation subscores within a semester, and are there significant differences in motivation subscores between course (general chemistry I vs. general chemistry II), sex, and major (nonpre-professional science major vs. pre-professional)?

RQ2: What is the single categorical assignment of motivation for general chemistry I and II students, and does the single categorical assignment of motivation vary by sex or major?

RQ3: How does the single categorical assignment of motivation vary within a semester for general chemistry I and II students?

RQ4: What is the single categorical assignment of motivation for students who exhibited above average learning gains from the scale-themed intervention? What is the single categorical assignment of motivation for students who exhibited below average learning gains from the scale-themed intervention?

5.7. Methods

This study had three main phases: (1) instrument development and data collection, (2) instrument validation, and (3) data analysis. Figure 5.3 depicts an overview of the methodology utilized in this study.

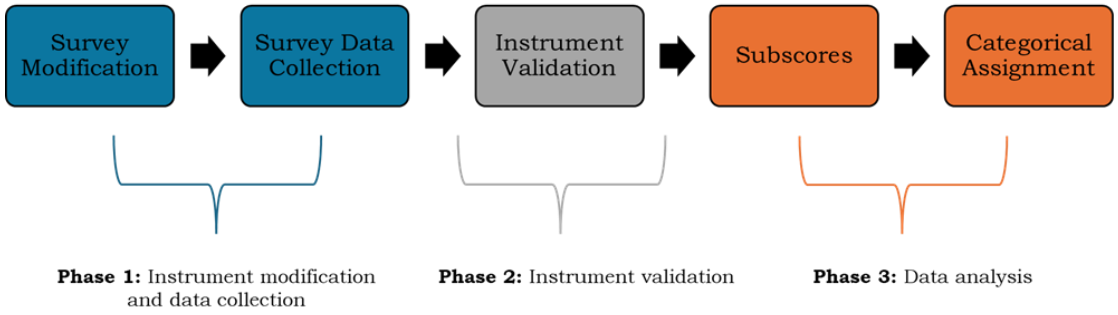


Figure 5.3. Method overview

5.7.1. Survey Modification and Data Collection

The survey utilized was comprised of two sections. The first section included the entire AMS-Chemistry survey,[34] with the same ordering of items and use of the 7-point scale as reported in literature. The second section of the survey included the five grade motivation items and five self-determination items from the SMQ II, using the same 5-point scale as reported in literature.[28] These items were presented on the survey in a randomized order, and the prompt was slightly modified, changing the word "science" for "chemistry." The grade motivation items from the SMQ II were selected to purposefully include extrinsic motivators beyond the future salary and career matters included in the AMS-Chemistry extrinsic items. That was particularly important to include, because it was hypothesized that grade factors would influence motivation in an introductory chemistry course. The AMS-Chemistry reflects items consistent with self-determined behaviors, so the SMQ II self-determination items were included as internal validation. The modified survey items and the corresponding underlying motivation subscales are listed in Table 5.1. The entire finalized survey can be found in Appendix E.

Table 5.1. Items in modified motivation survey including AMS-Chemistry statements (black) and SMQ II statements (red)

Survey:	**AMS – Chemistry**	***"Why are you enrolled in this chemistry course?"***
Item	**Subscale**	**Statement**
1	External regulation	Because without having taken chemistry I would not find a high-paying job later on.
2	To know	Because I experience pleasure and satisfaction while learning new things.
3	Identified regulation	Because I think that chemistry courses will help me better prepare for the career I have chosen.
4	To experience	For the feelings I experience when I am communicating chemistry ideas to others.
5	Amotivation	Honestly, I don't know; I really feel that I am wasting my time taking chemistry courses.
6	To accomplish	For the satisfaction I experience while improving my understanding of chemistry.
7	Introjected regulation	To prove to myself that I am capable of succeeding in chemistry.
8	External regulation	In order to obtain a better job later on.
9	To know	For the pleasure I experience when I learn new things about chemistry.
10	Identified regulation	Because taking chemistry will enable me to enter the job market in a field that I like.
11	To experience	For the pleasure that I experience when I perform chemistry experiments.
12	Amotivation	I once had good reasons for taking chemistry courses; however, now I wonder whether I should continue.
13	To accomplish	For the satisfaction I experience while succeeding in chemistry.
14	Introjected regulation	Because when I succeed in chemistry I feel smart.
15	External regulation	Because I want to have a well-paying career.
16	To know	For the pleasure that I experience in broadening my knowledge about chemistry.
17	Identified regulation	Because taking chemistry courses will help me make more informed choices about my career options.
18	To experience	For the enjoyment I experience when I think about the world in terms of atoms and molecules.
19	Amotivation	I don't know why I take chemistry courses, I couldn't care less about them.
20	To accomplish	For the satisfaction I feel as I work toward an understanding of chemistry.
21	Introjected regulation	To show myself that I am an intelligent person.
22	External regulation	In order to have a better salary later on.
23	To know	Because studying chemistry allows me to continue to learn about things that interest me.
24	Identified regulation	Because I believe that chemistry courses will improve my skills in my chosen career.
25	To experience	For the satisfaction I experience while learning about various chemistry topics.
26	Amotivation	I don't know; I can't understand what I am doing taking chemistry courses.
27	To accomplish	Because chemistry courses allow me to experience satisfaction in my quest for knowledge.
28	Introjected regulation	Because I want to show myself that I can succeed in studying chemistry.
Survey:	**SMQ II**	***"When I am in a chemistry course…"***
Item	**Subscale**	**Statement**
29	Grade motivation	I like to do better than other students on chemistry tests.
30	Grade motivation	Getting a good chemistry grade is important to me.
31	Self-determination	I put enough effort into learning chemistry.
32	Self-determination	I use strategies to learn chemistry well.
33	Grade motivation	It is important that I get an "A" in chemistry.
34	Self-determination	I spend a lot of time learning chemistry.
35	Self-determination	I prepare well for chemistry tests and labs.
36	Grade motivation	I think about the grade I will get in chemistry.
37	Self-determination	I study hard to learn chemistry.
38	Grade motivation	Scoring high on chemistry tests and labs matters to me.

The modified survey was distributed via Qualtrics to general chemistry I (GC I) and general chemistry II (GC II) students at a research-intensive, Midwestern public university. The survey was distributed for the first time within the last two weeks of the Fall 2021 semester. Following the initial distribution, data was collected within the first two weeks of the semester (pre) and within the last two weeks of the semester (post). Students gave informed consent to participate in the survey, and for participation, students received extra credit upon completion.

The survey data was processed before performing any further analysis. Any cases that met any of the following criteria were removed from the data set.

- Incomplete survey
- Multiple submissions by same participant – the first submission was utilized in further analysis while the other submissions were removed
- Responses had a standard deviation of zero
- Time to complete survey exceeded 816 seconds or was under 90 seconds.

After initial data cleaning, there was a total of 1523 motivation surveys across six semesters in both GC I and GC II. Table 5.2 reports a breakdown of the sample numbers collected by course and semester. Data was not collected in GC I for Spring 2022 Pre and Fall 2022 Pre due to an oversight in survey distribution by the course instructor.

Table 5.2. Number of surveys per semester and course (n=1523)

	Fall 2021		**Spring 2022**		**Fall 2022**		**Spring 2023**		**Fall 2023**		**Spring 2024**	
	GC I	GC II	GC I	GC II	GC I	GC II	GC I	GC II	GC I	GC II	GC I	GC II
Pre	---	---	---	57	---	58	115	67	135	73	123	96
Post	36	67	58	12	88	34	98	65	116	77	79	69

5.7.2. Quantitative Methods of Instrument Validation

5.7.2.A – Factor Analysis

To determine the survey's factor structure and establish validity, statistical methods, EFA and CFA, were used in conjunction. In EFA, Principal Axis Factoring (PAF) was the extraction method with Varimax rotation. CFA was used subsequently to further verify the factor structure

from EFA. The results from both analyses will be discussed further in the Results section of this chapter.

5.7.3. Qualitative Methods of Instrument Validation

5.7.3. A – Interview Recruitment and Sample

Students were recruited from the general chemistry I and general chemistry II courses at a large, research-intensive, Midwestern university in Spring 2023. The recruitment process involved class announcements and class-wide emails. Students received an ACS General Chemistry Study Guide in exchange for participation. Table 5.3 summarizes the sample matrix, sorting the total GC I participants (n=11) and GC II participants (n=10) based on sex and high and low performance. Students were classified for performance based on their exam score in relation to the course average on exam 1 (76.6%). An above average score resulted in assignment to the high-performance group, while students sorted in the low-performance group scored below the exam 1 average. While no low performance male students in general chemistry II participated, based on the findings of the interviews, it is justifiable to assume the sample reached saturation as there were no major interpretation differences observed between general chemistry I and II students.

Table 5.3. Motivation survey interview matrix

	Male Students		**Female Students**	
	High Performance	Low Performance	High Performance	Low Performance
GC I (n = 11)	2	3	3	3
GC II (n = 10)	2	0	5	3

5.7.3. B – Interview Protocol

The interviews were conducted in two parts during an approximately one-hour period. All interviews were conducted in a private room and visual and audio data were recorded. All students provided informed consent under the Institutional Review Board (IRB #14.404)

Part 1 aimed at assessing the validity and interpretation of the survey items and scales. Students were presented with each survey item on an individual card in the same order as the survey. The students were asked to read the statement aloud, give their interpretation of the statement's meaning, give their rating using the scale, and explain their given rating. Before part 1 began, the author performed a training activity completing the required tasks with statements related to various factors on a fictitious restaurant survey.

In part 2 of the interview, students were asked to create their own "qualitative" factor structure with the survey items. The purpose of part 2 was to understand how students were grouping items together and to compare their groupings to the results generated from the preliminary EFAs. The students were given the survey items on randomized cards and were asked to group the cards based on like items. Once the students completed the sorting, they were asked to explain what each group had in common. Students were not limited by the number of groups they could form, nor was there a requirement for the number of items sorted into a group. Before the start of part 2, the researcher performed a second training activity involving the restaurant survey items being grouped as described above.

5.7.4. Motivation Subscore Averages and Comparisons

Subscore averages were utilized to assess significant differences between groups in various comparisons. The subscore averages for the five subcategories of motivation were calculated. The subscores for the self-determination and grade motivation items were normalized

because of the use of a different point scale for the SMQ II portion of the survey compared to the scale utilized in the AMS – Chemistry portion of the survey. Both weighted and unweighted subscores were considered in the analysis. In cases where both the weighted and unweighted subscores yielded similar significant results for the same comparison parameters, the unweighted subscores were reported. In the case of where there were significant results using weighted subscores and nonsignificant results using unweighted subscores for the same comparisons, the weighed subscores were reported. For reference, Appendix E contains the results for the weighted subscores (or unweighted subscores when applicable).

5.7.5. Categorical Assignment and Determination of Maximum Motivation Subscale

While subscore averages are useful for examining changes over time and/or differences between groups, subscore averages do not provide useful information regarding the motivation of individuals or what motivation factors are most predominant in the sample. For example, while subscore averages can show increases in grade motivation throughout the course, it does not provide information about how many students are predominately motivated by grade motivation. To gain insight into these points, the maximum motivation subcategory was determined for each participant using a single categorical assignment. The categorical assignment for each student was determined by assessing which motivation subscale had the highest subscore. If there was a tie between an AMS – Chemistry subscale and a SMQ II subscale, priority was given to the AMS – Chemistry subscale due to there being more AMS items on the survey. In the event of a tie between two AMS-Chemistry subscales or the two SMQ II subscales, the individual was deemed to have "no priority."

5.8. Results & Discussion

5.8.1. Instrument Validity

As previously stated, both quantitative and qualitative methods were employed to establish instrument validity. EFA was utilized iteratively to determine the factor structure of the instrument using the combined cleaned data from GC II Fall 2021 Post and GC II Spring 2022 Post (n = 76). There were many iterations of EFA, but three EFA structures (EFA 1, EFA 2, EFA 3) were most useful for determining the underlying factor structure in conjunction with student interview results. The results for the items' factors are summarized in Table 5.4, where colors visually represent those items that factored together per EFA iteration and interview.

In EFA 1, amotivation items did not factor and both the grade and self-determination items from the SMQ II factored together despite measuring different aspects of motivation (blue). All three of the intrinsic items (to experience, to accomplish, and to know) factored together (purple), while in the original AMS-Chemistry survey, each subscale of intrinsic motivation factored separately. The combined grouping of the three subscales was not concerning in our case, considering all items broadly measured intrinsic motivation. The external items factored with identified regulation items (yellow), which was not concerning as identified regulation is a subscale of external motivation. A grade motivation item (Item 29) cross-loaded with the other grade motivation items and the external items (green). The introjected items were also cross-loading with the intrinsic items, which was unexpected as introjected regulation is farther on the external motivation side of the motivation continuum. Perhaps the students in this sample were not picking up on the nuances between the two.

In EFA 2, the identified regulation items were removed. This resulted in the amotivation items factoring together (orange). Similar findings with the cross-loading of the introjected and

intrinsic items (purple) and the cross-loading of item 29 (green) and the SMQ II items with grade motivation items were observed (blue). In EFA 3, all identified and introjected regulation items were removed along with grade motivation item 29. This resulted in the cleanest structure with four factors: Intrinsic (purple), SMQ- II items (blue), External (yellow), and Amotivation (orange)

Table 5.4. Item factors by color for EFAs and interviews. In a column, the same-colored shading indicates the items factored together.

Item	Subscale	Statement	EFA 1	EFA 2	EFA 3	Interviews
1	External Regulation	Because without having taken chemistry I would not find a high-paying job later on.				
2	To know	Because I experience pleasure and satisfaction while learning new things.				
3	Identified regulation	Because I think that chemistry courses will help me better prepare for the career I have chosen.		REMOVED	REMOVED	
4	To experience	For the feelings I experience when I am communicating chemistry ideas to others.				
5	Amotivation	Honestly, I don't know; I really feel that I am wasting my time taking chemistry courses.	**No Factor**			
6	To accomplish	For the satisfaction I experience while improving my understanding of chemistry.				
7	Introjected regulation	To prove to myself that I am capable of succeeding in chemistry.			REMOVED	Ambiguous
8	External Regulation	In order to obtain a better job later on.				
9	To know	For the pleasure I experience when I learn new things about chemistry.				
10	Identified regulation	Because taking chemistry will enable me to enter the job market in a field that I like.		REMOVED	REMOVED	
11	To experience	For the pleasure that I experience when I perform chemistry experiments.				
12	Amotivation	I once had good reasons for taking chemistry courses; however, now I wonder whether I should continue.	**No Factor**			
13	To accomplish	For the satisfaction I experience while succeeding in chemistry.				Ambiguous
14	Introjected regulation	Because when I succeed in chemistry I feel smart.			REMOVED	Ambiguous
15	External Regulation	Because I want to have a well-paying career.				
16	To know	For the pleasure that I experience in broadening my knowledge about chemistry.				
17	Identified regulation	Because taking chemistry courses will help me make more informed choices about my career options.		REMOVED	REMOVED	
18	To experience	For the enjoyment I experience when I think about the world in terms of atoms and molecules.				
19	Amotivation	I don't know why I take chemistry courses, I couldn't care less about them.	**No Factor**			
20	To accomplish	For the satisfaction I feel as I work toward an understanding of chemistry.				
21	Introjected regulation	To show myself that I am an intelligent person.			REMOVED	Ambiguous
22	External Regulation	In order to have a better salary later on.				
23	To know	Because studying chemistry allows me to continue to learn about things that interest me.				
24	Identified regulation	Because I believe that chemistry courses will improve my skills in my chosen career.		REMOVED	REMOVED	
25	To experience	For the satisfaction I experience while learning about various chemistry topics.				
26	Amotivation	I don't know; I can't understand what I am doing taking chemistry courses.	**No Factor**			
27	To accomplish	Because chemistry courses allow me to experience satisfaction in my quest for knowledge.				
28	Introjected regulation	Because I want to show myself that I can succeed in studying chemistry.			REMOVED	Ambiguous
29	Grade motivation	I like to do better than other students on chemistry tests.	Crossloads w. blue and yellow	Crossloads w. blue and yellow	REMOVED	Ambiguous
30	Grade motivation	Getting a good chemistry grade is important to me.				
31	Self-determination	I put enough effort into learning chemistry.				
32	Self-determination	I use strategies to learn chemistry well.				
33	Grade motivation	It is important that I get an "A" in chemistry.				
34	Self-determination	I spend a lot of time learning chemistry.				
35	Self-determination	I prepare well for chemistry tests and labs.				
36	Grade motivation	I think about the grade I will get in chemistry.				
37	Self-determination	I study hard to learn chemistry.				
38	Grade motivation	Scoring high on chemistry tests and labs matters to me.				

The student interview results assisted in determining a finalized factor structure. Results from the first segment of the interviews indicated that the students interpreted the survey items and scales appropriately. Results from the second segment of the interviews were utilized and compared to the factor structure determined by EFA. In terms of consistency, as seen in the EFA results, almost every student in both courses sorted all the amotivation items in one grouping (orange) and all the intrinsic items in another (purple). Also, students were consistently grouping the external items and identified items together as seen in the EFAs (yellow). Students sorted the introjected regulation items inconsistently and ambiguously (grey), which supports the unexpected factoring of those items in the EFA. Lastly, unlike in the EFA, the students were sorting the SMQ II self-determination (pink) and grade motivation (dark orange) items separately from each other, indicating the students interpreted these items differently as they were designed to be.

Next, considering the interview findings, another EFA using the same parameters as EFA 3 was performed with a larger sample with data collected from Fall 2021 Post to Fall 2022 post (n = 382). Ultimately, both the EFA and interview findings were utilized to propose a finalized factor structure to use for CFA. The proposed finalized factor structure resulted from the removal of the items listed previously and the separation of the SMQ II items. The final factor structure includes five factors: Intrinsic Motivation, External Motivation, Self-determination, Grade Motivation, and Amotivation. The motivation continuum utilized in the original AMS – Chemistry (Figure 5.2) was modified per this sample after completing the instrument validation and determining the finalized factor structure (Figure 5.4).

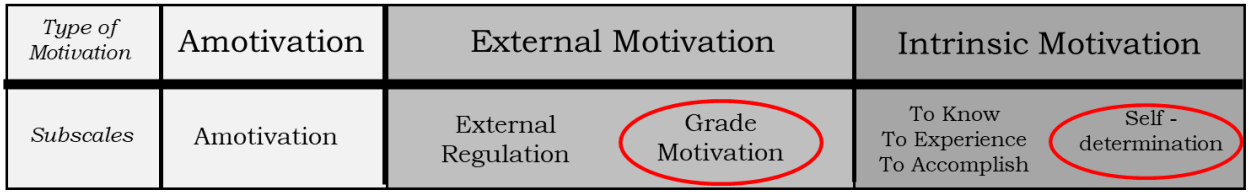


Figure 5.4. Motivation continuum based on the factor structure determined in this study

Following CFA practices, it is recommended that a different sample of the data be utilized for CFA than for EFA.[51] Thus, CFA was performed using all survey responses collected Spring 2023 Pre – Fall 2023 Post (n = 680). The CFA results support underlying latent constructs proposed with pertinent CFA values indicating good model fit. According to measures of good fit, the resulting factor loadings from the CFA were all greater than 0.6 (Table 5).[52] Other values indicative of good model fit are CFI values greater than 0.95, RMSEA values close to 0.05, SRMR values less than 0.05, and TLI values greater than 0.90.[53] The obtained values are reported in Table 5.5. The final factor structure with item loadings determined by CFA is reported in Table 5.6.

Table 5.5. Obtained CFA values compared to value ranges of good model fit

	Obtained Value	**Parameters for Good Model Fit[53]**
CFI	0.960	>0.95
RMSEA	0.052	~ 0.05
SRMR	0.049	<0.05
TLI	0.956	>0.90

Table 5.6. Factor structure for CFA

Factor 1: Intrinsic Motivation	*F1*	*F2*	*F3*	*F4*	*F5*
Because I experience pleasure and satisfaction while learning new things.	**0.814**				
For the feelings I experience when I am communicating chemistry ideas to others.	**0.723**				
For the satisfaction I experience while improving my understanding of chemistry.	**0.815**				
For the pleasure I experience when I learn new things about chemistry.	**0.911**				
For the pleasure that I experience when I perform chemistry experiments.	**0.862**				
For the satisfaction I experience while succeeding in chemistry.	**0.823**				
For the pleasure that I experience in broadening my knowledge about chemistry.	**0.861**				
For the enjoyment I experience when I think about the world in terms of atoms and molecules.	**0.861**				
For the satisfaction I feel as I work toward an understanding of chemistry.	**0.939**				
Because studying chemistry allows me to continue to learn about things that interest me.	**0.721**				
For the satisfaction I experience while learning about various chemistry topics.	**0.926**				
Because chemistry courses allow me to experience satisfaction in my quest for knowledge.	**0.849**				
Factor 2: External Motivation					
Because without having taken chemistry I would not find a high-paying job later on.		**0.861**			
In order to obtain a better job later on.		**0.871**			
Because I want to have a well-paying career.		**0.937**			
In order to have a better salary later on.		**0.939**			
Factor 3: Self-Determination					
I put enough effort into learning chemistry			**0.860**		
I use strategies to learn chemistry well			**0.809**		
I spend a lot of time learning chemistry			**0.807**		
I prepare well for chemistry tests and labs			**0.796**		
I study hard to learn chemistry			**0.860**		
Factor 4: Grade Motivation					
Getting a good chemistry grade is important to me				**0.838**	
It is important that I get an "A" in chemistry				**0.688**	
I think about the grade I will get in chemistry				**0.716**	
Scoring high on chemistry tests and labs matters to me				**0.904**	
Factor 4: Amotivation					
Honestly, I don't know; I really feel that I am wasting my time taking chemistry courses.					**0.829**
I once had good reasons for taking chemistry courses; however, now I wonder whether I should continue.					**0.606**
I don't know why I take chemistry courses, I couldn't care less about them.					**0.886**
I don't know; I can't understand what I am doing taking chemistry courses.					**0.869**

5.8.2. Motivation Subcategory Subscore Comparisons

The following section addresses RQ1. *Are there significant differences in motivation subscores within a semester, and are there significant differences in motivation subscores between course (general chemistry I vs. general chemistry II), sex, and major (nonpre-professional science major vs. pre-professional)?*

Data was further cleaned for pre and post comparisons, where students who did not complete both the pre and post motivation survey were excluded from analysis in the following sections.

5.8.2.A. – Subscore Comparisons by Course

In GC I (n = 158), there was a significant decrease in intrinsic motivation and significant increase in amotivation pre to post (Table 5.7). Table 5.8 reports GC II motivation subscores using weighted subscores, because the weighted subscores had additional significant results than with the unweighted subscores. There were significant increases in grade and amotivation for GC II students, and a significant decrease in intrinsic motivation.

As instructors, it is concerning to see amotivation increase and intrinsic motivation decrease over the semester. In GC II, grade motivation increased over the semester. When comparing the two courses, there were only significant differences observed in the post grade motivation subscores, with grade motivation being significantly higher in GC II than GC I (Table 5.9). This observation may be because students are more concerned about their grades as they advance to higher levels of chemistry; for example, organic chemistry is a higher-level chemistry course that often is required for pre-professional applications.

Table 5.7. GC I motivation average subscore comparisons pre to post of the semester

GC I Motivation Pre to Post Comparison (n = 158)				
	Pre	**Post**	***p***	**Effect Size**
Intrinsic Motivation	**3.53**	**3.23**	**0.028**	**0.176**
External Motivation	4.40	4.37	0.868	-----
Self - determination	4.83	4.71	0.269	-----
Grade Motivation	5.62	5.43	0.080	-----
Amotivation	**1.57**	**1.82**	**0.021**	**-0.185**

Table 5.8. Motivation average (weighted) subscore comparisons for GC II students pre to post of the semester

GC II Motivation Pre to Post Comparison (n = 144)				
	Pre	**Post**	***p***	**Effect Size**
Intrinsic Motivation	**2.85**	**2.68**	**0.022**	**0.194**
External Motivation	3.83	3.80	0.650	-----
Self - determination	3.94	4.05	0.117	-----
Grade Motivation	**4.39**	**4.51**	**0.046**	**-0.332**
Amotivation	**1.33**	**1.48**	**0.048**	**-0.166**

Table 5.9. Motivation average subscore comparisons between GC I and GC II students pre and post of the semester

GC I Student (n = 158) and GC II Student Comparison (n =144)								
	PRE				**POST**			
	GC I	**GC II**	***p***	**Effect Size**	**GC I**	**GC II**	***p***	**Effect Size**
Intrinsic Motivation	3.53	3.39	0.390	------	3.23	3.19	0.820	------
External Motivation	4.40	4.41	0.921	------	4.37	4.36	0.983	------
Self - determination	4.83	4.76	0.559	------	4.71	4.90	0.147	------
Grade Motivation	5.62	5.56	0.665	------	**5.43**	**5.69**	**0.027**	**-0.255**
Amotivation	1.57	1.67	0.344	------	1.82	1.87	0.721	------

5.8.2.B. – Subscore Comparisons by Sex

Motivation differences over the course of the semester were observed in GC I by both male (n = 52) and female students (n = 106). Males decreased in intrinsic motivation over the course of the semester (Table 5.10). Female students decreased in grade motivation and increased in amotivation (Table 5.11). Increases in amotivation among females in an introductory level course such as general chemistry I can be concerning when considering the decreased retention rate of females in STEM.[54] There were no significant differences comparing GC I male and female students (Table 5.12).

Table 5.10. Pre to post motivation subscore average comparisons for GC I male students

GC I Male Pre to Post Comparison (n = 52)				
	Pre	**Post**	***p***	**Effect Size**
Intrinsic Motivation	**3.74**	**3.37**	**0.035**	**0.300**
External Motivation	4.58	4.26	0.101	-----
Self - determination	4.72	4.61	0.190	-----
Grade Motivation	5.42	5.41	0.887	-----
Amotivation	1.77	1.88	0.525	-----

Table 5.11. Pre to post motivation subscore average comparisons for GC I female students

GC I Female Pre to Post Comparison (n = 106)				
	Pre	**Post**	***p***	**Effect Size**
Intrinsic Motivation	3.43	3.16	0.056	-----
External Motivation	4.31	4.42	0.335	-----
Self - determination	4.90	4.76	0.154	-----
Grade Motivation	**5.71**	**5.44**	**< 0.001**	**0.332**
Amotivation	**1.47**	**1.79**	**0.001**	**-0.320**

Table 5.12. Motivation average subscore comparisons between GC I female and male students pre and post of the semester

GC I Female Student (n = 106) and Male Student Comparison (n = 52)								
	PRE				**POST**			
	Female	**Male**	***p***	**Effect Size**	**Female**	**Male**	***p***	**Effect Size**
Intrinsic Motivation	3.43	3.74	0.204	------	3.16	3.37	0.381	------
External Motivation	4.31	4.58	0.237[a]	------	4.42	4.26	0.558	------
Self - determination	4.72	4.90	0.357	------	4.76	4.61	0.422	------
Grade Motivation	5.71	5.42	0.084	------	5.44	5.40	0.845	------
Amotivation	1.47	1.77	0.052[a]	------	1.79	1.88	0.658	------

[a] *Equal variance not assumed*

For pre to post comparisons for GC II female students, weighted subscores were utilized instead of the unweighted subscores, because there were additional significant items when using

the weighted subscores. GC II female students (n = 99) experienced significant increases in self-determination and grade motivation (Table 5.13). There was also a significant decrease in intrinsic motivation. While self-determination is a part of the umbrella term "intrinsic motivation" on the motivation continuum, the items were designed to measure various aspects related to intrinsic motivation. Therefore, it is plausible to observe different significant changes in self-determination than changes observed in intrinsic motivation.

Table 5.13. Pre to Post motivation average (weighted) subscore comparisons for GC II female students

GC II Female Pre to Post Comparison (n = 99)				
	Pre	**Post**	***p***	**Effect Size**
Intrinsic Motivation	**2.81**	**2.59**	**0.005**	**0.287**
External Motivation	3.77	3.80	0.803	------
Self - determination	**3.97**	**4.16**	**0.023**	**0.233**
Grade Motivation	**4.42**	**4.56**	**0.038**	**0.211**
Amotivation	1.26	1.39	0.117	------

Table 5.14. Pre to Post motivation average subscore comparisons for GC II male students

GC II Male Pre to Post Comparison (n = 45)				
	Pre	**Post**	***p***	**Effect Size**
Intrinsic Motivation	3.53	3.44	0.622	------
External Motivation	4.62	4.35	0.158	------
Self - determination	4.71	4.60	0.504	------
Grade Motivation	5.51	5.55	0.726	------
Amotivation	1.88	2.14	0.315	------

GC II male students (n = 45) had no significant differences (Table 5.14). Comparing GC II male and female students, female students exhibited higher self-determination at the end of the semester compared to male students (Table 5.15); this finding aligns with those found in a previous study.[30]

Table 5.15. Motivation average subscore comparisons pre and post for GC II male and female students

GC II Female Student (n = 99) and Male Student Comparison (n = 45)								
	PRE				POST			
	Female	**Male**	***p***	**Effect Size**	**Female**	**Male**	***p***	**Effect Size**
Intrinsic Motivation	3.33	3.53	0.396[a]	------	3.08	3.44	0.157	------
External Motivation	4.32	4.63	0.276	------	4.37	4.35	0.932	------
Self - determination	4.78	4.71	0.726	------	**5.03**	**4.60**	**0.035**	**0.383**
Grade Motivation	5.59	5.51	0.714	------	5.76	5.55	0.296	------
Amotivation	1.58	1.89	0.100	------	1.75	2.14	0.069	------
[a] *Equal variance not assumed*								

It is promising to see that female students in GC II did not increase in amotivation over the semester like seen in GC I; in fact, female students became more self-determined in chemistry. Perhaps female students who advanced to GC II became more confident in their abilities and more motivated after having a semester of chemistry under their belt.

In this study, and in previous motivation work, results were mixed when comparing male and female students. One thing seems to be evident; there is consistency in observing inconsistent motivation results for male and female students. This suggests that male and female students' motivations may be impacted by their environments and not inherently the sex of the individual itself. Further research is needed to fully understand the settings or contexts where male and female students are exhibiting particular and differing motivations.

5.8.2.C. – Subscore Comparisons by Major

Most students enrolled in GC I and GC II at this institution are science majors and/or declared a pre-professional emphasis (e.g. pre-medicine, pre-dentistry, pre-pharmacy etc.). To make comparisons by major, the science major students were separated into two groups: Pre-professionals and science majors with no pre-professional emphasis (referred to science majors herein). Students who did not fit this criterion were excluded from this portion analysis.

For pre-to-post comparisons for GC I science major students, weighted subscores are reported, because there were not significant results using the unweighted subscores. GC I science major students (n=86) had a significant increase in amotivation. It was found that GC I pre-professionals decreased in grade motivation pre to post (Table 5.16). Comparing pre-professionals and science majors in GC I, there were only significant differences in pre subscores; pre-professionals had significantly higher external and grade motivation subscores than science majors (Table 5.17).

Table 5.16. Pre to Post motivation average (weighted) subscore comparisons for GC I science major students

GC I Science Major Pre to Post Comparison (n = 86)				
	Pre	**Post**	***p***	**Effect Size**
Intrinsic Motivation	2.86	2.71	0.196	------
External Motivation	3.72	3.83	0.351	------
Self – determination	3.91	3.86	0.510	------
Grade Motivation	4.29	4.24	0.466	------
Amotivation	**1.23**	**1.41**	**0.048**	**-0.216**

Table 5.17. Pre to Post motivation average subscore comparisons for GC I pre-professional students

GC I Pre - Professional Pre to Post Comparison (n = 53)				
	Pre	**Post**	***p***	**Effect Size**
Intrinsic Motivation	3.68	3.32	0.087	------
External Motivation	4.79	4.58	0.226	------
Self - determination	4.98	4.80	0.108	------
Grade Motivation	**5.91**	**5.60**	**0.004**	**0.408**
Amotivation	1.66	1.94	0.121	------

Table 5.18. Motivation average subscore comparisons for GC I pre-professional and science major students pre and post of the semester

GC I Science Major (n = 86) and Pre – professional Comparison (n = 53)								
	PRE				**POST**			
	Pre - Professionals	**Science Majors**	***p***	**Effect Size**	**Pre - Professionals**	**Science Majors**	***p***	**Effect Size**
Intrinsic Motivation	3.69	3.40	0.252	------	3.33	3.22	0.663	------
External Motivation	**4.79**	**4.29**	**0.047**	**0.350**	4.58	4.41	0.525	------
Self - determination	4.99	4.73	0.168	------	4.80	4.66	0.454	------
Grade Motivation	**5.91**	**5.43**	**0.004**[a]	**0.482**	5.60	5.36	0.175[a]	------
Amotivation	1.67	1.56	0.499	------	1.94	1.78	0.444	------

[a] *Equal variance not assumed*

Pre-professionals may be motivated by more external factors (ex. grades, future career, future salary) as their grades are essential toward their application for pre-professional programs, and many careers that require a pre-professional emphasis are higher paying. Furthermore, prior research indicates that the pressure of competition can heighten the perception of control of external factors and take away from inherent interest.[41] It is not unreasonable to say that pre-professionals may experience this because pre-professional programs can be very competitive.

GC II science majors (n=78) significantly decreased in intrinsic motivation pre to post (Table 19); GC II pre-professionals (n=53) increased significantly in grade motivation (Table 5.20). In GC II, in both pre and post, pre-professionals had significantly higher subscores in external and grade motivation compared to the science majors (Table 5.21). Seeing this finding

in both GC I and GC II for pre-professionals further supports that pre-professionals are differently motivated than their nonpre-professional science major peers.

Table 5.19. Motivation average subscore comparisons for GC II science majors pre to post of the semester

GC II Science Major Pre to Post Comparison (n = 78)				
	Pre	**Post**	***p***	**Effect Size**
Intrinsic Motivation	**3.23**	**3.03**	**0.025**	**0.259**
External Motivation	4.20	4.14	0.615	------
Self - determination	4.68	4.91	0.055	------
Grade Motivation	5.43	5.51	0.367	------
Amotivation	1.77	1.94	0.149	------

Table 5.20. Motivation average subscore comparisons for GC II pre-professional students pre to post of the semester

GC II Pre - Professional Pre to Post Comparison (n = 53)				
	Pre	**Post**	***p***	**Effect Size**
Intrinsic Motivation	3.64	3.34	0.087	------
External Motivation	4.99	4.93	0.728	------
Self - determination	4.92	4.99	0.629	------
Grade Motivation	**5.84**	**6.10**	**0.032**	**-0.302**
Amotivation	1.49	1.76	0.054	------

Table 5.21. Motivation average subscore comparisons pre and post of the semester for GC II science major and pre-professional students

GC II Science Major (n = 78) and Pre – professional Comparison (n = 53)								
	PRE				POST			
	Pre - Professionals	Science Majors	*p*	Effect Size	Pre - Professionals	Science Majors	*p*	Effect Size
Intrinsic Motivation	3.64	3.29	0.178[a]	------	3.39	3.03	0.177[a]	------
External Motivation	**4.99**	**4.20**	**0.005**	**0.513**	**4.93**	**4.14**	**0.004**	**0.518**
Self - determination	4.92	4.68	0.247	------	4.99	4.91	0.694	------
Grade Motivation	**5.84**	**5.43**	**0.027**	**0.398**	**6.10**	**5.51**	**<0.001[a]**	**0.561**
Amotivation	1.49	1.77	0.120	------	1.76	1.95	0.393	------
[a] *Equal variance not assumed*								

5.8.2.D. – Subscore Comparisons by Learning Gains in GC II

As stated in previous chapters, a revised, targeted scale – themed curriculum intervention was implemented in general chemistry II. Using the multiple regression model, [55] student learnings gains can be generated to provide insight into the success of the intervention materials. General chemistry II students who completed the motivation surveys and had learning gains available were split into two groups: those with positive learning gains (intervention was beneficial) and those with negative learning gains (intervention not as beneficial). Due to a small sample size for the negative learning gain group (n = 9), no statistical methods were appropriate to assess the pre and post subscore averages. The positive learning gain group (n =35) had a significant increase pre-to-post in self-determination (Table 5.22).

Table 5.22. Motivation average subscore comparisons pre to post of the semester for positive learning gain group

Positive Learning Gain Group Motivation Pre to Post Comparison (n = 35)				
	Pre	**Post**	***p***	**Effect Size**
Intrinsic Motivation	3.44	3.34	0.251	-----
External Motivation	4.03	4.28	0.206	-----
Self - determination	**4.54**	**4.94**	**0.033**	**-0.375**
Grade Motivation	5.44	5.64	0.156	-----
Amotivation	1.37	1.64	0.155	-----

5.8.2.E. – Subscore Analysis Summary

The subscore analysis provided insight into the motivation profile of general chemistry students by examining motivation differences between various groupings. Across all comparisons, the highest subscore averages were found in grade motivation. In the context of this study, it is not necessarily a concerning result to observe high grade motivation subscore averages; although, as instructors fostering interest in science, more intrinsic and/or self-determined behaviors would be considered more ideal for chemistry achievement.[34,36] While amotivation was the lowest subscore average across all comparisons, amotivation may be a more concerning observation in the context of science instruction, interest, and chemistry achievement. This is especially true when considering subsets of the population, such as female students, given the lower retention rate for women in STEM related fields.[54] Evaluating the findings to previous work,[30,31] in this study, female students had higher self-determination than male students in GC II. Comparing majors, science majors were less extrinsically motivated than their pre-professional peers. This finding may be due to the rigorous academic qualifications many pre-professionals must meet in their future schooling and careers. Science majors without a pre-professional emphasis may experience more intrinsic motivation due to an enhanced personal interest in science. It is also possible that the added pressures of meeting grade and application

requirements for pre-professional programs supersede pre-professionals' personal science interests or intrinsic motivators. Lastly, findings from this part of the analysis show that those with more positive learning gains are increasing in self-determination over the semester. A deeper analysis into the motivation of the positive learning gains students is needed before making any claims about the relationship between student motivation and the scale-themed instruction.

The motivation subscore averages do provide useful information about the motivations of students. Yet, with any reported average, the specificity of individuals' motivations is masked and may lead to overall generalization of findings. For example, just because amotivation increases throughout the semester, it does not mean that the students are predominately amotivated and not being motivated more by other factors. There is a need for an alternative and/or supplemental approach to subscore analysis on surveys.

5.8.3. Categorical Assignment & Predominant Motivation Subscale

The following section aims to address RQ2 and RQ3:

> **RQ2:** What is the single categorical assignment of motivation for general chemistry I and II students, and does the single categorical assignment of motivation vary by sex or major?
>
> **RQ3:** How does the single categorical assignment of motivation vary within a semester for general chemistry I and II students?

Categorical assignment was used further to evaluate any potential changes in students' predominant motivation subscale over the semester. Categorical assignment refers to an individual being assigned to the motivation subscale for which they had the highest subscore. Both unweighted and weighted subscores were utilized initially in categorical assignment. The

weighted subscores ultimately ended up being the best measure, because a subset of GC I students (24% pre / 21% post) and GC II students (20% pre / 15% post) had a different category assignment when using unweighted subscores versus when using weighted subscores. Due to grade motivation being under the umbrella of external motivation, the two subscales were collapsed under the overarching term "external." Intrinsic motivation and self-determination were collapsed under the umbrella term "intrinsic" for the same reasoning.

Categorical assignment revealed that students in GC I and GC II were predominantly grade motivated throughout the course of the semester (Table 5.23). This result was also observed when comparing male and female students in each course (Tables 5.24-5.25). In both GC I and GC II, approximately 28% of female students' category assignment transitioned from external to intrinsic compared to the (23% GC II / 22% GC II) male students with the same transition. It is promising to see females are ending the semester more intrinsically motivated, especially when considering the "leaky pipeline" for women in STEM.[54] Only a small portion of the sample (3% or less) ended the semester in the amotivation category. This finding makes the increases in amotivation observed in the subscore analysis less concerning. Despite this, it is still important to note that more female students were assigned to the amotivation category compared to male students.

Table 5.23. Categorical assignment transitions pre to post of the semester: (A) GC I (B) GC II

A

Transition (Pre → Post)	*Percentage (# of students)*	*Total # of Students*
External → External	60.1 % (95)	114
Intrinsic → External	12.0 % (19)	
Amotivation → External	0.0% (0)	
Intrinsic → Intrinsic	17.1% (27)	42
External → Intrinsic	9.5 % (15)	
Amotivation → Intrinsic	0.0% (0)	
Any → Amotivation	1.3% (2)	2

"External" is comprised of external motivation and grade motivation
"Intrinsic" is comprised of internal motivation and self-determination
n = 158

B

Transition (Pre → Post)	*Percentage (# of students)*	*Total # of Students*
External → External	59.7 % (86)	101
Intrinsic → External	10.4% (15)	
Amotivation → External	0.0% (0)	
Intrinsic → Intrinsic	14.6% (21)	39
External → Intrinsic	11.8% (17)	
Amotivation → Intrinsic	0.70% (1)	
Any → Amotivation	2.8% (4)	4

"External" is comprised of external motivation and grade motivation
"Intrinsic" is comprised of internal motivation and self-determination
n = 144

Table 5.24. Categorical assignment transitions from pre to post of the semester for GC I male and female students

Transition (Pre → Post)	*Percentage of Male Students (# of students)*	*Total # of Male Students*	*Percentage of Female Students (# of students)*	*Total # of Female Students*
External → External	63.5% (33)	40	58.5% (62)	74
Intrinsic → External	13.5% (7)		11.3% (12)	
Amotivation → External	0.0% (0)		0.0% (0)	
Intrinsic → Intrinsic	17.3 %(9)	12	17.0% (18)	30
External → Intrinsic	5.7% (3)		11.3% (12)	
Amotivation → Intrinsic	0.0% (0)		0.0% (0)	
Any → Amotivation	0.0% (0)	0	1.9% (2)	2

"External" is comprised of external motivation and grade motivation
"Intrinsic" is comprised of internal motivation and self-determination
Male students (n=52)
Female students (n=106)

Table 5.25. Categorical assignment transitions from pre to post of the semester for GC II male and female students

Transition (Pre → Post)	*Percentage of Male Students (# of students)*	*Total # of Male Students*	*Percentage of Female Students (# of students)*	*Total # of Female Students*
External → External	64.4% (29)	33	57.6% (57)	68
Intrinsic → External	8.9% (4)		11.1% (11)	
Amotivation → External	0.0% (0)		0.0% (0)	
Intrinsic → Intrinsic	15.6% (7)	10	14.1 % (14)	28
External → Intrinsic	6.7% (3)		14.1 (14)	
Amotivation → Intrinsic	0.0% (0)		0.0% (0)	
Any → Amotivation	2.2% (1)	1	3.0% (3)	3

"External" is comprised of external motivation and grade motivation
"Intrinsic" is comprised of internal motivation and self-determination
Male students (n=45)
Female student (n=99)

In both courses, most pre-professionals and science majors were externally motivated throughout the semester. However, more science majors transitioned from external to intrinsic assignment when compared to pre-professionals (Tables 5.26-5.27). As seen in other research,[39] science majors with no pre-professional emphasis tend to be more intrinsically motivated than their pre-professional peers.

Table 5.26. Categorical assignment transitions pre to post of the semester for GC I pre-professional and science major students

Transition (Pre → Post)	*Percentage of Pre-Professional Students (# of students)*	*Total # of Pre-Professional Students*	*Percentage of Science Major Students (# of students)*	*Total # of Science Major Students*
External → External	64.2% (34)	41	60.5% (52)	61
Intrinsic → External	13.2% (7)		10.4% (9)	
Amotivation → External	0.0% (0)		0.0% (0)	
Intrinsic → Intrinsic	15.1% (8)	11	18.6% (16)	24
External → Intrinsic	5.6% (3)		9.3% (8)	
Amotivation → Intrinsic	0.0% (0)		0.0% (0)	
Any → Amotivation	1.9% (1)	1	1.2% (1)	1

"External" is comprised of external motivation and grade motivation
"Intrinsic" is comprised of internal motivation and self-determination
Pre-professional students (n=53)
Science major students (n=86)

Table 5.27. Categorical assignment transitions pre to post of the semester for GC II pre-professional and science major students

Transition (Pre → Post)	*Percentage of Pre-Professional Students (# of students)*	*Total # of Pre-Professional Students*	*Percentage of Science Major Students (# of students)*	*Total # of Science Major Students*
External → External	67.9% (36)	43	57.7% (45)	52
Intrinsic → External	13.2% (7)		9.0% (7)	
Amotivation → External	0.0% (0)		0.0% (0)	
Intrinsic → Intrinsic	7.5% (4)	9	17.9% (14)	23
External → Intrinsic	9.4% (5)		10.3% (8)	
Amotivation → Intrinsic	0.0% (0)		1.3% (1)	
Any → Amotivation	1.9% (1)	1	3.8% (3)	3

"External" is comprised of external motivation and grade motivation
"Intrinsic" is comprised of internal motivation and self-determination
Pre-professional students (n=53)
Science major students (n=78)

In GC II, both the positive and negative learning gains groups are predominately extrinsically motivated. However, the positive learning gains group has a greater portion of students that are intrinsically motivated at the end of the semester compared to the negative

learning gains group (Table 5.28). This suggests that more intrinsically motivated students benefit from the scale – themed intervention, and in broader strokes, curricula interventions in general. Applying the idea that types of instructional methods can impact motivation, it is possible the scale-themed instruction increased intrinsic motivation for the group with higher learning gains. Overall, the findings from the categorical assignment method further support the observations found using average subscores and their connections to previous work.

Table 5.28. Categorical assignment transitions pre to post of the semester for GC II students with positive and negative learning gains

Transition (Pre → Post)	*Percentage of Positive Learning Gains Students (# of students)*	*Total # of Positive Learning Gains Students*	*Percentage of Negative Learning Gains Students (# of students)*	*Total # of Negative Learning Gains Students*
External → External	57.1 % (20)	21	55.6% (5)	7
Intrinsic → External	2.9% (1)		22.2% (2)	
Amotivation → External	0.0% (0)		0.0% (0)	
Intrinsic → Intrinsic	17.1% (6)	14	11.1 %(1)	1
External → Intrinsic	22.9% (8)		0.0% (0)	
Amotivation → Intrinsic	0.0% (0)		0.0% (0)	
Any → Amotivation	0.0% (0)	0	11.1% (1)	1

"External" is comprised of external motivation and grade motivation
"Intrinsic" is comprised of internal motivation and self-determination
Positive learning gains students (n=35)
Negative learning gains students(n=9)

5.9. Limitations

Limitations in this work focus on the inherent complexity of measuring motivation. Motivation cannot be measured directly; therefore, the reliability and validity of the instruments to measure motivation in this study must be considered as well as the overall accuracy and precision to which the true motivations of humans can be observed. Students in this study were asked to report their motivations in relation to several subscales of motivation in the context of

chemistry. It is plausible students' motivation in chemistry is influenced by other factors not explicitly considered in this study. Moreover, motivation was measured at the start and the end of the semester to assess changes over time. It is possible the students' motivations changed at different points or several times throughout the semester that were not captured in this study's design. Lastly, some aspects of this study were limited by small sample sizes (i.e. negative learning gains group). A greater sample size is needed to further substantiate trends with statistical methods.

5.10. Conclusions, Implications, and Future Work

The motivation of general chemistry students was assessed through the validation of motivation surveys, the analysis of motivation subscore comparisons of selected groups, and employing categorical assignments to understand changes in maximum motivation subscales over the course of the semester. Overall, the artifacts of this work suggest students across general chemistry are primarily externally motivated. When considering the motivation of male and female students, at certain timepoints, more female students were self-determined / more intrinsically motivated than male students. Additionally, female students experienced amotivation more than male students.

Findings in this study further support the finding that pre-professionals are more extrinsically and grade motivated than science majors with no pre-professional emphasis. Additionally, this work reports findings that suggest more intrinsically motivated students may be more receptive and benefit more greatly from scale – themed instruction. It is also possible the scale-themed instruction increased intrinsic motivation for the group with higher learning gains. While further research is needed to understand how this finding applies to other contexts and curricula interventions, this work opens a dialogue among instructors to consider students'

motivations in course design and interventions. With this knowledge, instructors can adjust learning objectives to best align with students' goals and interests.

5.11. References

(1) Schunk, D. H. *Learning Theories: An Educational Perspective* (6th Ed.); Pearson Education: Boston, MA, **2012**. 338–339.

(2) Bybee, R. W.; Buchwald, C. E.; Crissman, S.; Heil, D. R.; Kuerbis, P. J.; Matsumoto, C.; McInerney, J. D. *Science and Technology Education for the Elementary Years: Frameworks for Curriculum and Instruction*; National Center for Improving Science Education: Washington, DC, **1989**.

(3) American Association for the Advancement of Science. *Science for All Americans: A Project 2061 Report on Literacy Goals in Science, Mathematics, and Technology*; Oxford University Press: New York, NY, **1989.**

(4) President's Council of Advisors on Science and Technology PCAST. *Engage to Excel: Producing One Million Additional College Graduates with Degrees in Science, Technology, Engineering, and Mathematics. Report to the President*; Washington, DC: Executive Office of the President. **2016.**

(5) Schunk, D. H., Meece, J. L., & Pintrich, P. R. *Motivation in Education: Theory, Research, and Applications* (4th Ed.); Pearson Education: Boston, MA, **2014.**

(6) Bandura, A. Perceived self-efficacy in cognitive development and functioning. *Educational Psychologist.* **1993**, *28* (2), 117–148.

(7) Bandura, A. *Social Foundations of Thought and Action: A Social Cognitive Theory;* Prentice-Hall: Englewood Cliffs, NJ, **1986.**

(8) Bandura, A. Social cognitive theory: An agentive perspective. *Annual Review of Psychology*, **2001,** *52,* 1–26.

(9) Bandura, A. *Self-Efficacy: The Exercise of Control*; Freeman.: New York, NY. **1997.**

(10) Bandura, A. Self-Efficacy: Toward a unifying theory of behavioral change. Psychological Review. **1977a,** *84,* 191–215.

(11) Schunk, D. H.; DiBenedetto, M. K. Motivation and social cognitive theory. *Contemporary Educational Psychology.* **2020**, *60*, Article 101832.

(12) Deci, E. L.; Ryan, R. M. *Intrinsic Motivation and Self-Determination in Human Behavior*; Plenum:New York, NY, **1985.**

(13) Ryan, R. M.; Deci, E. L. Self-Determination theory and the facilitation of intrinsic motivation, social development, and well-being. *American Psychologist.* **2000**, *55*(1), 68–78.

(14) Deci E. L.; Ryan R. M. The ‘“What”’ and ‘“Why”’ of Goal Pursuits: Human Needs and the Self-Determination of Behavior, *Psychol. Inq.* **2000**, *11*(4), 227–268.

(15) Deci, E. L.; Ryan, R. M. Self-determination theory: A macrotheory of human motivation, development, and health. *Canadian Psychology.* **2008**, *49* (3), 182–185.

(16) Ryan, R. M.; Deci, E. L. A self-determination theory approach to psychotherapy: The motivational basis for effective change. *Canadian Psychology.* **2008**, *49* (3), 186–193.

(17) Schiefele, U. Interest, learning, and motivation. *Educational Psychologist.* ***1991****, 26* (3-4), 299–323.

(18) Schunk D. H., Pintrich P. R. and Meece J. L. *Motivation in education: Theory, research, and applications,* Pearson: Upper Saddle River, New Jersey, **2008**.

(19) Skrondal, A.; Rabe-Hesketh, S. Latent variable modelling: A Survey*. *Scandinavian J Statistics.* **2007**, *34* (4), 712–745.

(20) Muthén, B. O. Beyond SEM: General latent variable modeling. *Behaviormetrika.* **2002**, *29* (1), 81–117.

(21) Cai, L. Latent variable modeling. *Shanghai Arch Psychiatry.* **2012**, *24* (2), 118–120.

(22) Stains, M. Keeping Up-to-Date with chemical education research standards. *J. Chem. Educ.* **2022**, *99* (6), 2213–2216.

(23) American Educational Research Association; American Psychological Association; National Council on Measurement in Education. *Standards for Educational and Psychological Testing*; American Educational Research Association: Washington, DC, **2014.**

(24) Fabrigar, L. R., Wegener, D. T., MacCallum, R. C., & Strahan, E. J. Evaluating the use of exploratory factor analysis in psychological research. *Psychological Methods.* **1999**, *4*(3), 272–299.

(25) Beavers, A. S.; Lounsbury, J. W.; Richards, J. K.; Huck, S. W.; Skolits, G. J.; Esquivel, S. L. Practical Considerations for Using Exploratory Factor Analysis in Educational Research. *Practical Assessment, Research, and Evaluation.* **2013**, *18* (6).

(26) Tourangeau, R. Survey reliability: Models, methods, and findings. *Journal of Survey Statistics and Methodology.* **2021**, *9* (5), 961-991.

(27) Glynn, S. M.; Taasoobshirazi, G.; Brickman, P. Science motivation questionnaire: Construct validation with nonscience majors. *Journal of Research in Science Teaching.* **2009**, *46* (2), 127–146.

(28) Glynn, S. M.; Brickman, P.; Armstrong, N.; Taasoobshirazi, G. Science motivation questionnaire II: Validation with science majors and nonscience majors. *Journal of Research in Science Teaching.* **2011**, *48* (10), 1159–1176.

(29) Komperda, R.; Hosbein, K. N.; Barbera, J. Evaluation of the influence of wording changes and course type on motivation instrument functioning in chemistry. *Chem. Educ. Res. Pract.* **2018**, *19* (1), 184–198.

(30) Salta, K.; Koulougliotis, D. Assessing motivation to learn Chemistry: Adaptation and validation of science motivation questionnaire II with Greek secondary school students. *Chem. Educ. Res. Pract.* **2015**, *16* (2), 237–250.

(31) Ardura, D.; Pérez-Bitrián, A. The effect of motivation on the choice of chemistry in secondary schools: Adaptation and validation of the science motivation questionnaire II to Spanish students. *Chem. Educ. Res. Pract.* **2018**, *19* (3), 905–918.

(32) Vallerand, R.; Pelletier, L.; Blais, M.; Brière, N.; Senécal, C.; Vallieres, E. The academic motivation scale: A measure of intrinsic, extrinsic, and amotivation in education. *Educational and Psychological Measurement.* **1992**, *52*, 1003–1003.

(33) Deci E. L. *Intrinsic Motivation*; Plenum Press: New York, NY, **1975.**

(34) Liu, Y.; Ferrell, B.; Barbera, J.; Lewis, J. E. Development and evaluation of a chemistry-specific version of the academic motivation scale (AMS-Chemistry). *Chem. Educ. Res. Pract.* **2017**, *18* (1), 191–213.

(35) Frost, S. J. H.; Rocabado, G. A.; Pratt, J. M.; De Arellano, D. C.-R.; Fields, K. B.; Raker, J. R. Motivation differences in first-semester organic chemistry: A comparison between first-time-in-college students and transfer students. *J. Chem. Educ.* **2024**, *101* (2), 354–363.

(36) Liu, Y.; Raker, J. R.; Lewis, J. E. Evaluating student motivation in organic chemistry courses: Moving from a lecture-based to a flipped approach with peer-led team learning. *Chem. Educ. Res. Pract.* **2018**, *19* (1), 251–264.

(37) Brouse C. H., Basch C. E., LeBlanc M., McKnight K. R. and Lei T. College Students' Academic Motivation: Differences by Gender, Class, and Source of Payment, College Quarterly. **2010,** *13*(1), 1–10.

(38) 2023 Facts: Applicants and Matriculants Data. Https://Www.Aamc.Org/Data-Reports/Students-Residents/Data/2023-Facts-Applicants-and-Matriculants-Data Accessed Sep. 14, 2024).

(39) Pacifici, L. B.; Thomson, N. Undergraduate science research: A comparison of influences and experiences between premed and non–premed students. *LSE*. **2011**, *10* (2), 199–208.

(40) Albaum, L. *Exploring the Relationship Between Pre-Medical Student Motivation and Academic Performance: Strategies to Improve Student Success*. Ph.D. Thesis, University of South Florida, Tampa, FL, **2020.**

(41) Stipek, D. J. *Motivation and Instruction.* In D. C. Berliner & R. C. Calfee, *Handbook of Educational Psychology;* Macmillan: New York, NY, **1996.**

(42) Lam, S.; Cheng, R. W.; Ma, W. Y. K. Teacher and student intrinsic motivation in project-based learning. *Instr. Sci.* **2009**, *37* (6), 565–578.

(43) *Garbarino, J.* The impact of anticipated reward upon cross-aged tutoring. *Journal of Personality and Social Psychology.* **1975**, *32,* 421–428.

(44) Assor, A., Kaplan, H., Kanat-Maymon, Y., & Roth, G. Directly controlling teacher behaviors as predictors of poor motivation and engagement in girls and boys: The role of anger and anxiety. *Learning and Instruction*. **2005**, *15*, 397–413.

(45) Lam, S.-F.; Law, Y.-K. The Roles of Instructional Practices and Motivation in Writing Performance. *The Journal of Experimental Education* **2007**, *75* (2), 145–164.

(46) Ryan, R. M., & Grolnick, W. S. Origins and pawns in the classroom: Self-report and projective assessments of individual differences in children's perceptions. *Journal of Personality and Social Psychology.* **1986,** *50,* 550–558.

(47) Cordova, D. I., & Lepper, M. R. (1996). Intrinsic motivation and the process of learning: Beneficial effects of contextualization, personalization, and choice. *Journal of Educational Psychology.* **1996,** *88*, 715–730.

(48) Grolnick, W. S., & Ryan, R. M. Autonomy in children's learning: An experimental and individual difference investigation. *Journal of Personality and Social Psychology*. **1987,** 52, 890–898.

(49) Kadir, M. S.; Yeung, A. S.; Ryan, R. M.; Forbes, A.; Diallo, T. M. O. Effects of a dual-approach instruction on students' science achievement and motivation. *Educ. Psychol. Rev.* **2020**, *32* (2), 571–602.

(50) Vaino, K.; Holbrook, J.; Rannikmäe, M. Stimulating students' intrinsic motivation for learning chemistry through the use of context-based learning modules. *Chem. Educ. Res. Pract.* **2012**, *13*, 410–419.

(51) Anderson, J. C.; Gerbing, D. W. Structural equation modeling in practice: A review and recommended two-step approach. *Psychological Bulletin.* **1988,** *103*(3), 411–423.

(52) MacCallum, R. C., Widaman, K. F., Zhang, S., & Hong, S. Sample size in factor analysis. *Psychological Methods.* **1999,** 4(1), 84–99.

(53) Hu, L.; Bentler, P. M. Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Structural Equation Modeling: A Multidisciplinary Journal*. **1999**, *6* (1), 1–55.

(54) Travis, J. *The Pipeline Is Leaking Women All the Way Along*. Science. 1993, *260* (5106), 409-411.

(55) Gerlach, K.; Trate, J.; Blecking, A.; Geissinger, P.; Murphy, K. Valid and reliable assessments to measure scale literacy of students in introductory college chemistry courses. *J. Chem. Educ.* **2014**, *91* (10), 1538–1545.

Chapter 6

Conclusions

In this chapter, the impact and importance of this body of work will be demonstrated via the presentation of the project's conclusions. Concluding remarks will be discussed in four main sections: conclusions, limitations, implications for practice, and future work.

6.1. Conclusions

This project aimed to achieve an in-depth investigation into scale-literacy and the refinement of a general chemistry scale-themed curriculum. Based on the previous iterations of this work, an existing scale-themed instruction across general chemistry courses reported larger student learnings gains in GC I compared to GC II. These findings highlighted a need for further research into scale instruction for GC II. The body of work herein further explores scale instruction in chemistry via a three-component investigation.

Key areas of the course were identified to target for the revisions to the scale-themed curriculum in GC II. Identifying these areas was crucial to the later installments of this project and resulted in the creation of course materials with increased scaffolding (Chapters 2-3). The targeted areas and scaffolded materials integrated into the revised curriculum were concluded to have been successful as demonstrated by increased learning gains, over the course of five semesters (Chapter 3). It was hypothesized that GC II students were experiencing a ceiling effect in scale instruction; but based on the increases in learning gains, it appears a ceiling effect was unlikely. Student interviews further supported this claim as demonstrated by the evaluation of linked prompts to reveal areas of the course in need of additional scaffolded support (Chapter 4). Student interviews provided additional insight into students' scale abilities in the context of solutions and kinetics. The success of the intervention was also explored by using affective

measures such as student motivation (Chapter 5). Findings from the motivation work suggest that the students were very extrinsically motivated in the course, yet more intrinsically motivated students had greater learning gains and assumingly benefitted more from the scale-themed intervention. The achievement of the project's central aims is exemplified when assessing the findings from each component together. Ultimately, this work demonstrates the success of the revised scale-themed intervention in GC II and the variety of methods employed in this investigation.

6.2. Limitations

Limitations in this work center on generalizability. The identified areas of the course to target and revised materials were dependent on course features, internal measures, and external measures specific to this GC II course. The extent to which these methods and claims can be applied for other general chemistry curricula or students cannot be determined as representative without much further related research at various institutions. Additionally, students' interviews, motivation, and learning gains were only studied from one course at one institution. The extent to which the findings can be applied to all the general chemistry students within and outside of the institution of focus cannot be determined.

6.3. Implications for Teaching

There are overarching implications of this work in terms of scale literacy, higher education, and chemistry. Presented herein are several approaches for designing and modifying course curricula in higher education contexts that can be easily adapted by discipline or educational setting. This work also presents a detailed approach to implementing instructional scaffolding and a scale-themed curriculum in undergraduate chemistry. Beyond chemistry, these methodologies add to the lacking body of research on the implementation of scale concepts in

science education and can potentially be modified for science courses across all levels of education.

In the context of general chemistry, findings from this work highlight areas to focus instructional efforts. From student interviews, most students in GC II possessed the necessary scale skills required to decode particulate diagrams. Depending on performance or content area, students demonstrated varying success in interpreting graphs and chemistry-related numerical values without or alongside particulate diagrams. Instructional efforts should focus on using particulate diagrams alongside highly graphical or numerical concepts to assist with chemistry understanding. Additionally, interviews highlighted content areas, such as solubility curves, saturation, half-life, and the Maxwell-Boltzmann distribution, where students exhibited misconceptions. Instruction should focus on using scaffolding to introduce these topics and spending time on honing number sense skills.

6.4. Future Work

Clearly, scale is an essential component of one's scientific literacy, yet it is often overlooked in science curricula. It is necessary to explicitly include scale in science education to foster a scientifically literate society. Future work related to the incorporation of scale into science courses other than chemistry would be vital to increasing scientific literacy. Based on the findings of this work, a longitudinal study on the development of chemistry students' scale literacy over time and exposure to chemistry would provide additional insight into how scale skills develop and change. This could be executed by incorporating scale into organic chemistry or other advanced chemistry courses.

Related to the scale literacy of GC II students and the improved scale-themed curriculum, the analysis of the other two interview sets (Equilibria and Thermodynamics &

Electrochemistry) would provide a larger picture of how GC II students develop and use scale in other content areas.

Expanding on the motivation work, it would be interesting to investigate if any motivation categories would be a significant predictor in the multiple regression model that was utilized throughout this study. Continual data collection and analysis on student learning gains and motivation will provide more clarity on the impact student motivation has on certain groups of students. Findings of this work suggest that students who are more intrinsically motivated benefit more from the intervention, or a group of students became more intrinsically motivated because of the scale-themed curriculum. This opens the opportunity to expand research on motivation and its impact on effectiveness of instructional interventions.

Appendix A

Table A.1. Rating descriptions for multiple choice exam item categorization

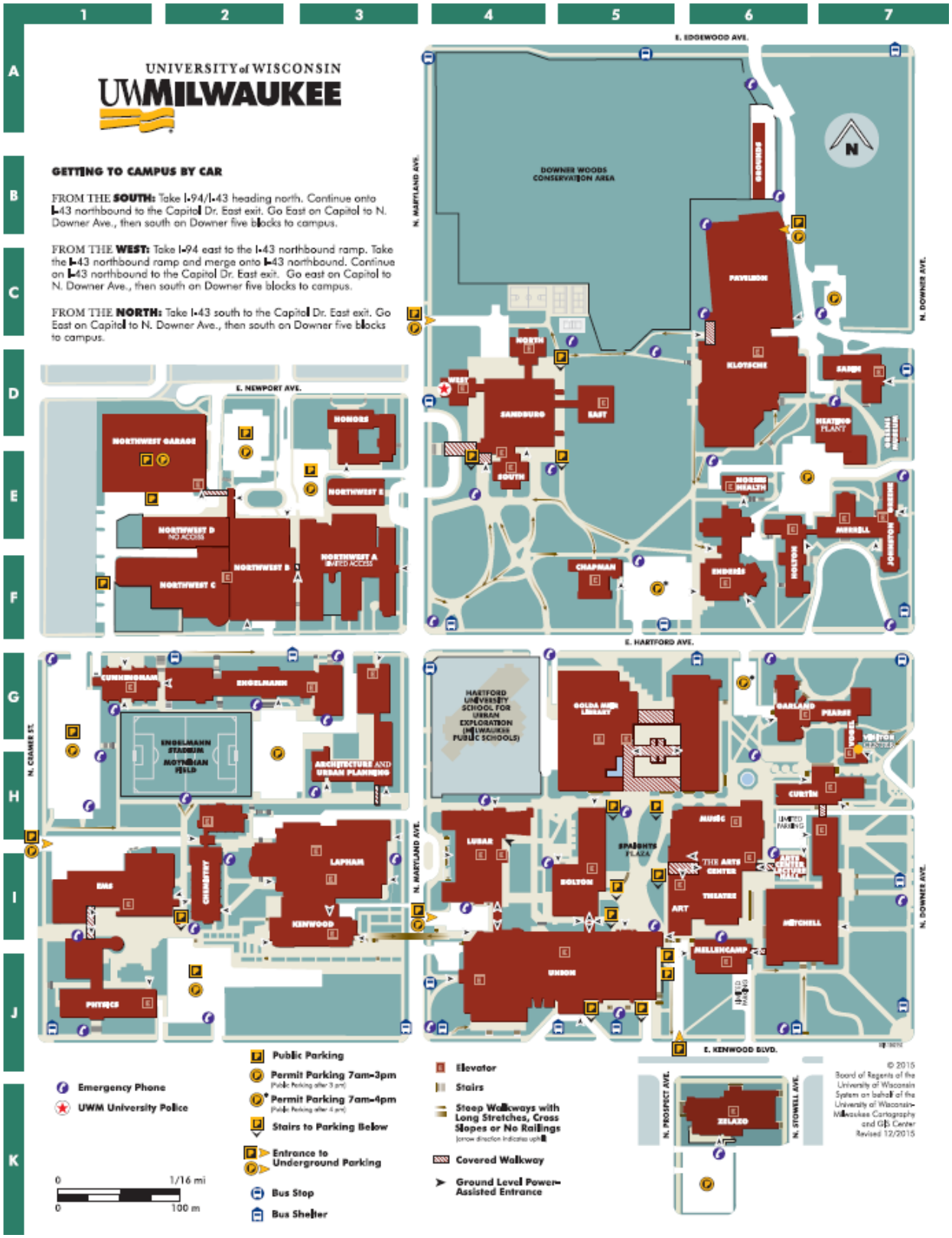
Type of Problem (Conceptual, Algorithmic, Recall)	
Rating	*Description*
0	Recall of definition or basic fact
1	Fully conceptual
2	
3	Both conceptual and algorithmic
4	
5	Fully algorithmic
Visual Spatial (Diagrams, Images, Graphs)	
Rating	*Description*
0	N/A
1	“See what's there"
2	Transform
3	Integrate image with words
4	Combined multiple pieces of visual info (i.e. several images / use of references)
5	Generate image
Level of Math	
Rating	*Description*
0	N/A
1	Basic arithmetic
2	Basic algebra
3	Advanced algebra
4	Logs/exponentials
5	Combination of advanced topics
Inclusion of Scale (Number sense, Understanding quantity, Unitizing)	
Rating	*Description*
0	N/A
1	Low inclusion
2	
3	
4	
5	High inclusion

Appendix B

Interview Training Activity

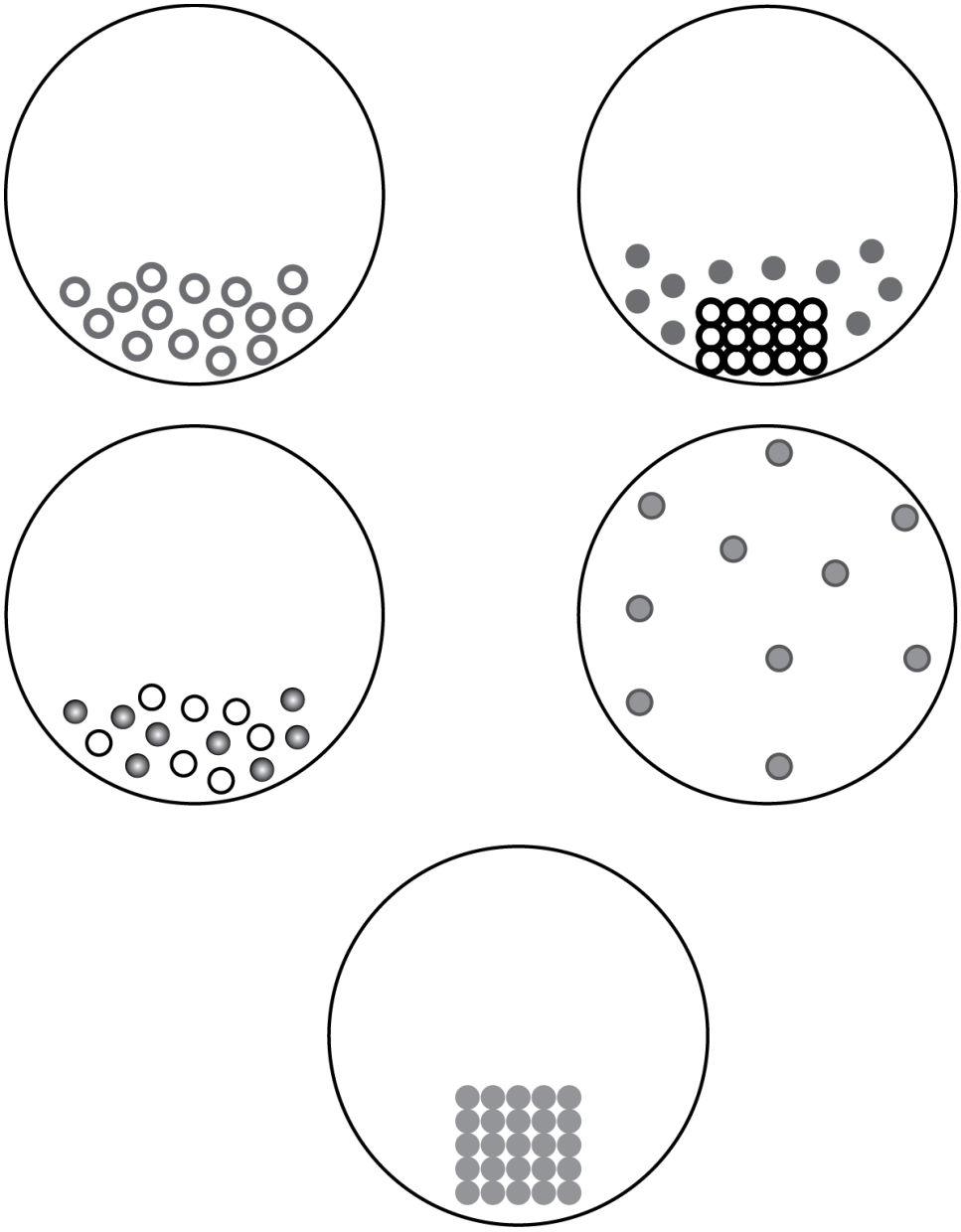
Training Exercises

1) Prompt: Describe what you see.
2) Prompt: Describe what you see and how it differs from the 2015 map
3) Prompt: Generate an image of the 2nd floor of the chemistry building

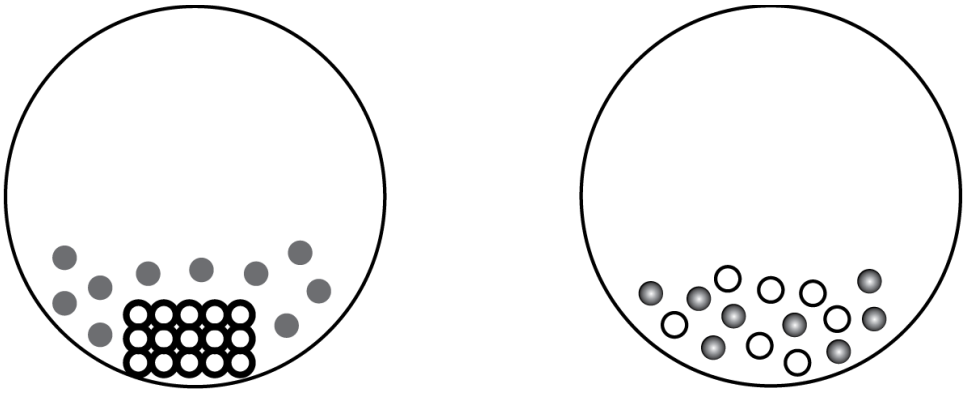

UNIVERSITY of WISCONSIN
UWMILWAUKEE
GETTING TO CAMPUS BY CAR
FROM THE SOUTH: Take I-94/I-43 heading north. Continue onto I-43 northbound to the Capitol Dr. East exit. Go East on Capitol to N. Downer Ave., then south on Downer five blocks to campus.
FROM THE WEST: Take I-94 east to the I-43 northbound ramp. Take the I-43 northbound ramp and merge onto I-43 northbound. Continue on I-43 northbound to the Capitol Dr. East exit. Go east on Capitol to N. Downer Ave., then south on Downer five blocks to campus.
FROM THE NORTH: Take I-43 south to the Capitol Dr. East exit. Go East on Capitol to N. Downer Ave., then south on Downer five blocks to campus.
E. EDGEWOOD AVE.
N. MARYLAND AVE.
N. DOWNER AVE.
DOWNER WOODS CONSERVATION AREA
GROUNDS
N
PAVILION
NORTH
WEST
SANDBURG
EAST
SOUTH
KLOTSCHE
SAEGER
HEATING PLANT
NORTH HEALTH
MERRILL
JOHNSTON
HOLTON
ENDERIS
CHAPMAN
E. NEWPORT AVE.
NORTHWEST GARAGE
HONORS
NORTHWEST E
NORTHWEST D
NO ACCESS
NORTHWEST B
NORTHWEST A
GATED ACCESS
NORTHWEST C
E. HARTFORD AVE.
N. CRAMER ST.
CUNNINGHAM
ENGELMANN
ENGELMANN STADIUM
NOTTINGHAM FIELD
ARCHITECTURE AND URBAN PLANNING
HARTFORD UNIVERSITY SCHOOL FOR URBAN EXPLORATION (MILWAUKEE PUBLIC SCHOOLS)
GOLDA MEIR LIBRARY
GARLAND
PEARSE
CURTIN
LUBAR
BOLTON
SPAIGHTS PLAZA
MUSIC
THE ARTS CENTER
THEATRE
ART
MITCHELL
MELLENCAMP
UNION
LAPHAM
KENWOOD
CHEMISTRY
EMS
PHYSICS
E. KENWOOD BLVD.
N. PROSPECT AVE.
N. STOWELL AVE.
ZELAZO
Emergency Phone
UWM University Police
Public Parking
Permit Parking 7am-3pm
Permit Parking 7am-4pm
Stairs to Parking Below
Entrance to Underground Parking
Bus Stop
Bus Shelter
Elevator
Stairs
Steep Walkways with Long Stretches, Cross Slopes or No Railings
Covered Walkway
Ground Level Power-Assisted Entrance
0
1/16 mi
0
100 m
© 2015 Board of Regents of the University of Wisconsin System on behalf of the University of Wisconsin-Milwaukee Cartography and GIS Center
Revised 12/2015

Solutions & Kinetics Interview Set

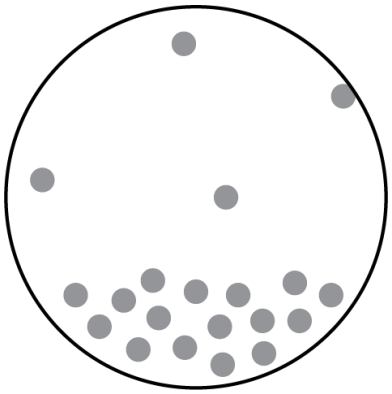
Prompt 1: Describe each figure and the differences between each figure.

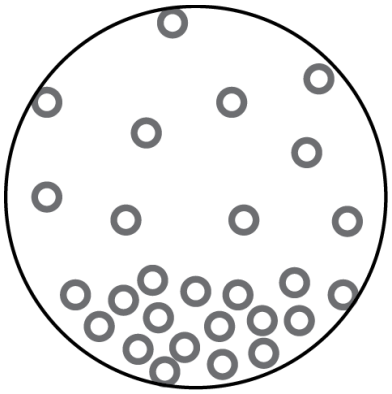


Prompt 2: Describe the solubility and the differences between the two figures.

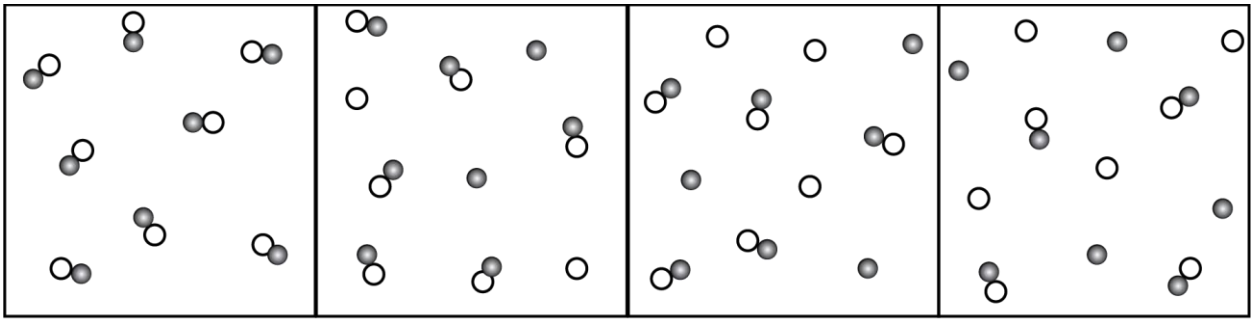


Prompt 3: Describe the intermolecular forces and the differences between the two figures.

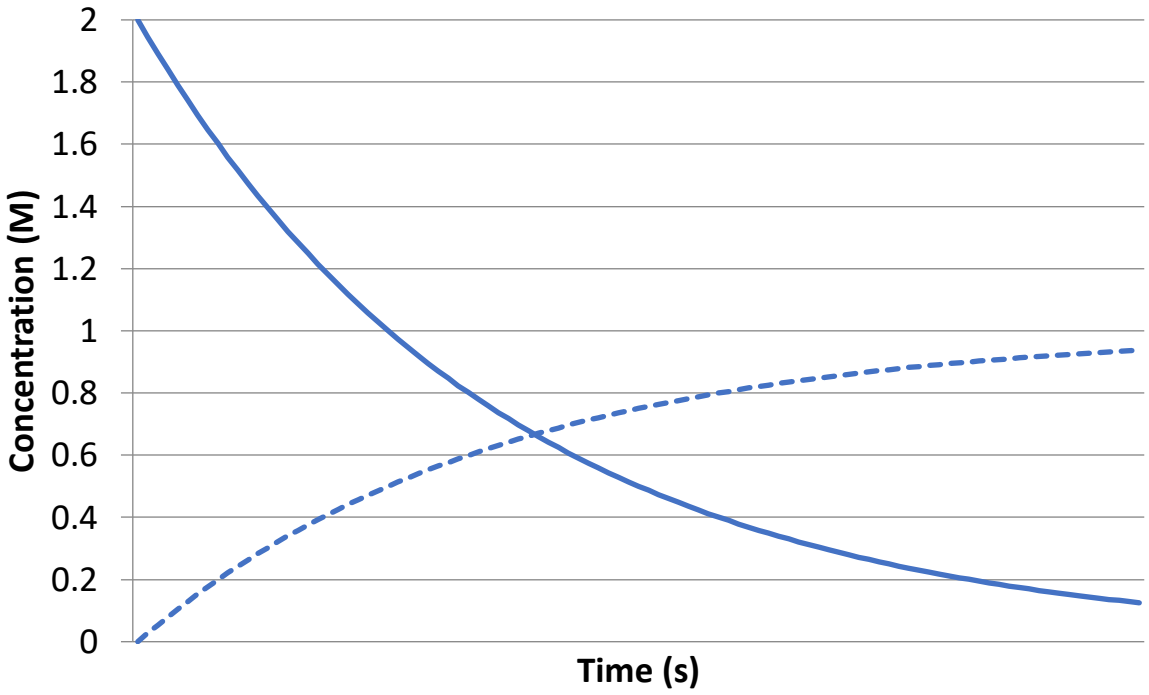




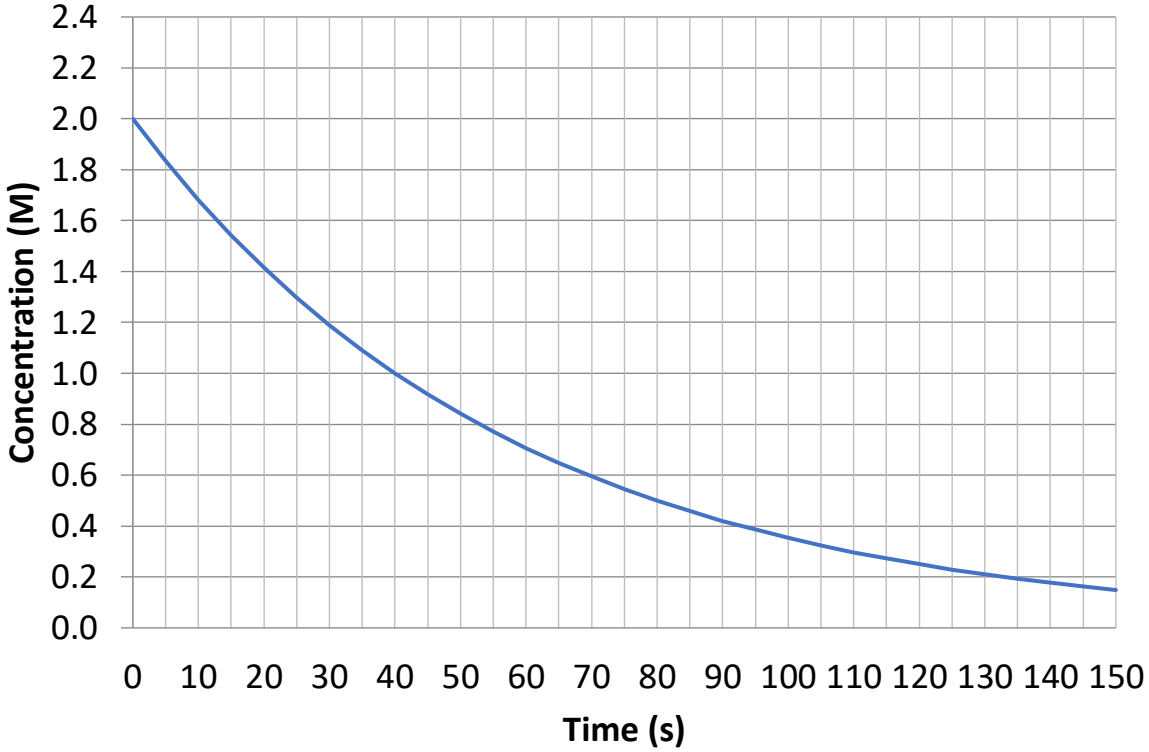
Prompt 4: Describe what is happening in the figure.



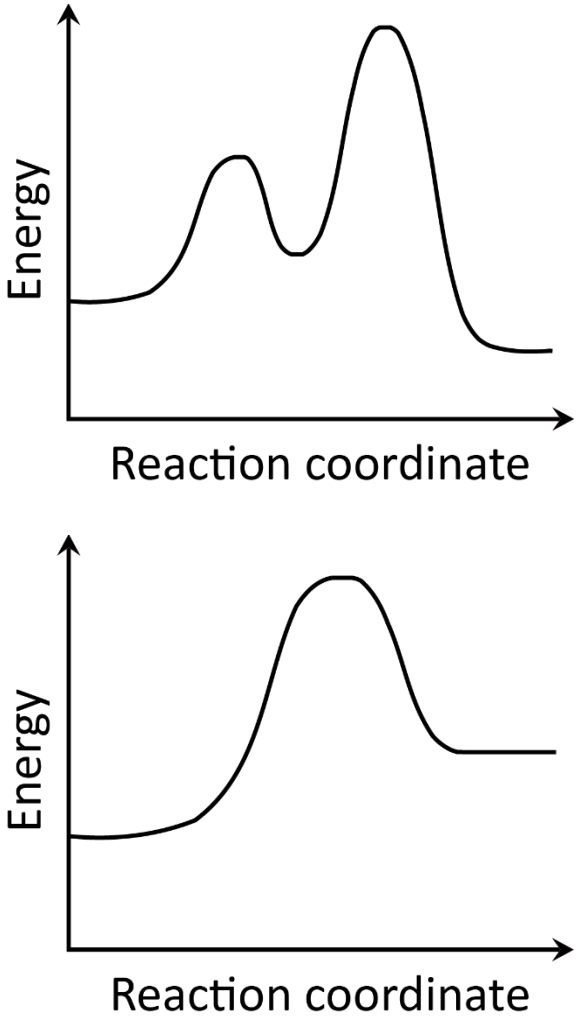
Prompt 5: Describe what is happening in the graph.



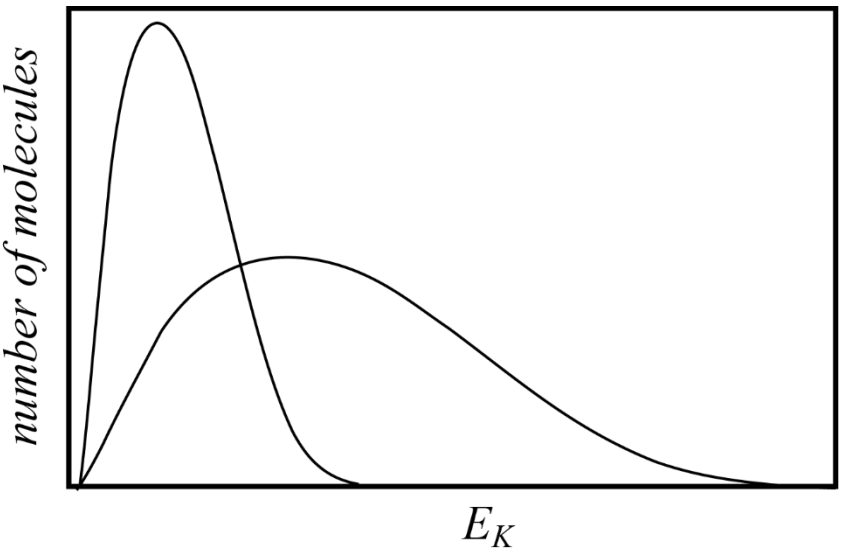
Prompt 6: Describe what is happening in the graph.



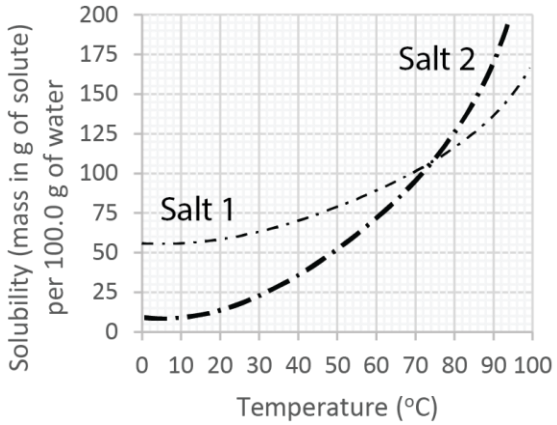
Prompt 7: Describe the figures and the differences between them.

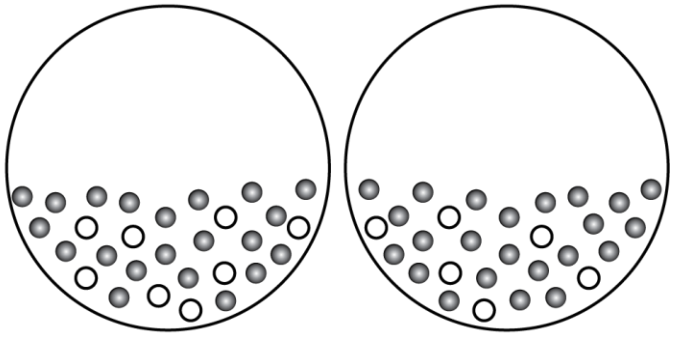


Prompt 8: Describe the figure.



Prompt 9: How does the graph connect to the diagrams?



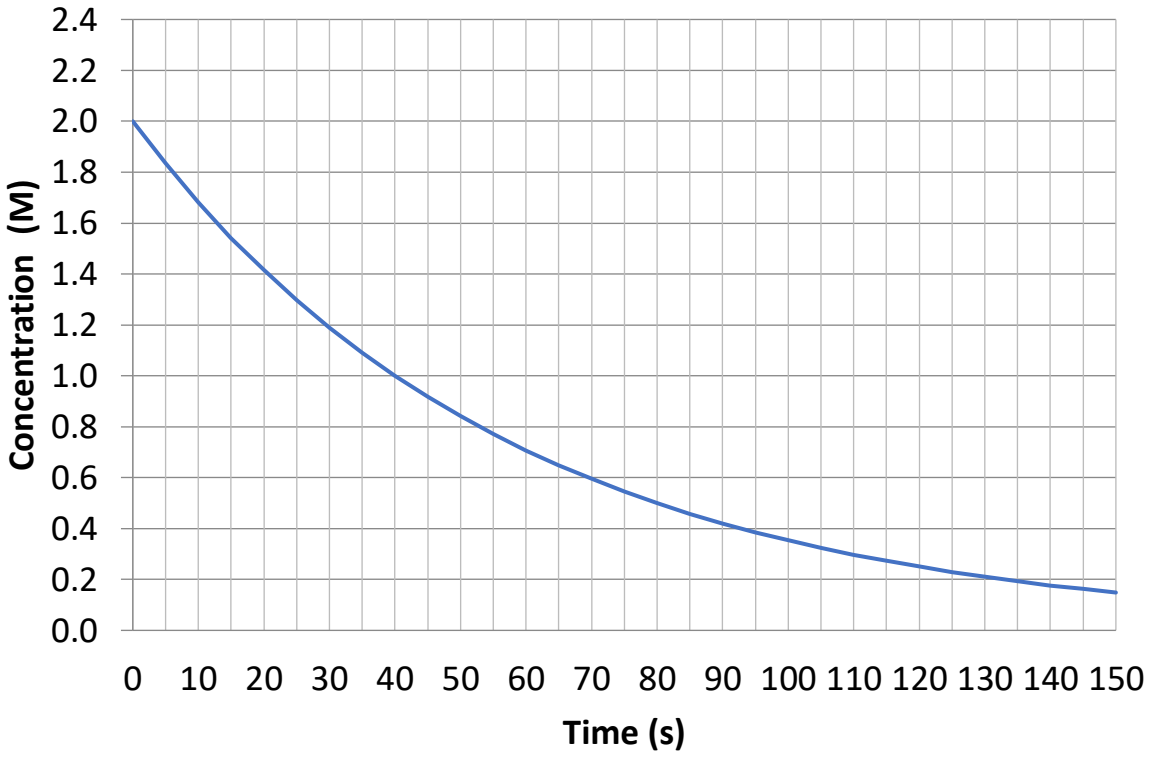


Prompt 10: Describe the difference in the values.

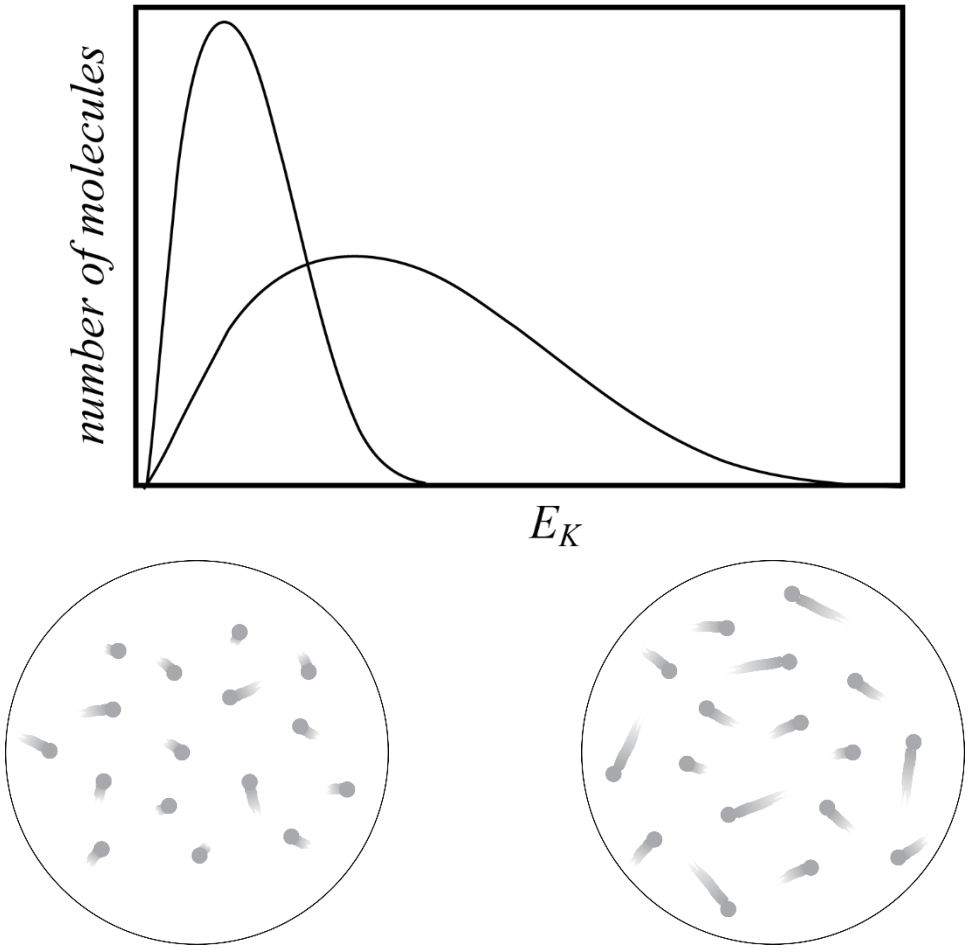
40% NaCl(aq) by mass

X_{NaCl} = 0.40 (in water)

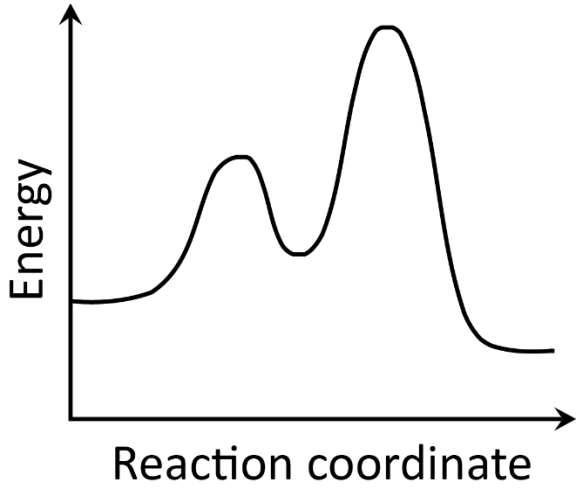
Prompt 11: What is the reaction order and half-life of the reaction?

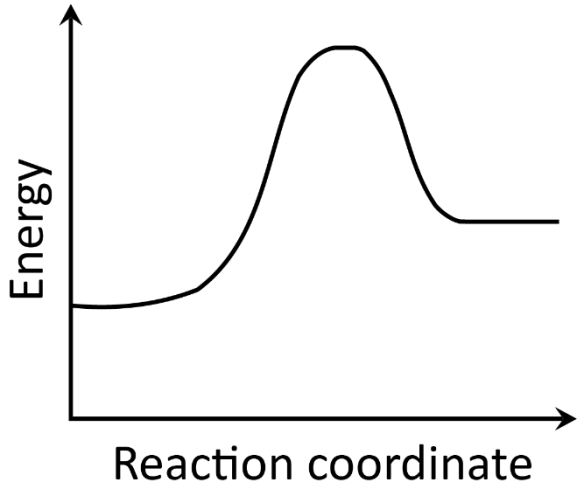


Prompt 12: How does the graph connect to the diagrams?



Prompt 13: How do the graphs connect to the proposed mechanisms?





Overall reaction: $A_2(g) + B_2(g) \rightarrow 2AB(g)$

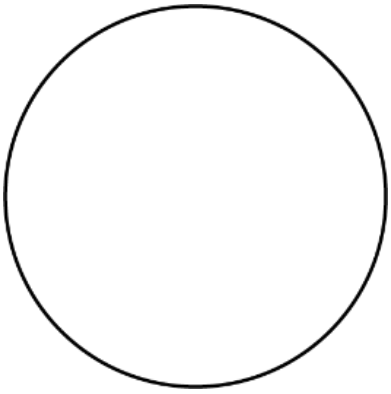
mechanism 1: $A_2(g) \rightarrow 2A(g)$
$2A(g) + B_2(g) \rightarrow 2AB(g)$

mechanism 2: $A_2(g) + B_2(g) \rightarrow 2AB(g)$

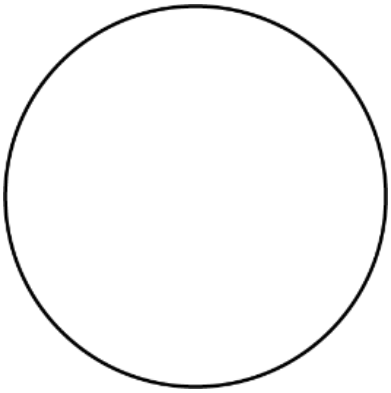
mechanism 3: $A_2(g) + C(g) \rightarrow A_2C(g)$
$A_2C(g) + B_2(g) \rightarrow 2AB(g) + C(g)$

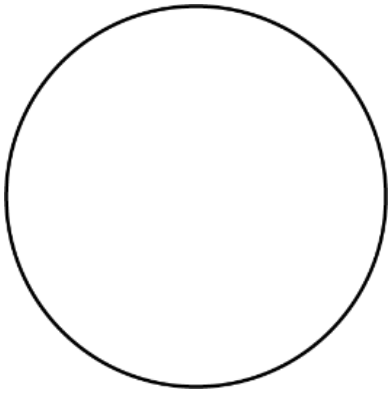
Prompt 14:

Generate a solution that is made up of water and an electrolyte

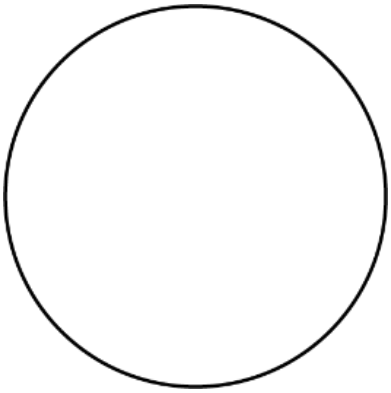


Generate a solution that is made of a nonvolatile solvent and a nonvolatile solute



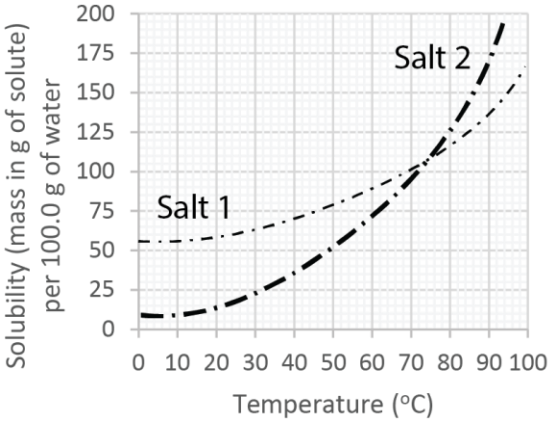


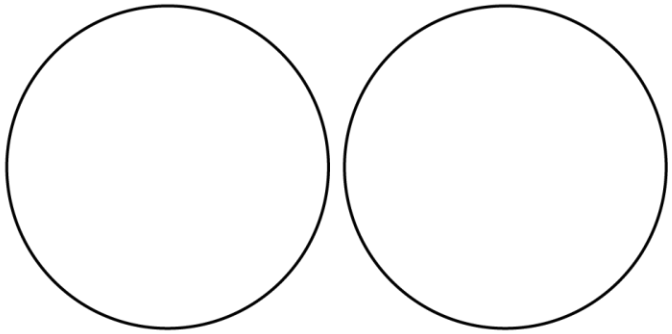
Generate a solution made up of a nonvolatile solvent and a volatile solute



Generate a solution made up of two volatile substances

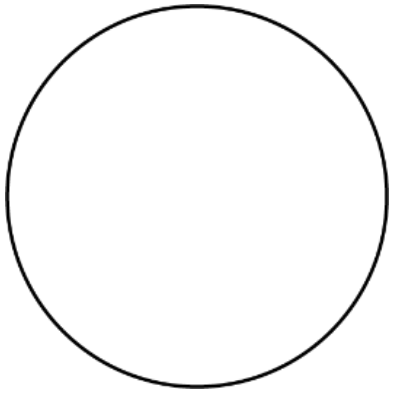
Prompt 15: Generate one or more diagrams based on the graph.



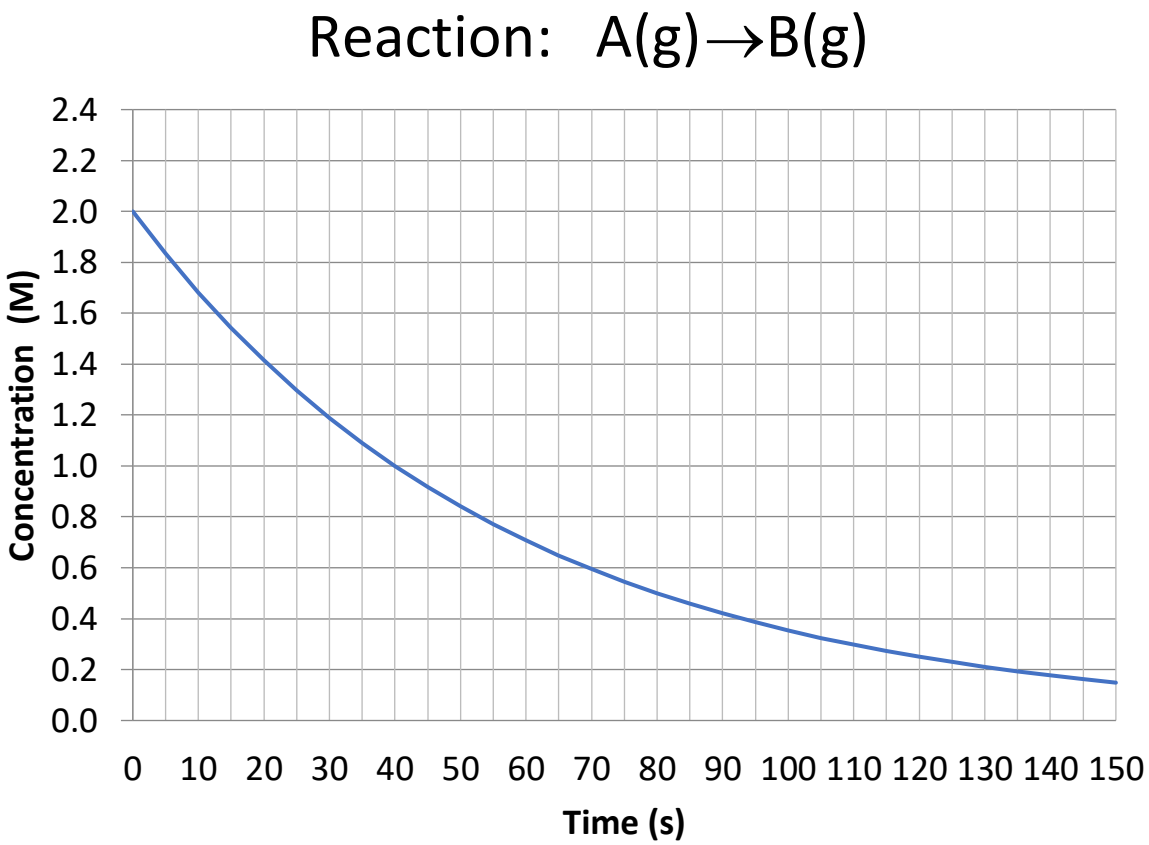


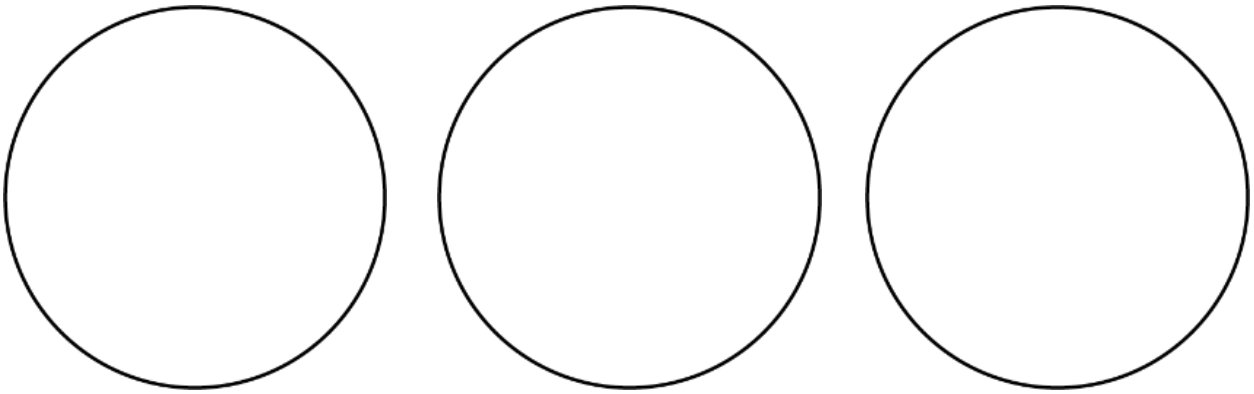
Prompt 16: Generate a diagram based on the value below.

X_{NaCl} = 0.40 (in water)



Prompt 17: Generate a diagram for three points of time.





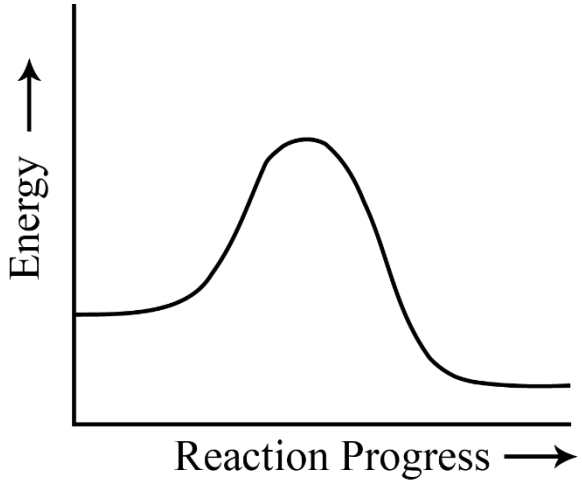
Time = 0 s

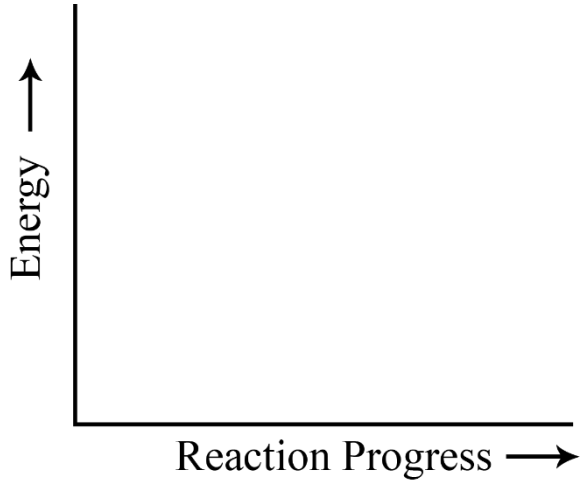
Time = 40 s

Time = 80 s

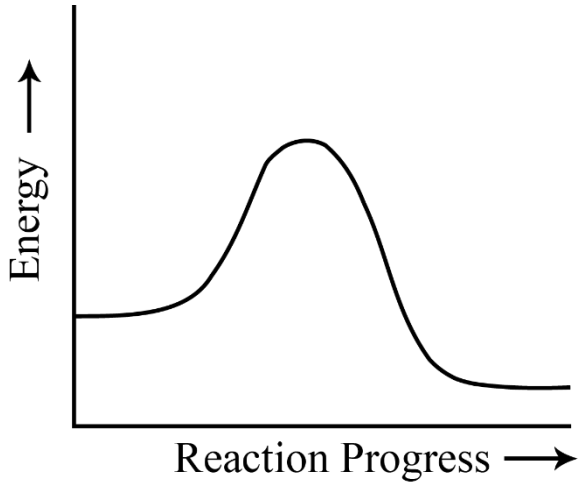
Prompt 18:

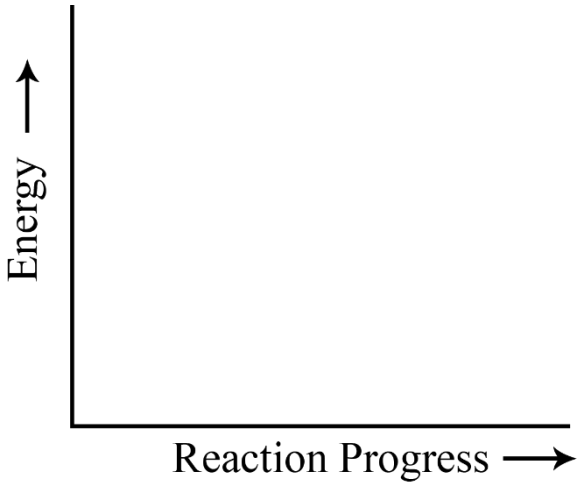
A) Generate an energy diagram with lower Ea than the diagram to the left





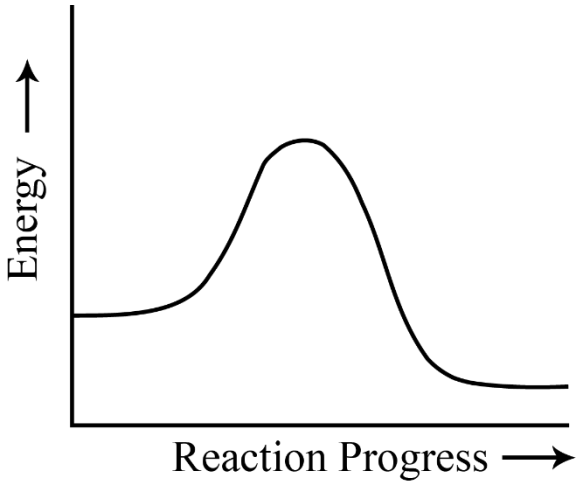
B) Generate an energy diagram with a faster rate than the diagram to the left.

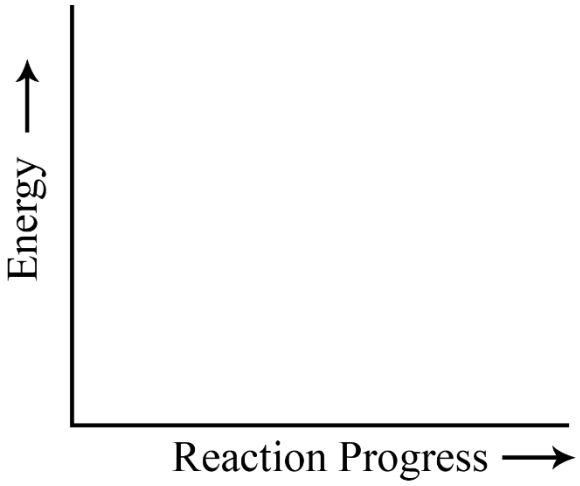




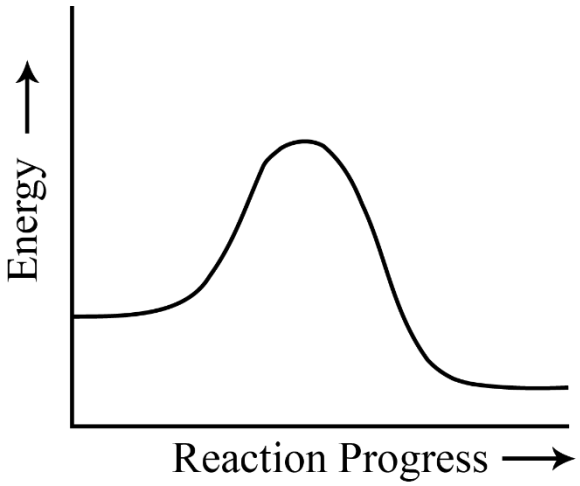
Prompt 19:

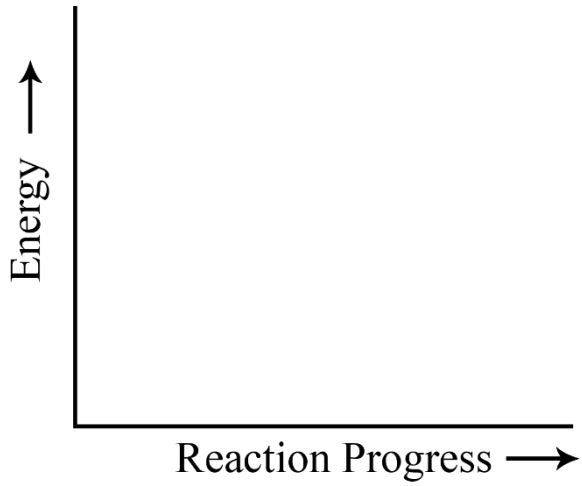
A) Generate an energy diagram with a catalyst.





B) Generate an energy diagram with 2 steps.

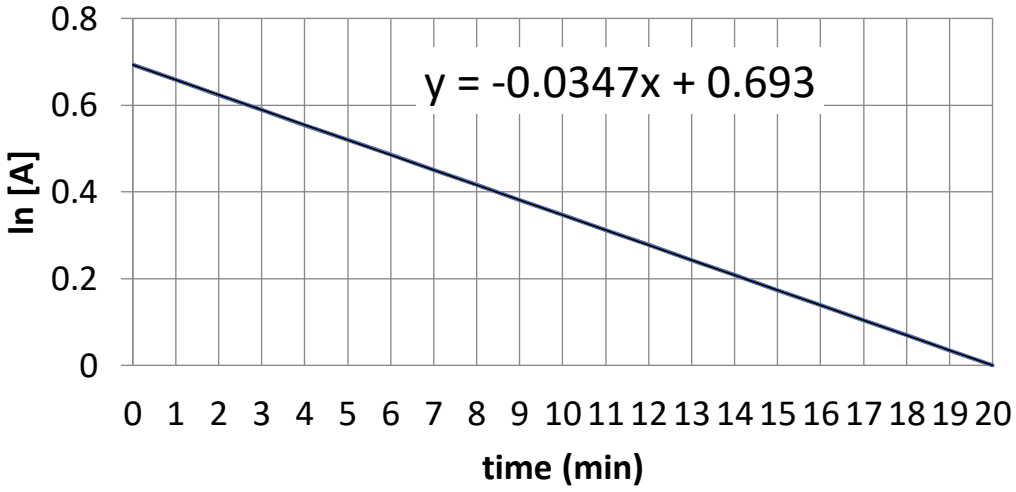




Prompt 20:

$$\ln\frac{[A]_0}{[A]_t} = kt \qquad \ln[A]_t = -kt + \ln[A]_0$$

A) What is the reaction order, *k*, and $t_{1/2}$ based on the plot below?

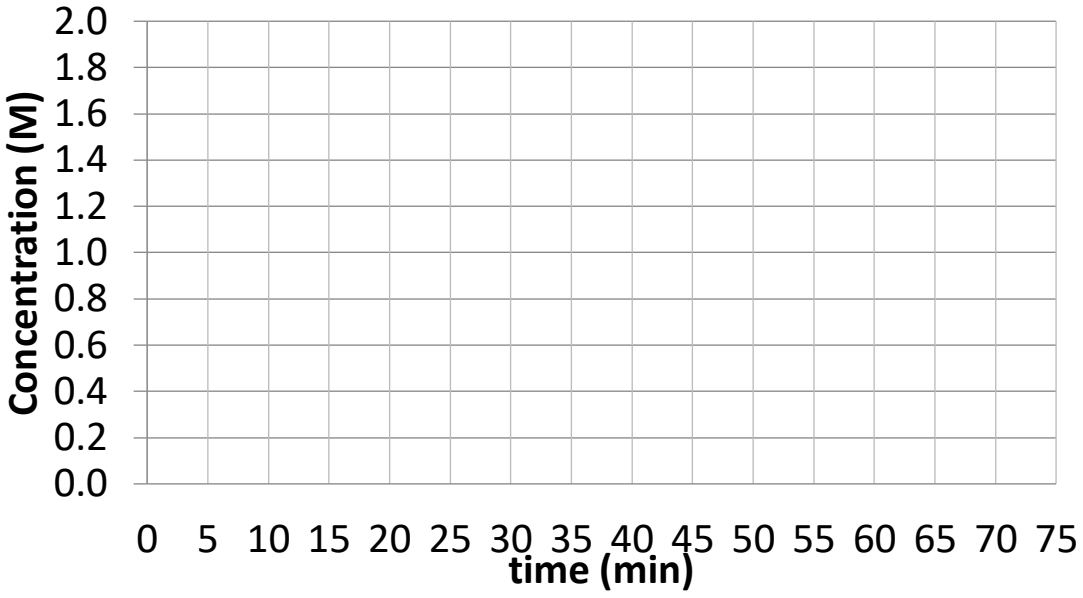


Reaction order:

k =

$t_{1/2}$ =

B) Draw the concentration vs. time plot based on the reaction above.



Equilibria Interview Set

Prompt 1: Describe each value

$K_{eq} = 1.5\times10^{5}$

$K_{eq} = 2.3\times10^{-6}$

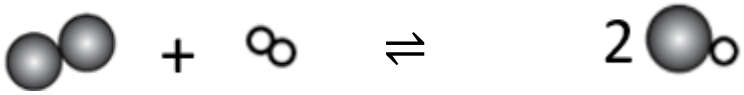
$K_{p} = 2.0\times10^{7}$

$K_{c} = 1.0\times10^{-9}$

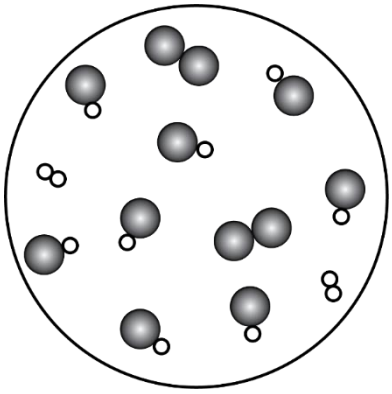
$Q = 3.5\times10^{-3}$

Prompt 2: For each of these diagrams the system is at equilibrium. Describe each scenario depicted.

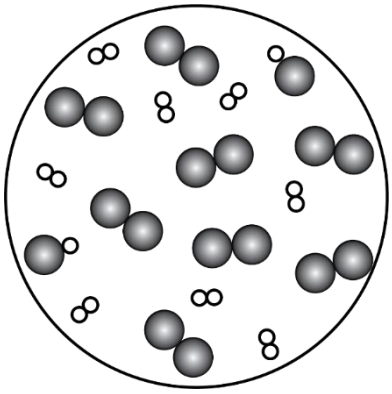
REACTION:



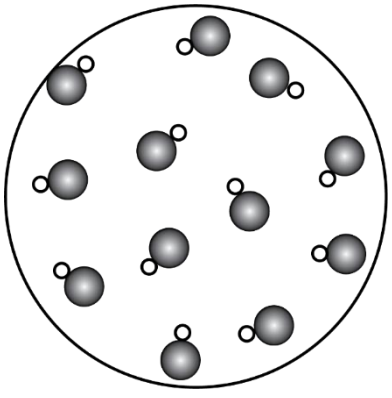
Scenario A



Scenario B

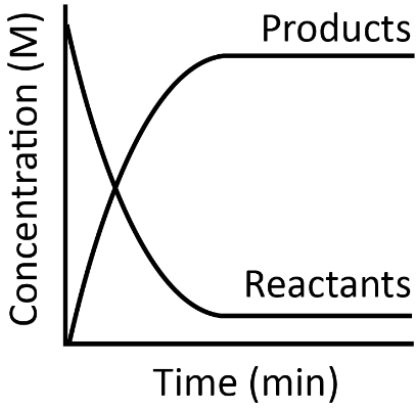


Scenario C

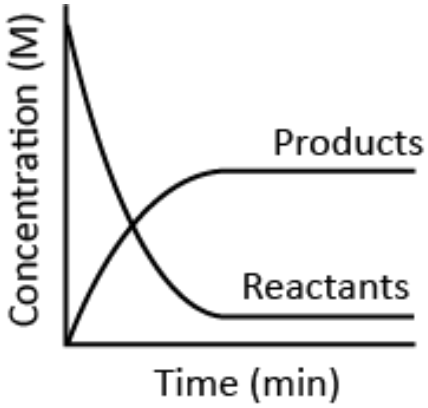


Prompt 3: Describe the differences between the plots.

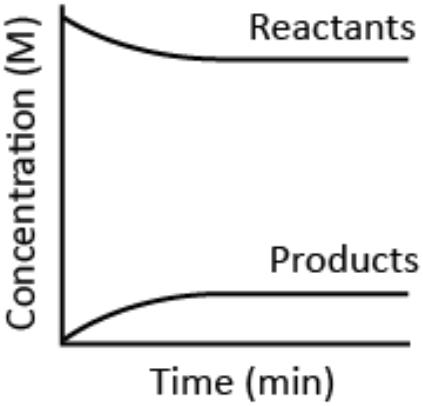
A



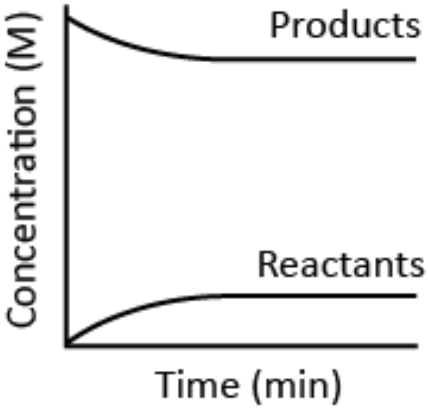
B



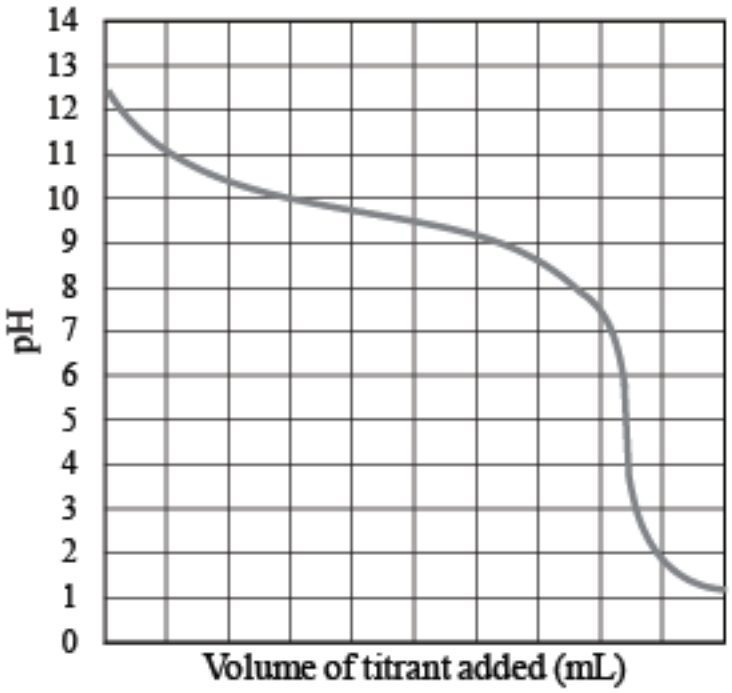
C

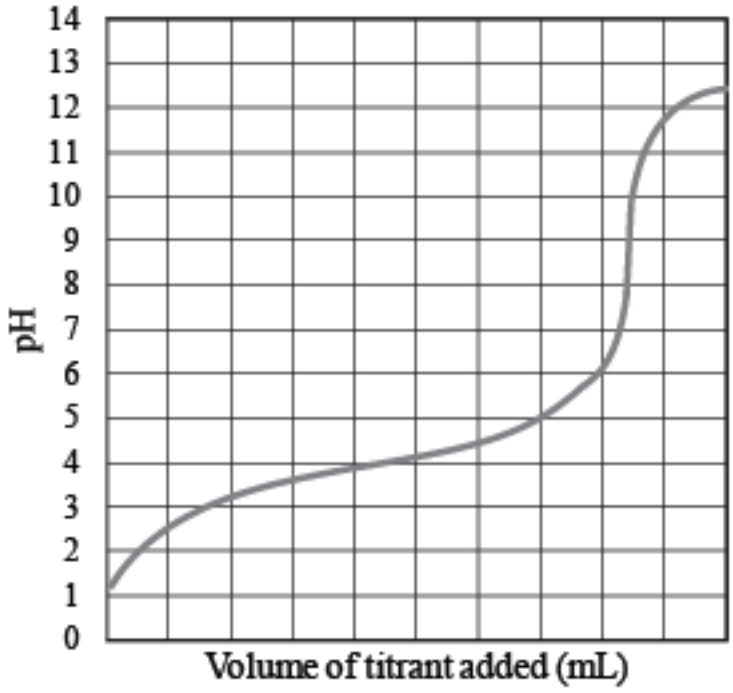


D



Prompt 4: Describe the following diagrams and their differences.

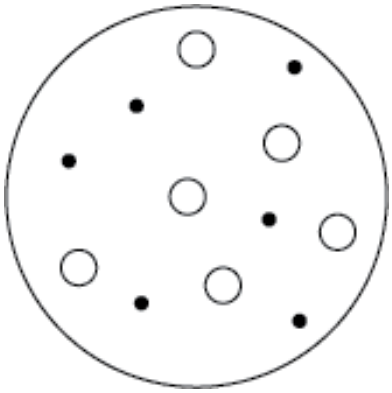




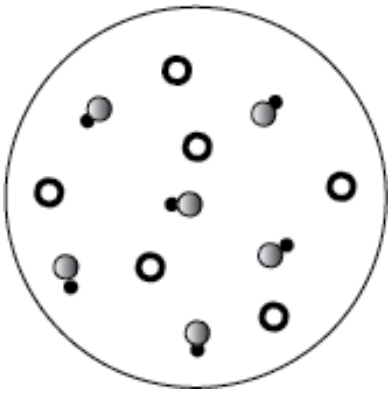
Prompt 5: Describe the differences between each diagram in terms of acidity.

Note: species are in solution Water molecules are omitted for clarity	***Key*** ● = H^+ ○ = A^- = OH^- ○ = HA O = Metal Ion ● = B ● = HB^+

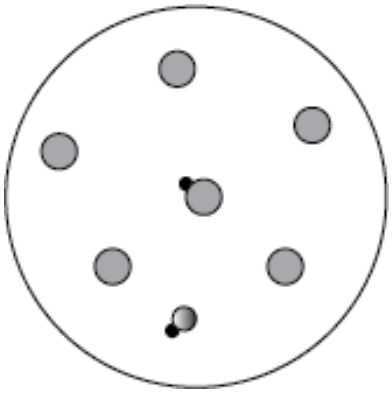
A



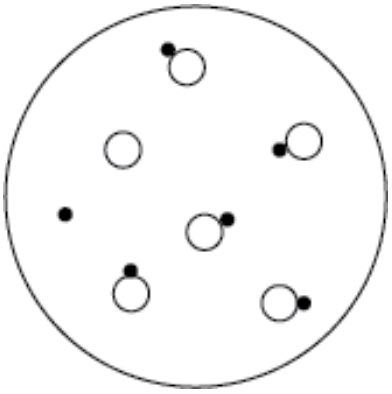
B



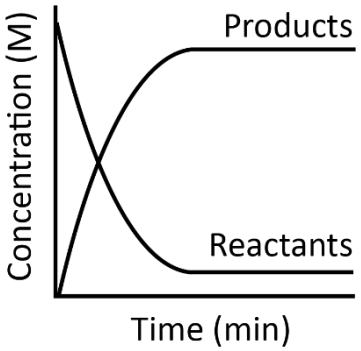
C

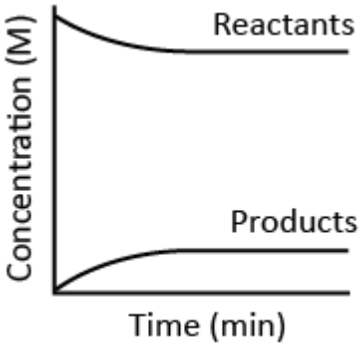


D



Prompt 6: Match the plots to the diagrams if at equilibrium.

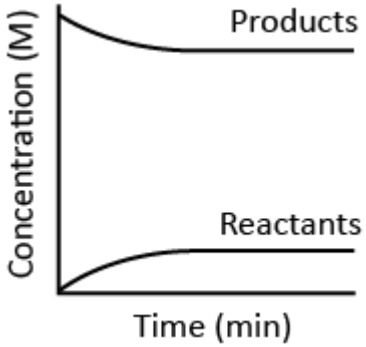


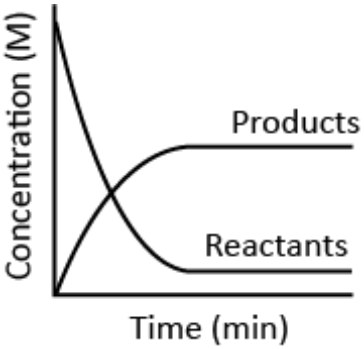


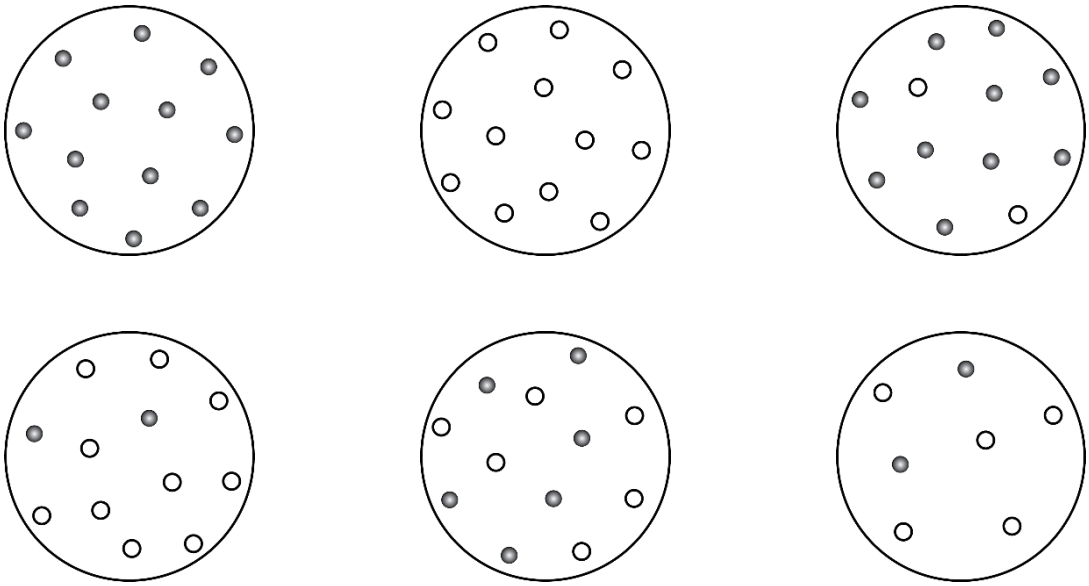
Key:

● = reactant

○ = product



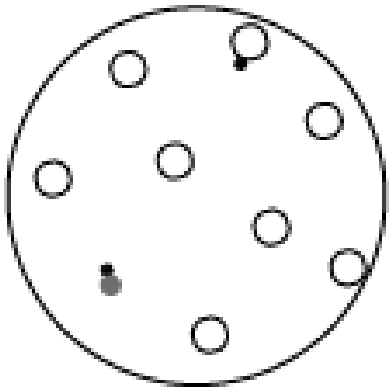




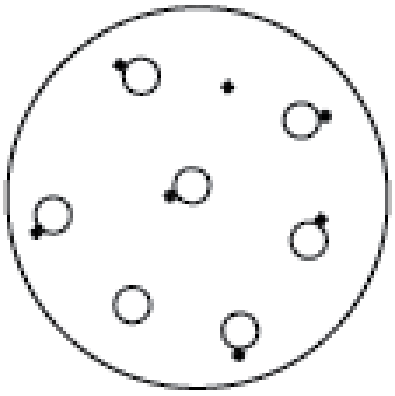
Prompt 7: Which diagram(s) represent(s) a buffer?

Note: species are in solution Water molecules are omitted for clarity	***Key*** = HA = A^- = OH^- = H^+

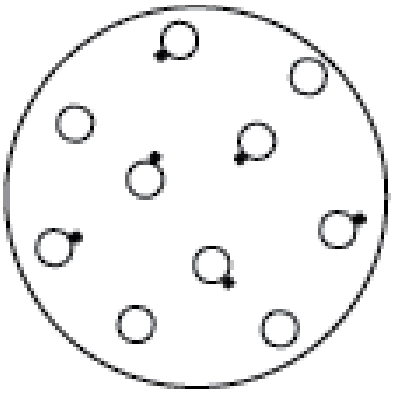
A



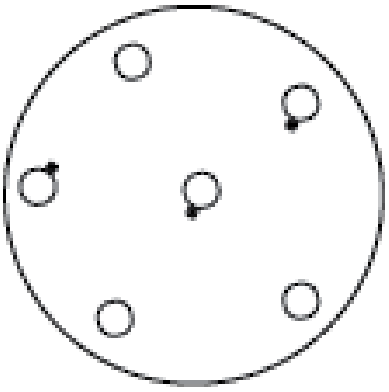
B



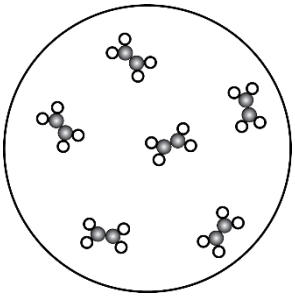
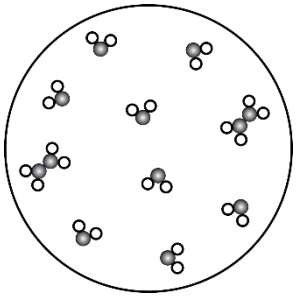
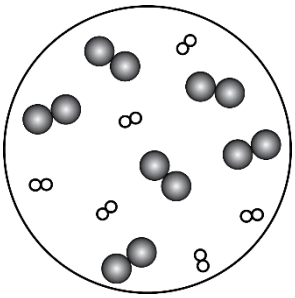
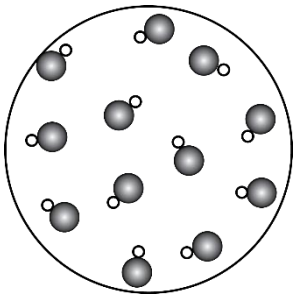
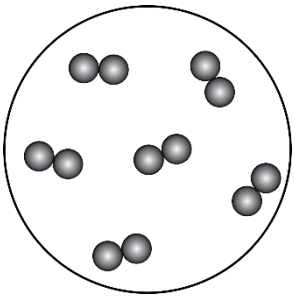
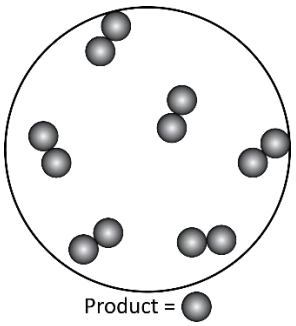
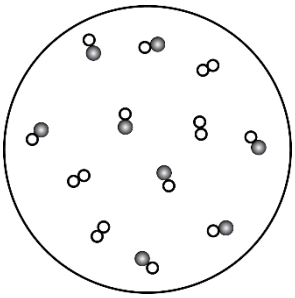
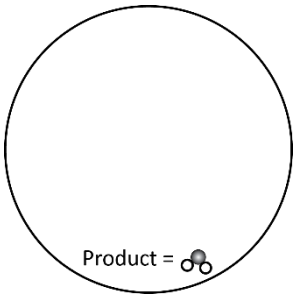
C



D



Prompt 8: Give the equilibrium expression and relative Kp value based on the diagrams

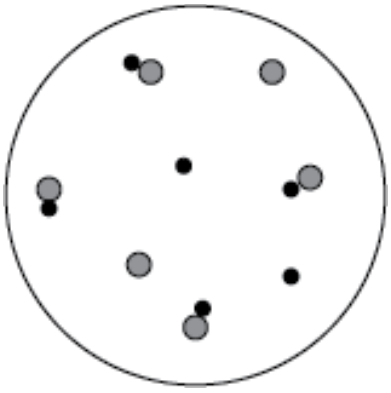
	Initial diagram	Final diagram	Equilibrium expression	Relative value of *K*
A			$K_p =$ —	*K* _____ 1
B			$K_p =$ —	*K* _____ 1
C		 Product =	$K_p =$ —	*K* _____ 1
D		 Product =	$K_p =$ —	*K* > 1

Prompt 9: Discuss the relative Ka and Kb values for each diagram.

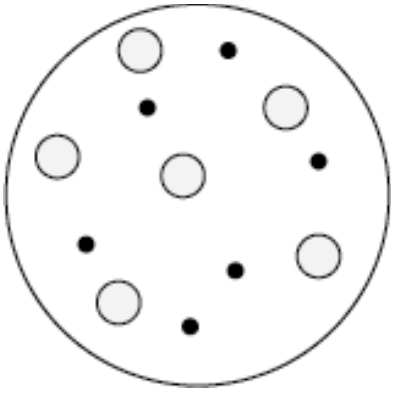
Note: species are in solution

Water molecules are omitted for clarity

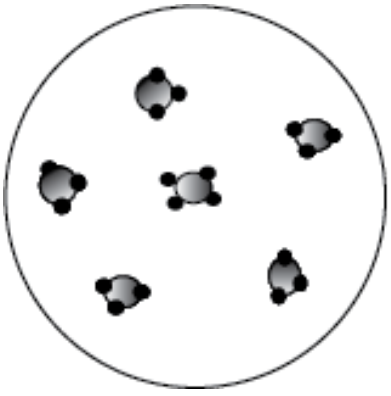
Key: HF = H^+ = F^- =



Key: HBr = H^+ = Br^- =

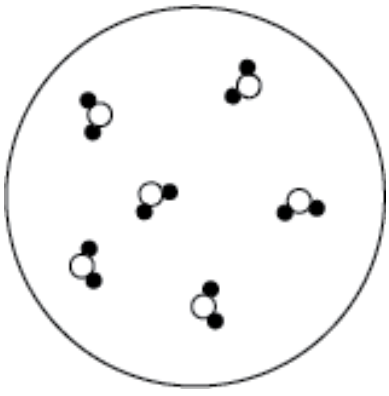


Key: NH_3 = NH_4^+ =



Key: H_2S = H^+ = S^{2-} =

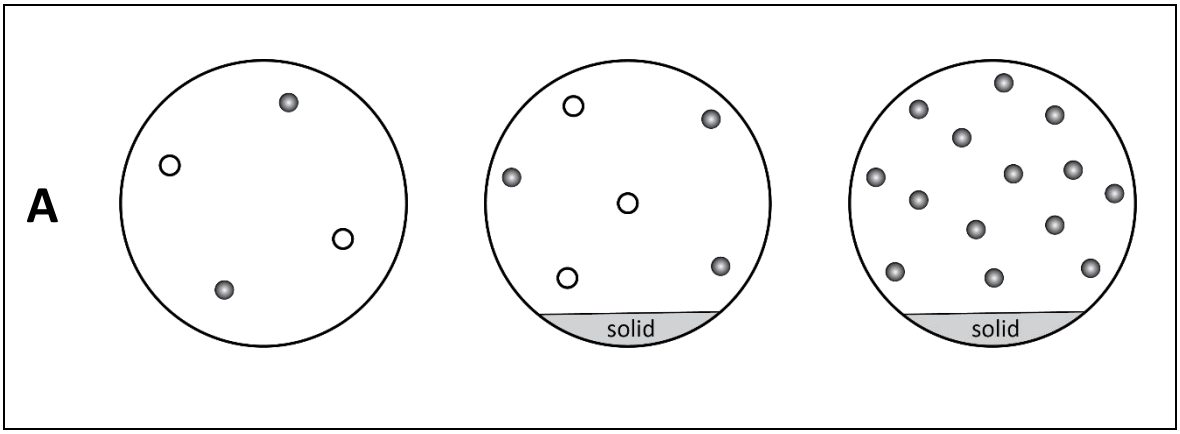
HS^- =

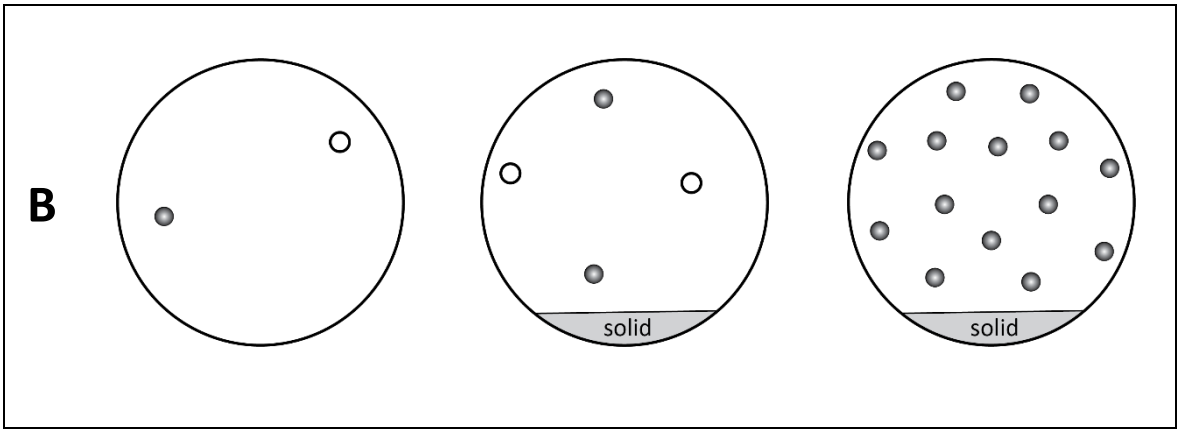


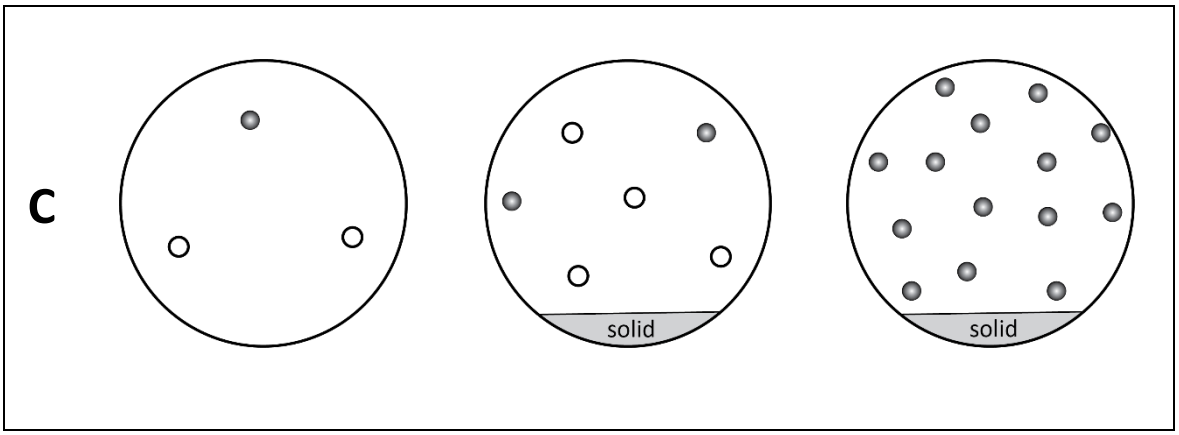
Prompt 10: Discuss the relative Ksp values for each diagram.

Note: species are in solution

Water molecules are omitted for clarity







Prompt 11: Which pairs of Ksp and Q values will form a precipitate?

Precipitate (yes or no)?	K_{sp} value	Q value
	1.08×10^{-10}	5.2×10^{-12}
	3.45×10^{-11}	4.7×10^{-11}
	8.46×10^{-12}	8.46×10^{-12}

Prompt 12: Explain how each ICE Table connects to the reaction.

$$N_2O_4(g) \rightleftharpoons 2NO_2(g) \quad K_c > 1$$

ICE Table 1

	$N_2O_4(g)$	$\rightleftharpoons$	$2NO_2(g)$
I	0.500 M		0
C	– x		+ 2x
E	0.500 – x		2x

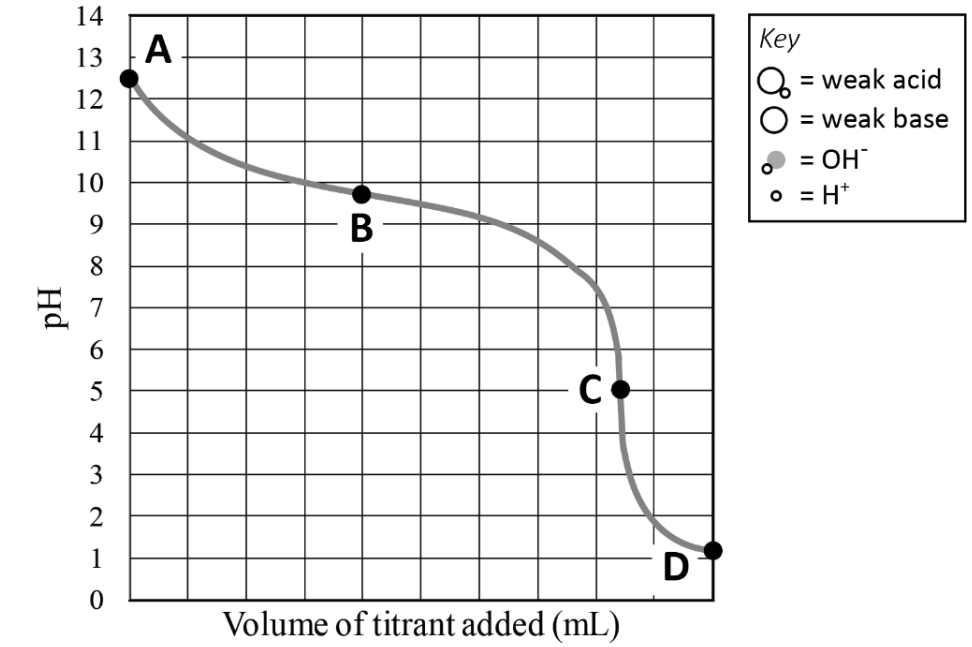
ICE Table 2

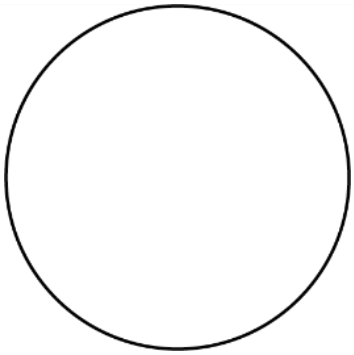
	$N_2O_4(g)$	$\rightleftharpoons$	$2NO_2(g)$
I	0		0.500 M
C	+ x		– 2x
E	x		0.500 – 2x

ICE Table 3

	$N_2O_4(g)$	$\rightleftharpoons$	$2NO_2(g)$
I	x		0.500 M
C	+ 0.225 M		– 0.450 M
E	x + 0.225 M		0.500 M – 0.450 M

Prompt 13: Generate diagrams for each labeled point on the plot.





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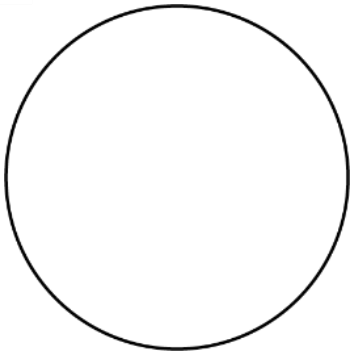

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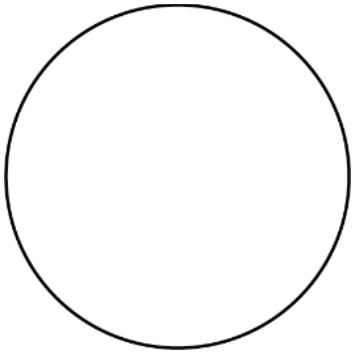

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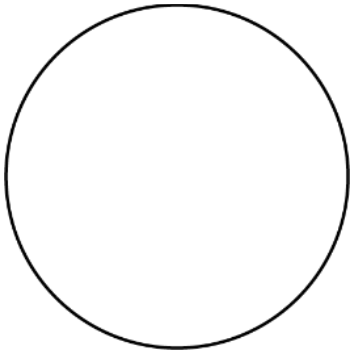
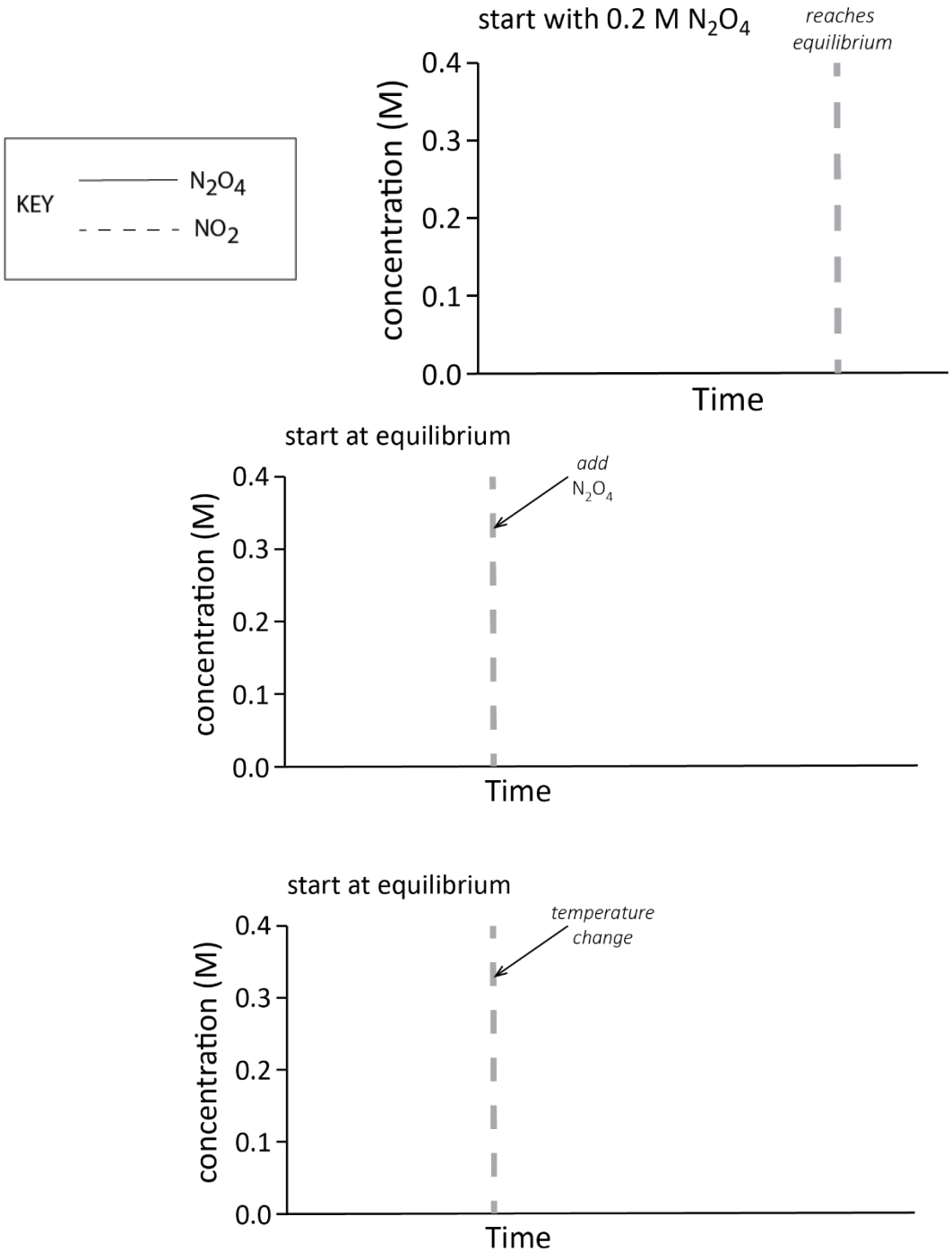


D

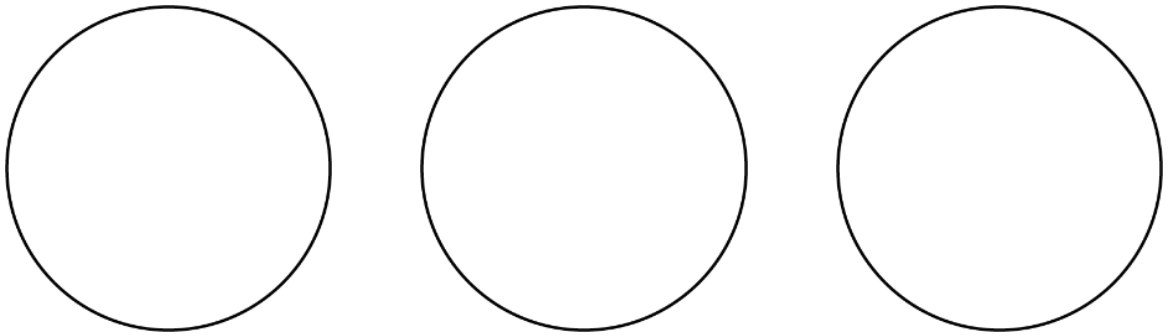
Prompt 14: Generate a concentration vs. time plot for the reaction given below.

$$N_2O_4(g) \rightleftharpoons 2NO_2(g) \quad K_{eq} > 1\text{, endothermic}$$



Prompt 15: Given the Ksp values and conditions, generate a diagram for each salt.

Salt	K_{sp} value	Conditions
CuBr	4.2×10^{-8}	$[Cu^{+}] = 1\times10^{-3}$ M and $[Br^{-}] = 1\times10^{-3}$ M
PbI_2	1.4×10^{-8}	$[Pb^{2+}] = 1\times10^{-3}$ M and $[I^{-}] = 1\times10^{-3}$ M
$Fe(OH)_3$	1.1×10^{-36}	$[Fe^{3+}] = 1\times10^{-3}$ M and $[OH^{-}] = 1\times10^{-3}$ M



CuBr PbI_2 $Fe(OH)_3$

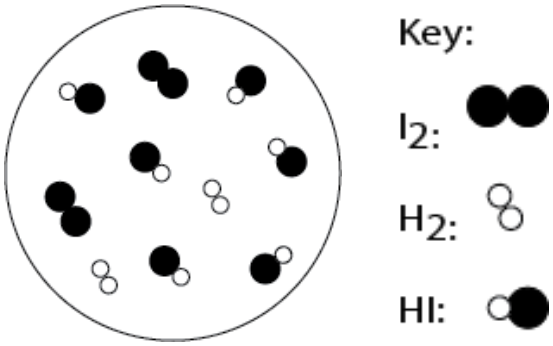
Prompt 16: Depict how the diagram changes after the system is altered and equilibrium is re-established.

$H_2(g) + I_2(g) \rightleftharpoons 2\ HI(g)$

Vessel Volume = 10.0 L

T = 448˚C , $K_c > 1$

Exothermic reaction



Add I_2	**Add He**
Remove HI	**Decrease temp.**
Increase volume	

Prompt 17: Show how the equilibrium constant is altered given the scenarios.

Original Reaction: $H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$

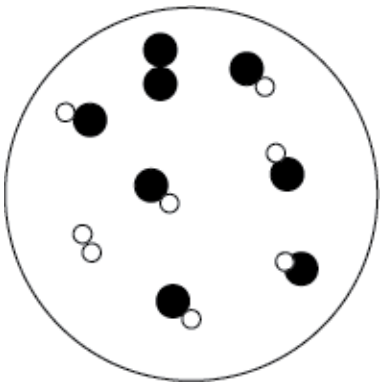
$K_p = 36$ at 448˚C

Key:

I_2:

H_2:

HI:



1) What is K_c of the reaction?

$K_p = K_c(RT)^{\Delta n}$

$R = 0.0821\ L \cdot atm \cdot mol^{-1} \cdot K^{-1}$

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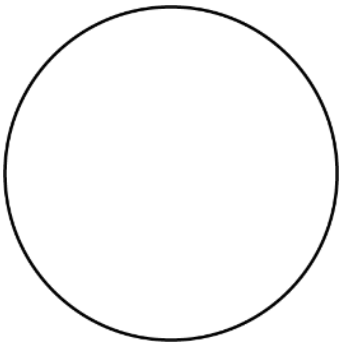
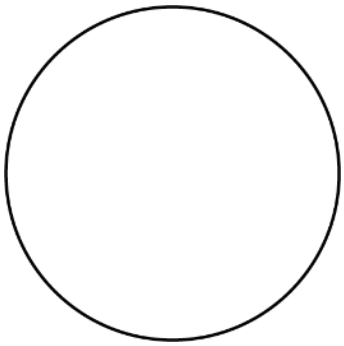
2) $2HI(g) \rightleftharpoons H_2(g) + I_2(g)$ $K_c =$_____



3) $HI(g) \rightleftharpoons \frac{1}{2}H_2(g) + \frac{1}{2}I_2(g)$ $K_c =$ _____

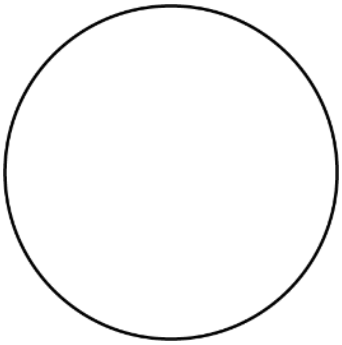


Prompt 18: Diagram with the addition of the common ion. Calculate concentration of ion.

$$PbF_2(s) \rightleftharpoons Pb^{2+}(aq) + 2F^-(aq) \quad K_{sp} = 4.1 \times 10^{-8} \text{ at } 25^oC$$

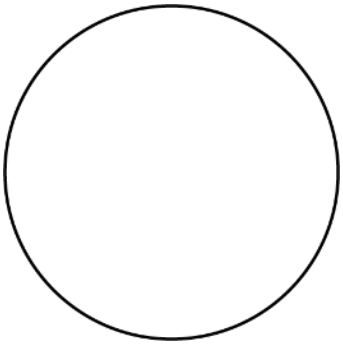
A) What is the molar solubility of PbF_2?

B) Generate a diagram of 2.0 g of PbF_2 in 1.0 L of water. *MM* (PbF_2) = 245 g·mol^{-1}

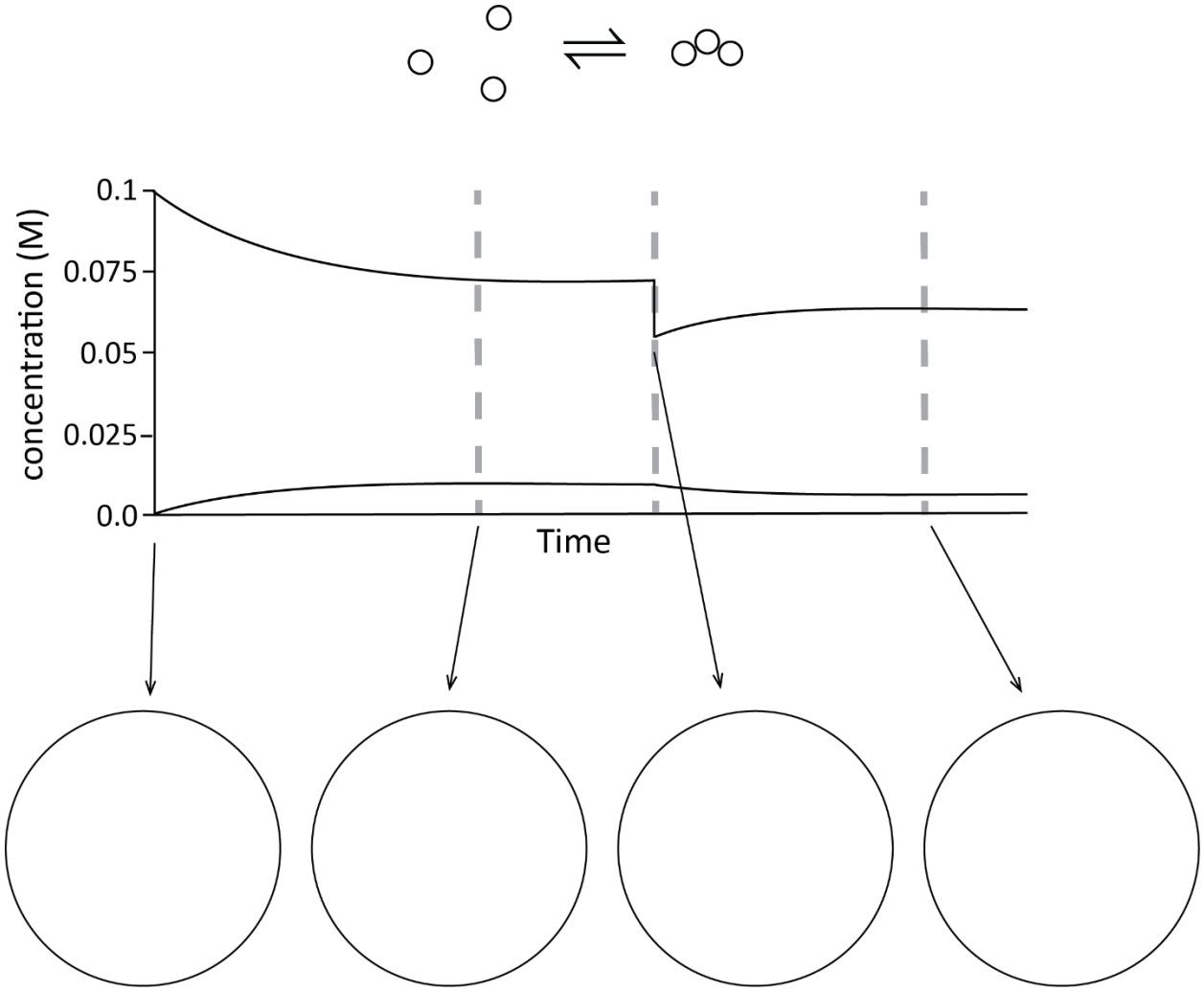


C) What is the concentration of [Pb^{2+}] after the addition of concentrated NaF to the PbF_2 solution at equilibrium such that [F^-] = 1.0 M, but the total volume does not change?

D) Generate a diagram of the solution now (after the addition of NaF).

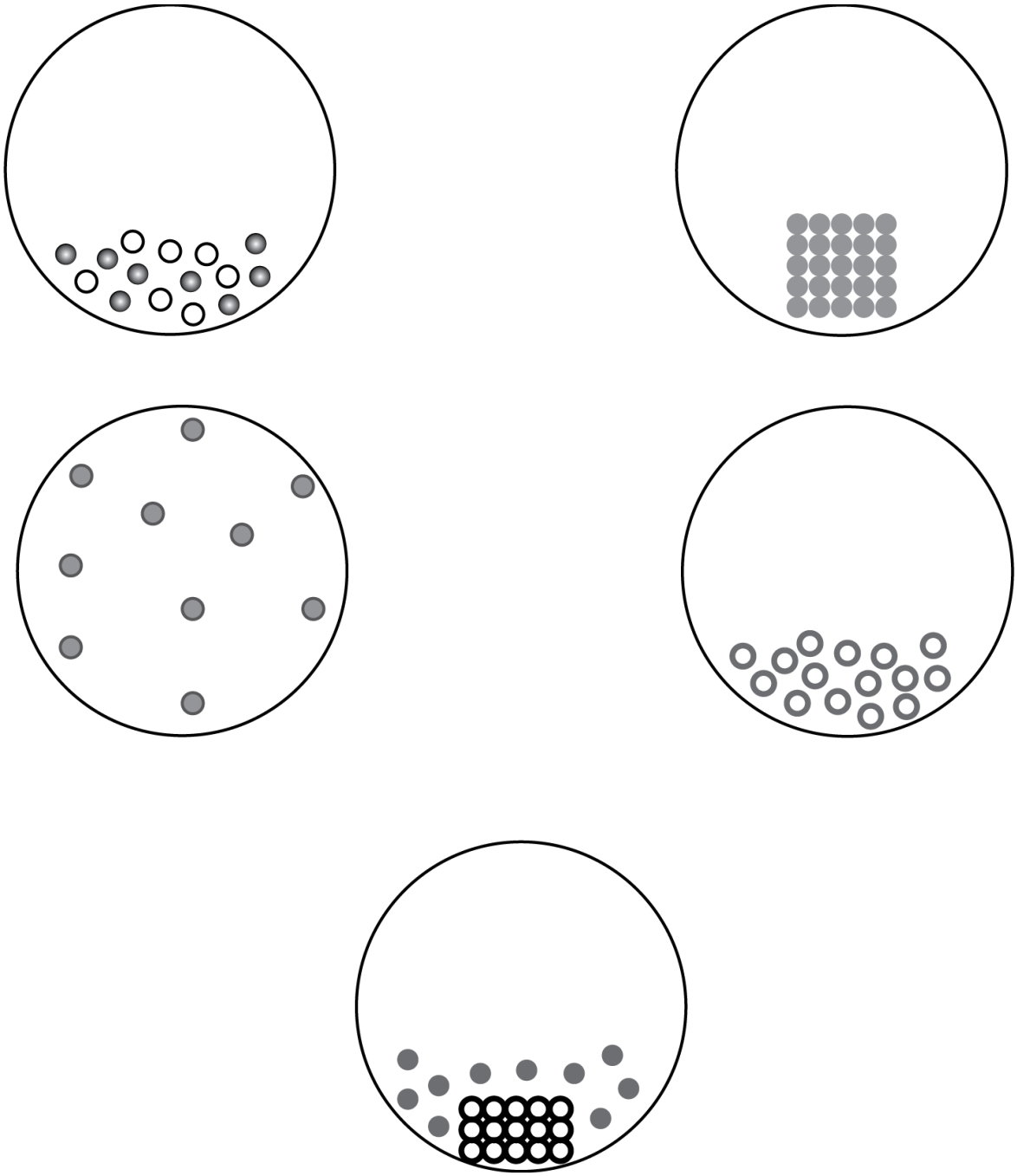


Prompt 19: Given the stoichiometry plot and balanced equation, determine the approximate values of K and Q and generate particulate diagrams at the points.



Thermodynamics & Electrochemistry Interview Set

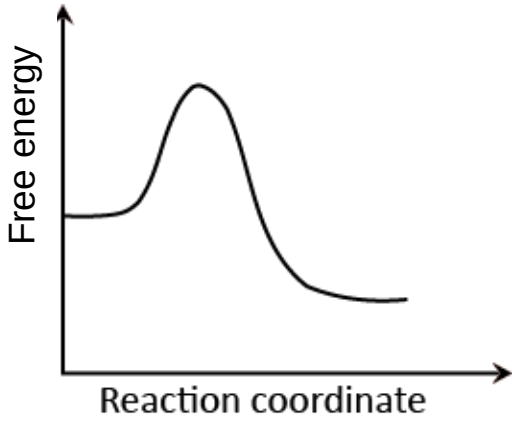
Prompt 1: Describe the diagrams and their differences in terms of entropy.

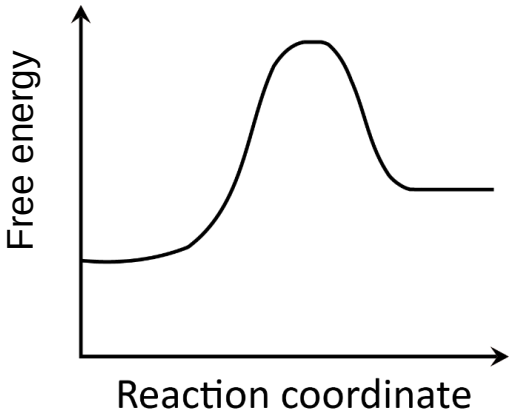


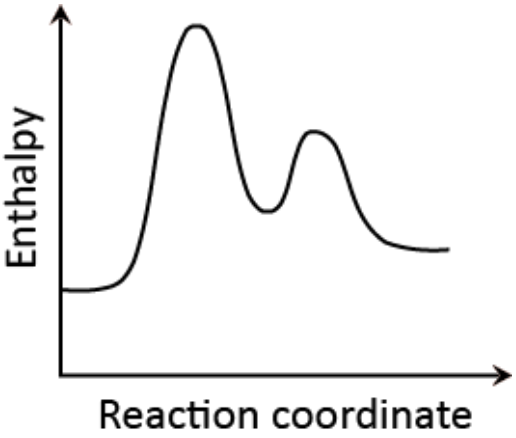
Prompt 2: Explain each of the given values.

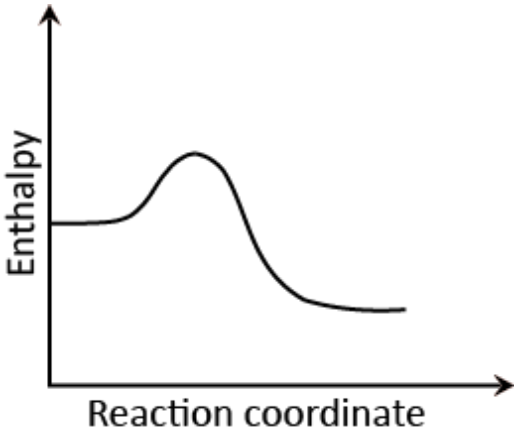
$\Delta H = 90.8$ kJ	$\Delta H = -104.1$ kJ
$\Delta S_{universe} = 0.9$ J/K	$\Delta S_{universe} = -0.3$ J/K
$\Delta G = -74$ kJ	$\Delta G = 142$ kJ
$E^{\circ}_{cell} = +1.17$ V	$E^{\circ}_{cell} = -0.025$ V
$E^{\circ}_{red} = -2.89$ V	$E^{\circ}_{ox} = 0.399$ V
$\Delta S_{system} = -284$ J/K	$\Delta S_{system} = 161$ J/K

Prompt 3: Describe the diagrams.

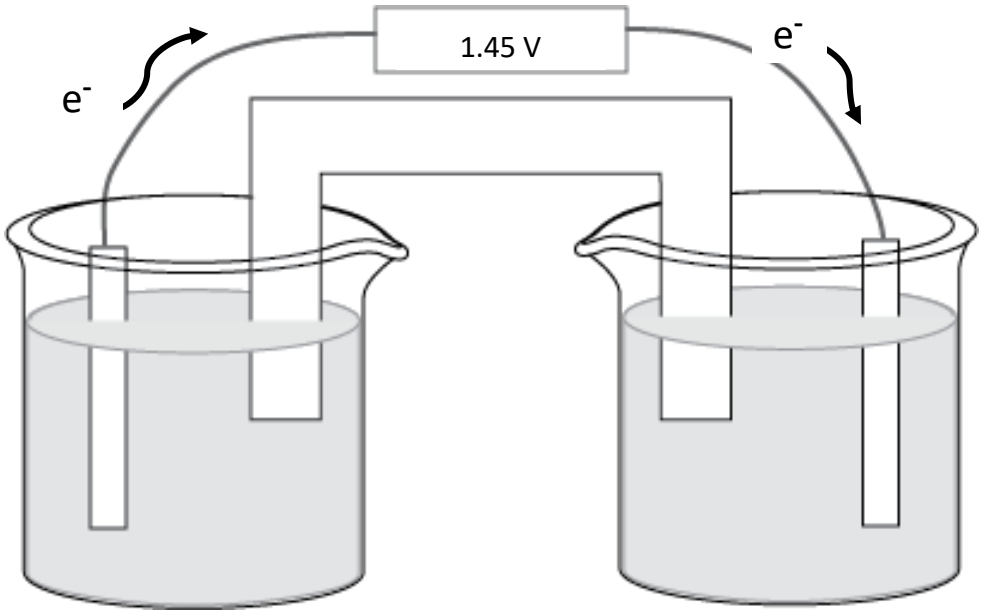




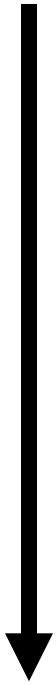




Prompt 4: Describe the diagram.

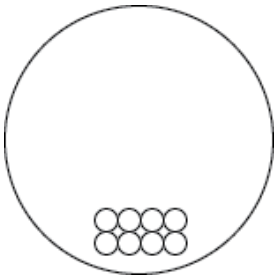
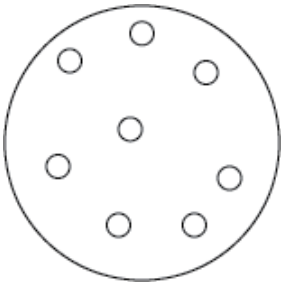
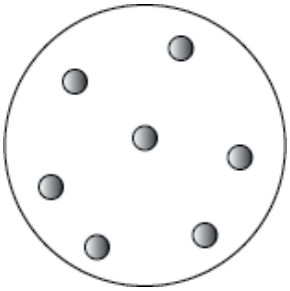
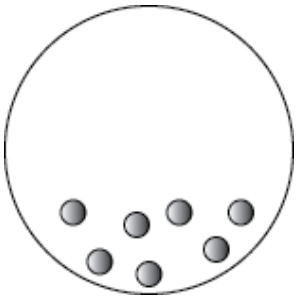
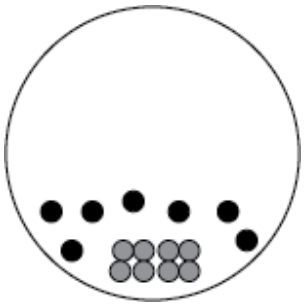
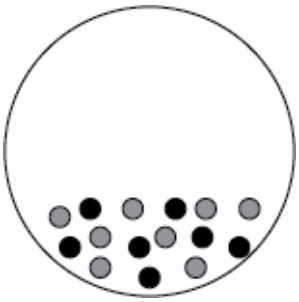


Prompt 5: Describe the chart.



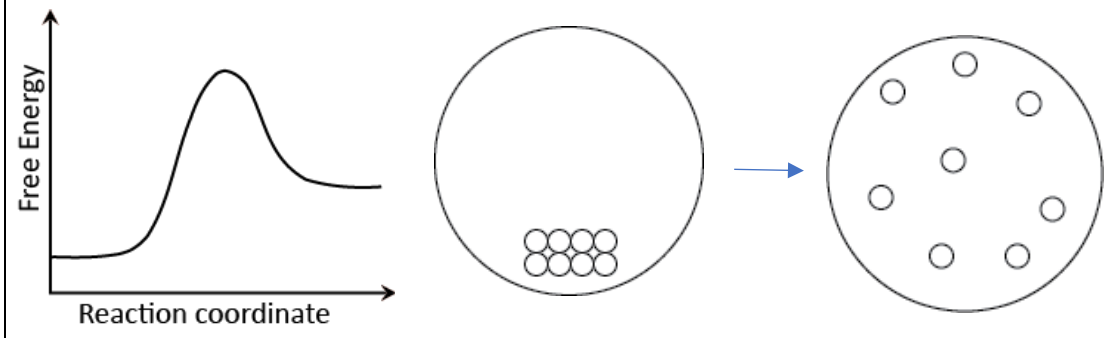
Name	Reaction	Standard Reduction Potentials
Sodium	$Na^{+}_{(aq)} + e^{-} \rightarrow Na_{(s)}$	-3.04 V
Calcium	$Ca^{2+}_{(aq)} + 2e^{-} \rightarrow Ca_{(s)}$	-2.868 V
Water	$2H_2O_{(l)} + 2e^{-} \rightarrow H_{2\,(g)} + 2\,OH^{-}_{(aq)}$	-0.83 V
Zinc	$Zn^{2+}_{(aq)} + 2e^{-} \rightarrow Zn_{(s)}$	-0.762 V
Iron	$Fe^{2+}_{(aq)} + 2e^{-} \rightarrow Fe_{(s)}$	-0.44 V
Hydrogen	$2\,H^{+}_{(aq)} + 2e^{-} \rightarrow H_{2\,(g)}$	0 V
Silver	$Ag^{+}_{(aq)} + e^{-} \rightarrow Ag_{(s)}$	0.799 V
Dichromate	$Cr_2O_7^{2-}{}_{(aq)} + 14H^{+}_{(aq)} + 6e^{-} \rightarrow 2Cr^{3+}_{(aq)} + 7H_2O_{(l)}$	1.36 V
Gold	$Au^{3+}_{(aq)} + 3e^{-} \rightarrow Au_{(s)}$	1.69 V

Prompt 6: Determine the signs of entropy and enthalpy for the given reactions.

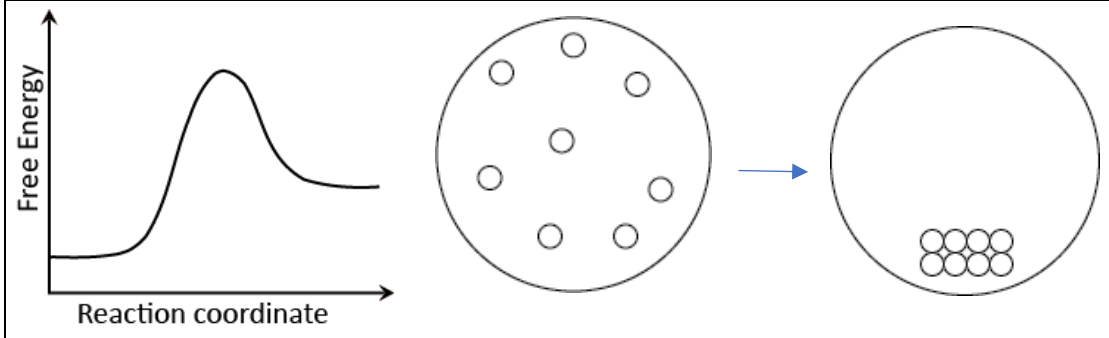
	Initial Diagram	Final Diagram
A		
B		
C		

Prompt 7: Given the diagrams below, determine the signs of ΔS, ΔG, and ΔH and if the reaction is spontaneous.

A



B



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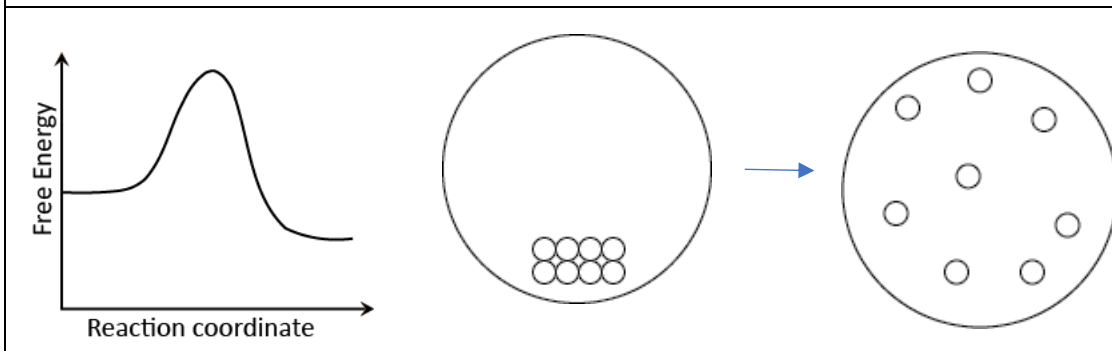

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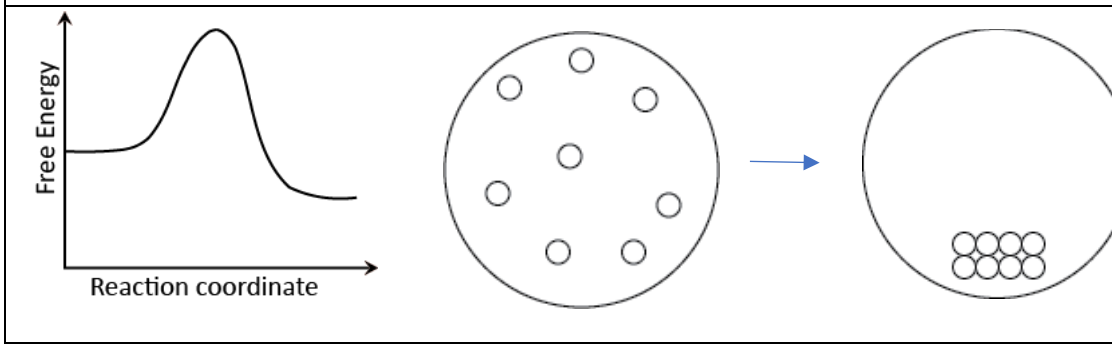
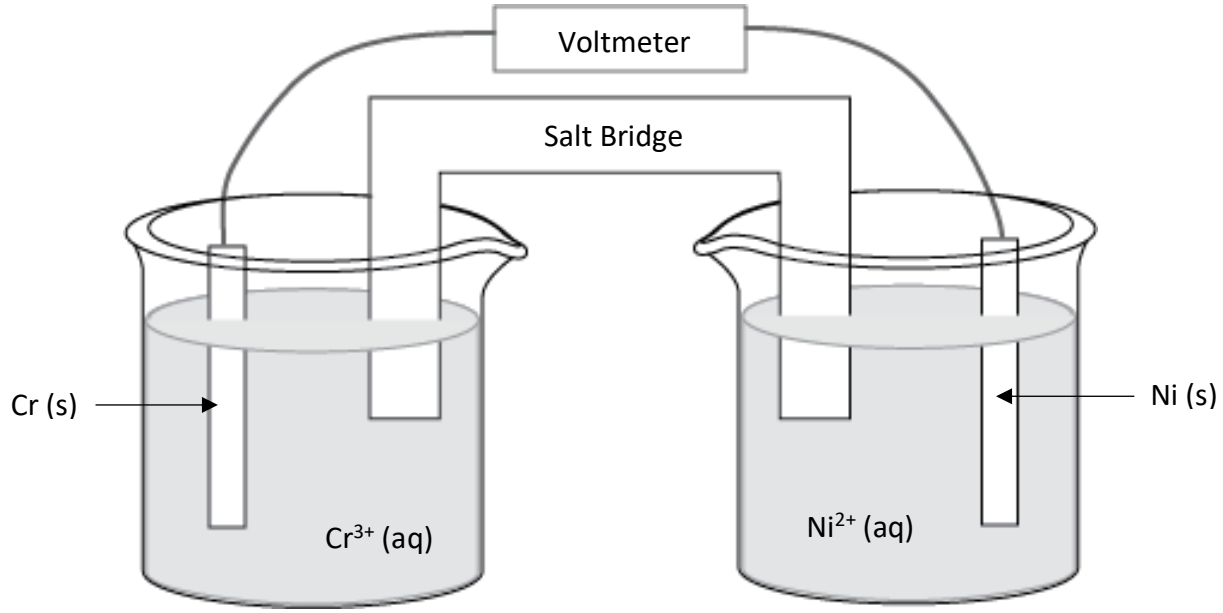


Prompt 8: Fill in the chart for the standard cell depicted below.



Balanced equations	Standard Reduction Potentials
Oxidation half-reaction:	$Ni^{2+}(aq) + 2e^- \rightarrow Ni\ (s)$ -0.25 V
Reduction half-reaction:	$Cr^{3+}\ (aq) + 3e^- \rightarrow Cr\ (s)$ -0.74 V
Overall balanced equation:	

# of electrons transferred	Element oxidized	Element reduced	oxidizing agent	reducing agent

Prompt 9: Balance the redox reaction in acidic solution.

$$Fe^{2+}\ (aq) + Cr_2O_7^{2-}\ (aq) \rightarrow Fe^{3+}\ (aq) + Cr^{3+}\ (aq)$$

Oxidation half-reaction:

Reduction half-reaction:

Overall reaction:

Prompt 10: Use the chart to determine the following.

Name	Reaction	Standard Reduction Potential
Hydrogen	$2\ H^+_{(aq)} + 2e^- \rightarrow H_{2\ (g)}$	0 V

A) Given the reduction potential values below, make your own activity series in the chart above.

Cu^{2+} / Cu (s) = 0.339 V
Na^{+} / Na (s) = -2.936 V
Pb^{2+} / Pb (s) = -1.26 V
Pt^{2+} / Pt (s) = 1.18 V

B) What is the standard cell potential (E^o_{cell}) for copper(II) sulfate reacting with platinum?

Reduction: E^o_{red} =

Oxidation: E^o_{ox} =

Overall: $E^o_{cell} = E^o_{red} + E^o_{ox}$

C) Is the reaction spontaneous?

Prompt 11: Use the chart to determine the following.

Name	Reaction	Standard Reduction Potentials
Sodium	$Na^{+}_{(aq)} + e^{-} \rightarrow Na_{(s)}$	-2.936 V
Calcium	$Ca^{2+}_{(aq)} + 2e^{-} \rightarrow Ca_{(s)}$	-2.868 V
Water	$2H_2O_{(l)} + 2e^{-} \rightarrow H_{2\,(g)} + 2OH^{-}_{(aq)}$	-0.83 V
Zinc	$Zn^{2+}_{(aq)} + 2e^{-} \rightarrow Zn_{(s)}$	-0.762 V
Iron	$Fe^{2+}_{(aq)} + 2e^{-} \rightarrow Fe_{(s)}$	-0.44 V
Hydrogen	$2\,H^{+}_{(aq)} + 2e^{-} \rightarrow H_{2\,(g)}$	0 V
Silver	$Ag^{+}_{(aq)} + e^{-} \rightarrow Ag_{(s)}$	0.799 V
Dichromate	$Cr_2O_7^{2-}{}_{(aq)} + 14H^{+}_{(aq)} + 6e^{-} \rightarrow 2Cr^{3+}_{(aq)} + 7H_2O_{(l)}$	1.36 V
Gold	$Au^{3+}_{(aq)} + 3e^{-} \rightarrow Au_{(s)}$	1.69 V

A) Will this reaction occur? $Zn\,(s) + HCl\,(aq) \rightarrow$

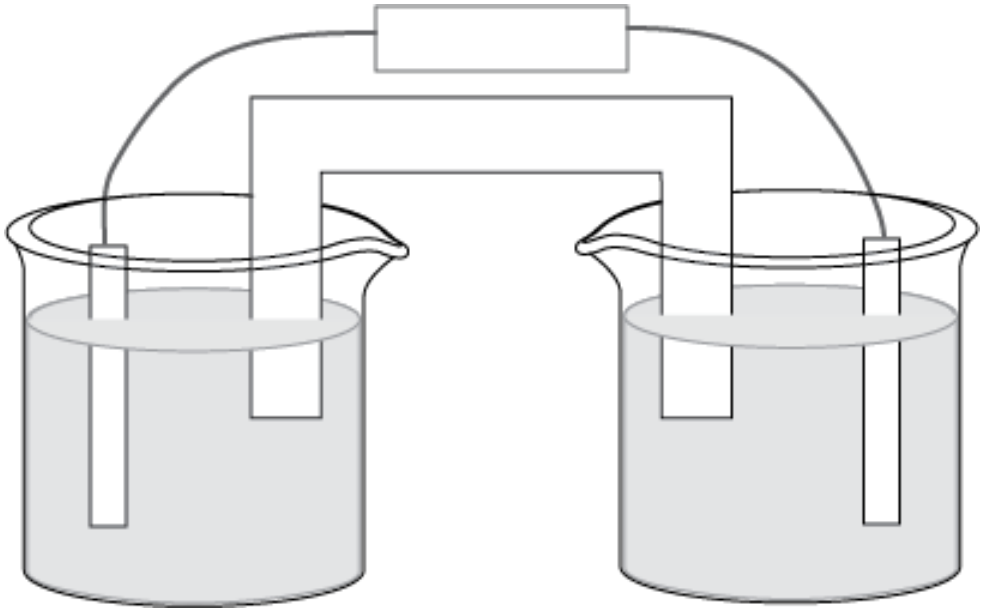
B) Will this reaction occur? $Ag\,(s) + NaNO_3\,(aq) \rightarrow$

C) Determine which metal will be the anode and cathode in the pairing of silver and zinc in an electrochemical cell.

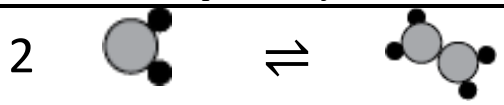
Prompt 12: Will this electrochemical cell run spontaneously?

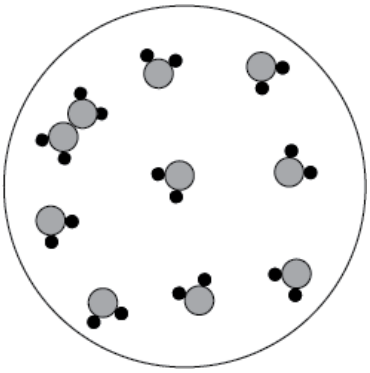
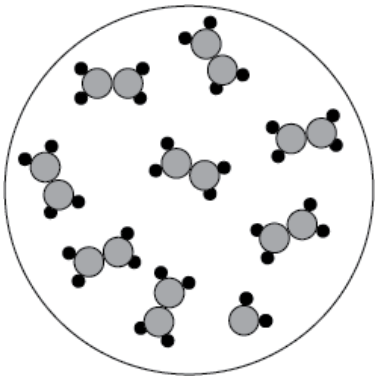
$Cu\ (s) + Co^{3+}\ (aq, 2.0\ M) \rightleftharpoons Cu^{+}\ (aq, 0.10\ M) + Co\ (s)$ Temperature = 25°C

$Cu^{+}_{(aq)} + e^{-} \rightarrow Cu_{(s)}$	$E^{\circ}_{red} = 0.55\ V$	$E_{cell} = E^{\circ}_{cell} - \frac{0.0592\ V}{n} \log Q$
$Co^{3+}_{(aq)} + 3e^{-} \rightarrow Co_{(s)}$	$E^{\circ}_{red} = 1.82\ V$	



Prompt 13: Determine the values and spontaneity of the reaction.



	Diagrams at Equilibrium	K_p value	ΔG°	Spontaneous?
A			ΔG° _____ 0	
B			ΔG° _____0	

Calculate the actual ΔG° for each scenario given the temperature

$$\Delta G° = -RTln(K) \quad R = 8.314 \frac{J}{K * mol}$$

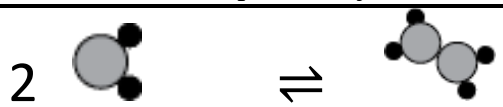
A

Temp = 133℃

B

Temp = 25 ˚ C

Prompt 14: Determine the relative values and spontaneity of the reaction.



Scenario	Relative ΔG° *Values*	Relative Values	Spontaneous?
1	A) $\Delta G^\circ < 0$	K ____ 1	
	B) $\Delta G > 0$	Q ___ K	
2	A) $\Delta G^\circ > 0$	K ____ 1	
	B) $\Delta G < 0$	Q ___ K	

Draw diagrams for each scenario below.

1A

1B

2A

2B

Appendix C

C.1. Solution and Kinetics

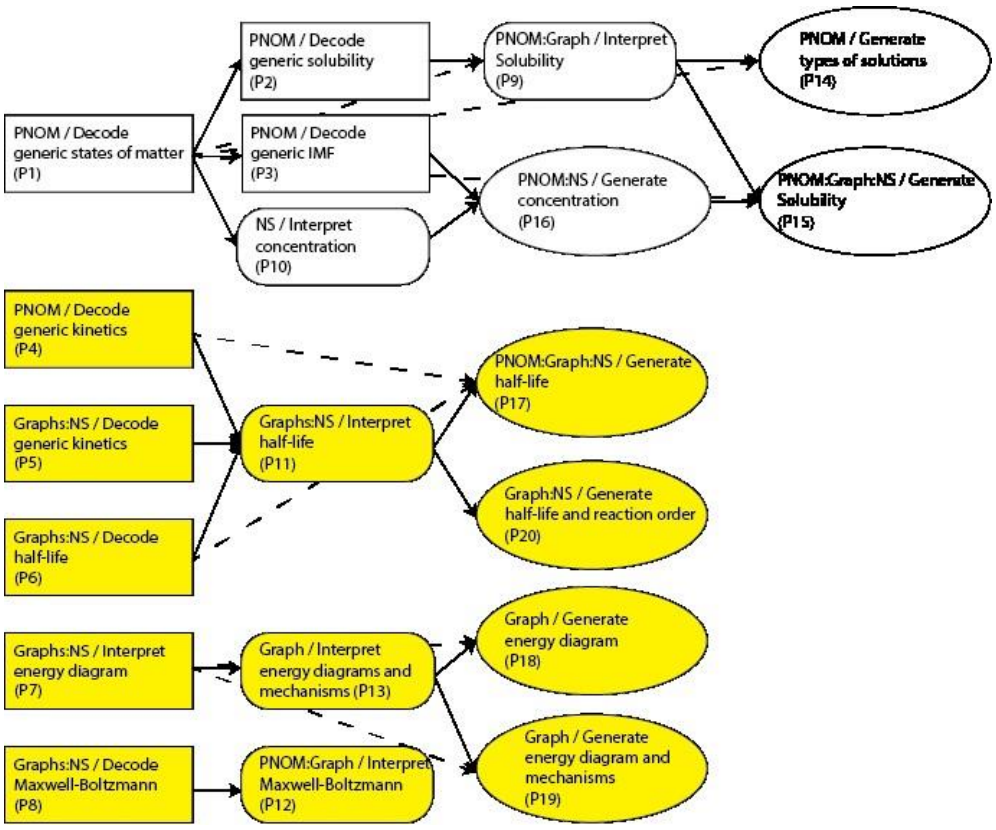


Figure C.1. Flow diagram solution and kinetics prompt design (PNOM = particulate nature of matter, NS = number sense)

C.2. Equilibrium

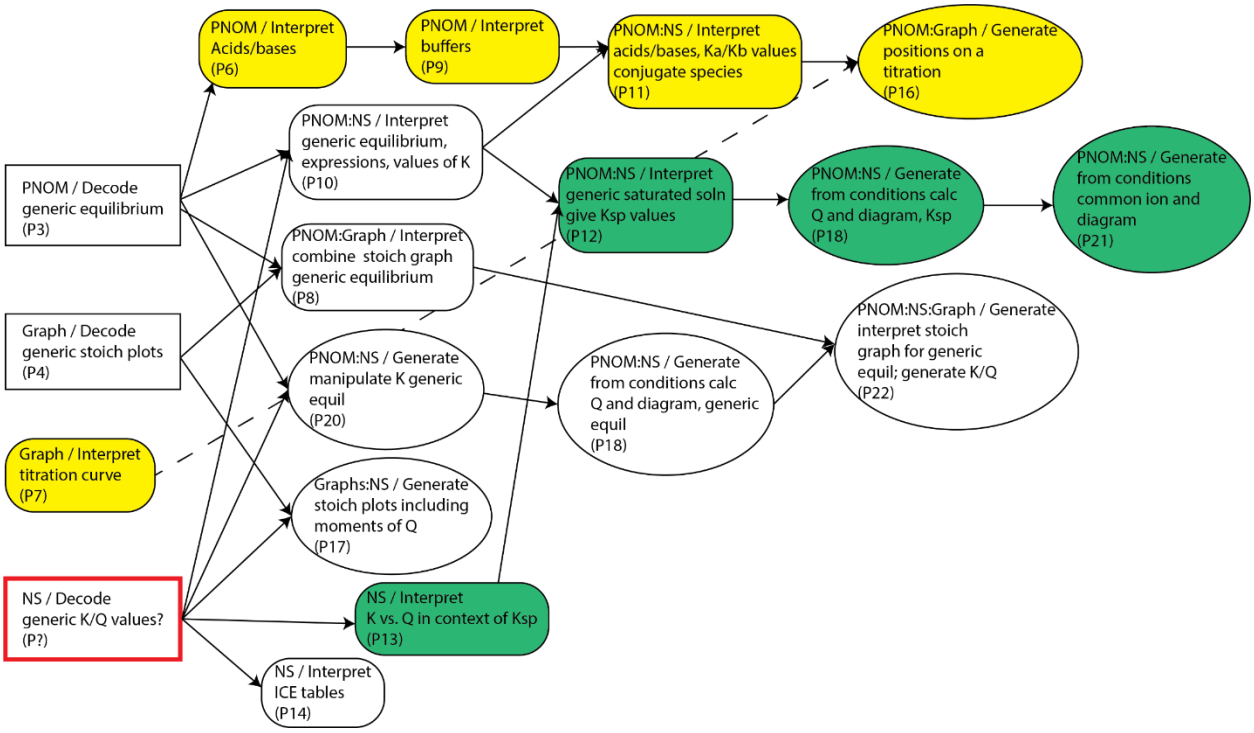


Figure C.2. Flow diagram equilibrium prompt design (PNOM = particulate nature of matter, NS = number sense)

C.3. Thermodynamics and Electrochemistry

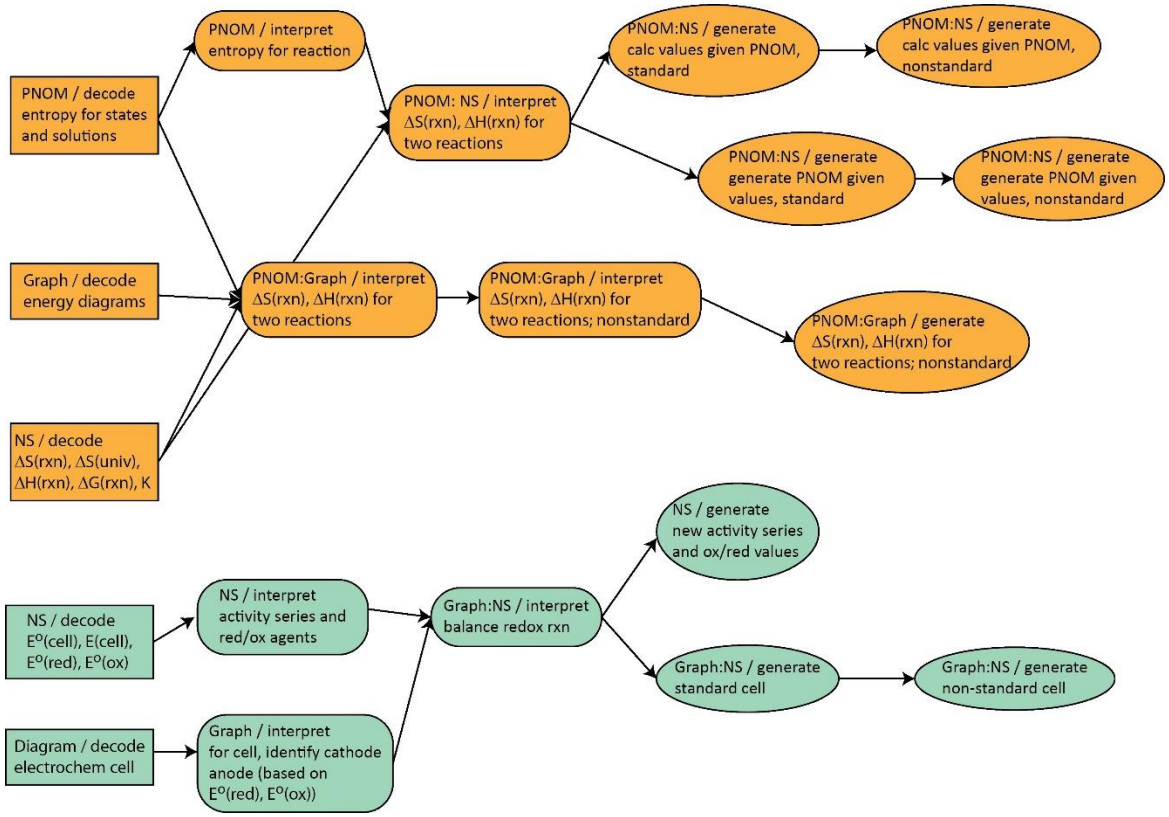


Figure C.3. Flow diagram thermochemistry and electrochemistry prompt design (PNOM = particulate nature of matter, NS = number sense)

Appendix D

D.1. Within Transcript Location Codes

Table D.1. Location codes used in transcription of interviews

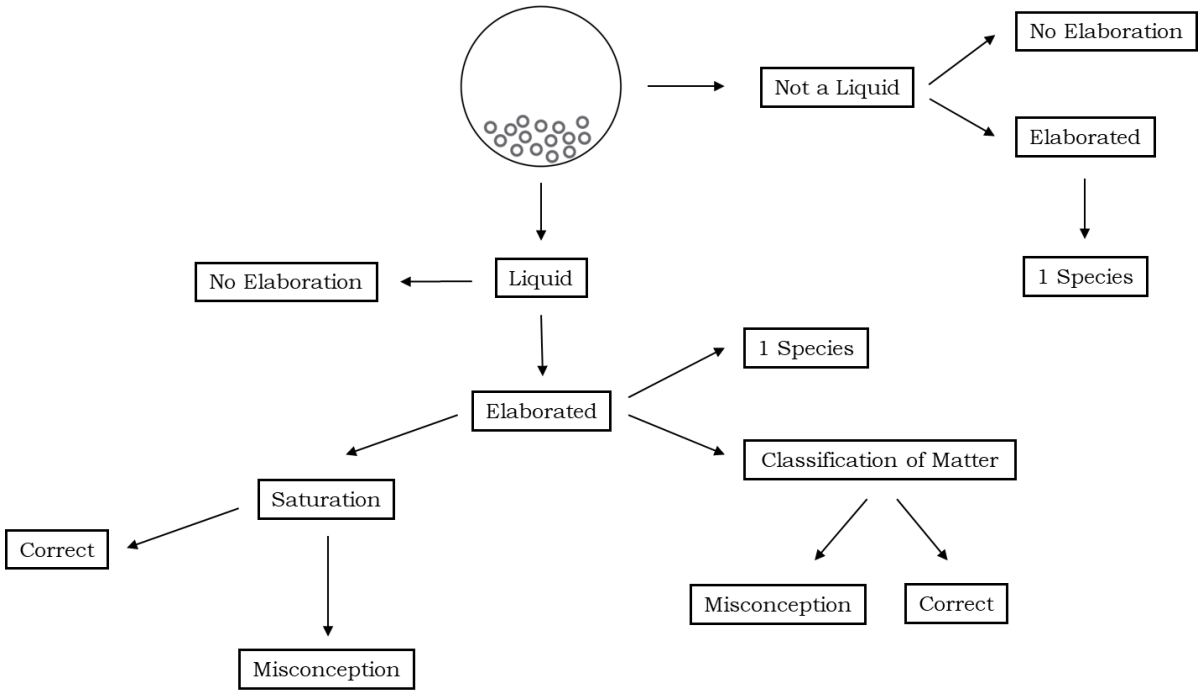
Prompt	Code	Meaning
Prompt 1	1A	Diagram A on page 1, refers to entire image
	1A_p	Diagram A on page 1, refers to particles
	1A_d	Diagram A on page 1, refers to distance
	1B	Diagram B on page 1, refers to entire image
	1B_p	Diagram B on page 1, refers to particles (non-specific)
	1B_p1	Diagram B on page 1, refers to dark particles
	1B_p2	Diagram B on page 1, refers to white particles
	1B_d1	Diagram B on page 1, refers to dark particles' distance
	1B_d2	Diagram B on page 1, refers to white particles' distance
	1C	Diagram C on page 1, refers to entire image
	1C_p	Diagram C on page 1, particles, non-specific
	1C_p1	Diagram C on page 1, refers to white particles
	1C_p2	Diagram C on page 1, refers to dark particles
	1C_d	Diagram C on page 1, refers to distance between particles
	1D	Diagram D on page 1, refers to whole image
	1D_p	Diagram D on page 1, refers to particles
	1D_d	Diagram D on page 1, refers to distance
	1E	Diagram E on page 1, refers to entire image
	1E_p	Diagram E on page 1, refers to particles
	1E_d	Diagram E on page 1, refers to particle distance
Prompt 2	2A	refers to entire image
	2A_p	refers to particles, non-specific
	2A_p1	refers to dark particles
	2A_p2	refers to white particles
	2A_d1	refers to dark particle distance
	2A_d2	refers to white particle distance
	2B	refers to entire image
	2B_p	refers to particles, non-specific
	2B_p1	refers to dark particles
	2B_p2	refers to white particles
	2B_d1	refers to dark particles distance
	2B_d2	refers to white particles distance
Prompt 3	3A	refers to entire image
	3A_p	refers to particles, non-specific
	3A_p1	refers to bottom particles
	3A_p2	refers to top particles
	3B	refers to entire image

Prompt	Code	Meaning
	3B_p	refers to particles, non-specific
	3B_p1	refers to bottom particles
	3B_p2	refers to top particles
Prompt 4	4	refers to entire process over time
	4_0	refers to t = 0 s image
	4_0p	refers to t = 0 s particles
	4_10	refers to t = 10 s image
	4_10p	refers to t= 10 s particles
	4_20	refers to t=20 s
	4_20p	refers to t=20 s particles
	4_30	refers to t= 30 s image
	4_30p	refers to t=30 s particles
	4_p1	open circle particle
	4_p2	dark circle particle
	4_cmpd	refers to the compound particles
	7B_pk	refers to peak specifically
Prompt 8	8	refers to entire image
	Ek	kinetic energy
	8_st	start of peak 1, origin point
	8_Y	refers to Y axis
	8_X	refers to X axis
	8_pk1_width	refers to the width of peak 1
	8_pk1	refers to peak 1
	8_pk2	refers to peak 2
Prompt 9	9G	refers to entire graph
	9AB	refers to both particle diagrams (non-specific)
	9G_Y	refers to graph Y axis
	9G_X	refers to graph X axis
	9G_s1	refers to salt 1 on graph
	9G_s2	refers to salt 2 on graph
	9G_s(1/2)_(st/end)	refers to a line on the graph's end or start point specifically
	9G_temp0	refers to point where temp is 0 degrees
	p1	dark particles
	p2	white particles
	temp axis pt	refers to specific temp point on x axis
	9A	refers to entire image A
	9A_p1	refers to dark particles in image A
	9A_p2	refers to white particles in image A
	9B	refers to entire image B
	9B_p1	refers to dark particles in image B
	9B_p2	refers to white particles in image B
	9G_above	area of graph above the curves
	9G_below	area of graph below the curves
	crosspt	refers to point where salt lines intersect
Prompt 10	10A	refers to first value (non-specific)
	10A_%	refers to percentage
	10A_NaCl	refers to NaCl

Prompt	Code	Meaning
	10A_aq	refers to aq state
	10A_mass	refers to mass / grams
	10B	refers to second value (non-specific)
	10B_X	refers to the mole fraction symbol
	10B_NaCl	refers to NaCl
	10B_0.40	refers to value
	10B_water	refers to water
Prompt 12	12_Y	refers to Y axis
	12_X	refers to X axis
	12(A/B)_p_(long/short)	refers to specific particle (s) with long or short tails
	12_pk1	refers to peak 1
	12_pk2	refers to peak 2
	tails	tails on molecules
	12A	refers to image A
	12A_tails	refers to tails of particles in image A
	12_pk1_width	references the width of peak 1
	12A_p	refers to particles in image A
	12B	refers to image B
	12B_tails	refers to tails of particles in image B
	12B_p	refers to particles in Image B
Prompt 14	14A	1st diagram (electrolyte)
	14B	2nd diagram (nonvolatile solvent and solute)
	14C	3rd diagram (nonvolatile solvent and volatile solute)
	14D	4th diagram (2 volatile substances)
Prompt 15	15_lines	refers to both lines on the plot, non-specific
	15A	open circle 1
	15B	open circle 2
Prompt 16	16	
Prompt 17	17_1	circle 1 has drawings
	17_2	circle 2 has drawings
	17_3	circle 3 has drawings
	17G	refers to graph, non-specific
	eq2	equation 2
	eq1	equation 1
	lobf	line of best fit
	20B_Y	refers to y axis of part b
	20B_X	refers to x axis of part b
	slope value	- 0.0347 value in the equation of a line
	1st half-life equation	generates the 1st order half-life reaction
	eq1_ t	referring to the t in equation 1
	20B_graph	refers to graph empty in part B
	20B_line	line on part B graph
	20A_st	starting point on graph

D.2. Prompt Codebook

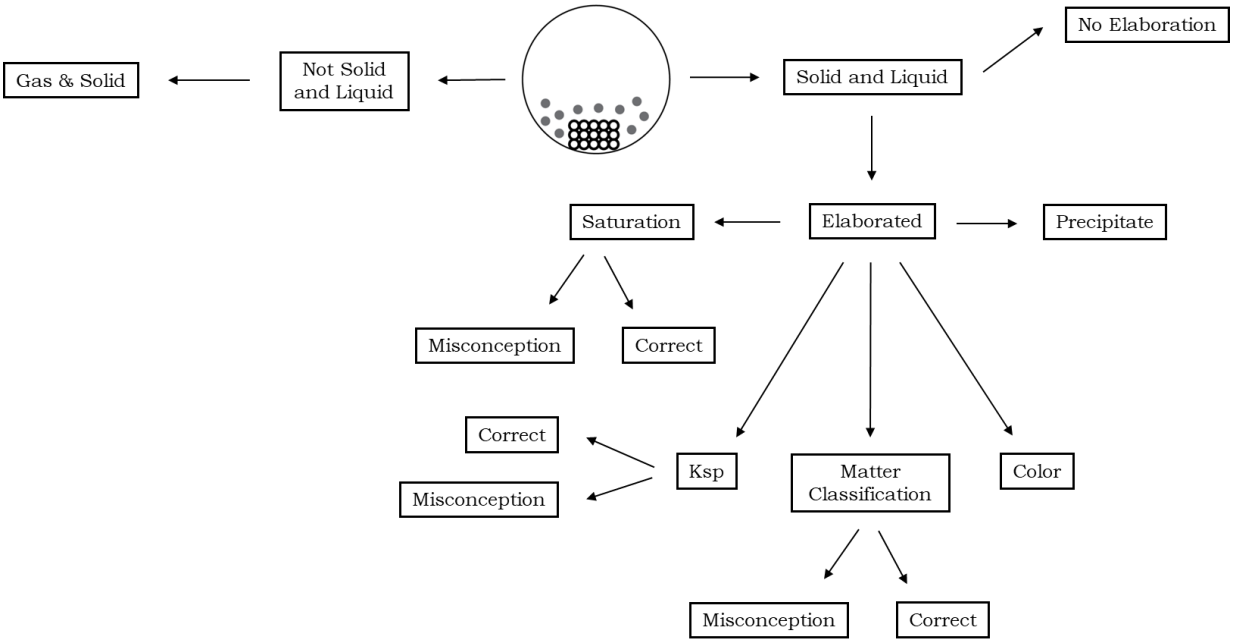
Prompt 1A



- **Liquid** = identifies substance as a liquid
    - **Elaborated** = student provided more information beyond identifying the state of matter depicted
        - **1 species** = verbalizes 1 species present
        - **Saturation** = discusses saturation of liquid depicted (correct or misconceptions)
        - **Classification of matter** = uses words such as "mixture, solution, aqueous etc." (correct or misconception)

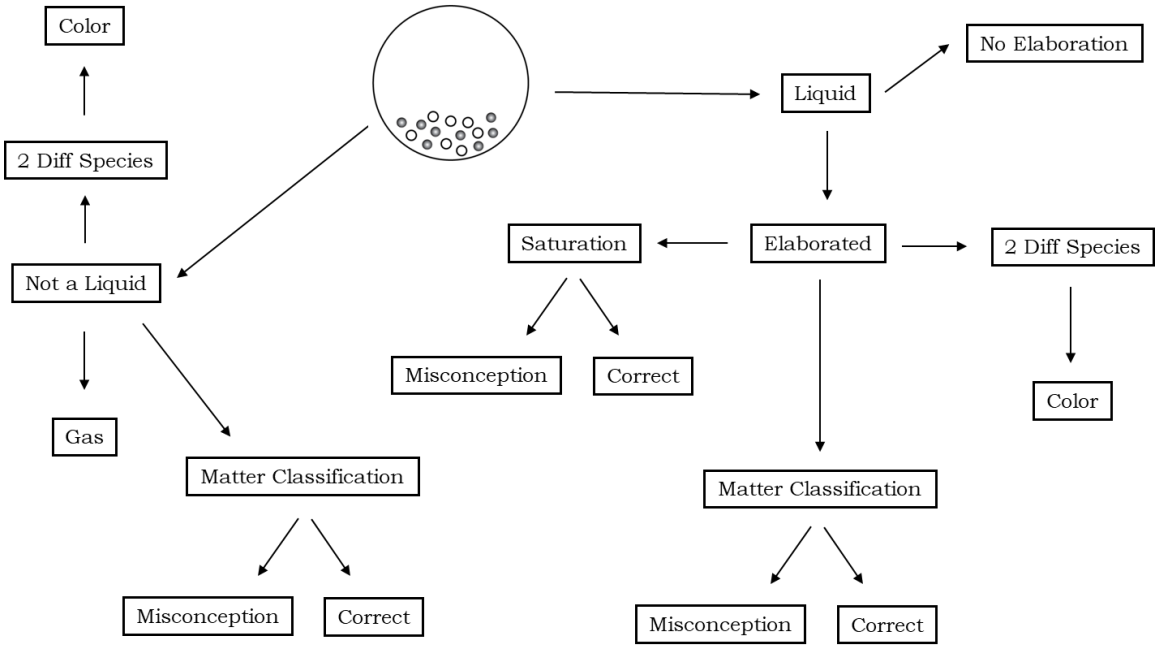
- **Not a liquid** = does not identify substance as a liquid
    - **Elaborated** = student provided more information beyond identifying the state of matter depicted
        - **1 species** = verbalizes 1 species present
    - **No elaboration** = student did not provide more information beyond identifying the state of matter depicted

Prompt 1B



- **Solid and liquid** = identifies substances as a solid and liquid
- **Not a solid or liquid**
    - **Gas & solid** = identifies substances as a gas and solid
- **Elaborated** = student provided more information beyond identifying the state of matter depicted
- **No elaboration** = student did not provide more information beyond identifying the state of matter depicted
    - **Saturation** = discusses saturation of liquid depicted (correct or misconception)
    - **Classification of Matter** = uses words such as "mixture, solution, aqueous etc." (correct or misconception)
    - **Ksp** (correct or misconception)
- **Precipitate** = uses word "precipitate"
- **Color** = references color of circles

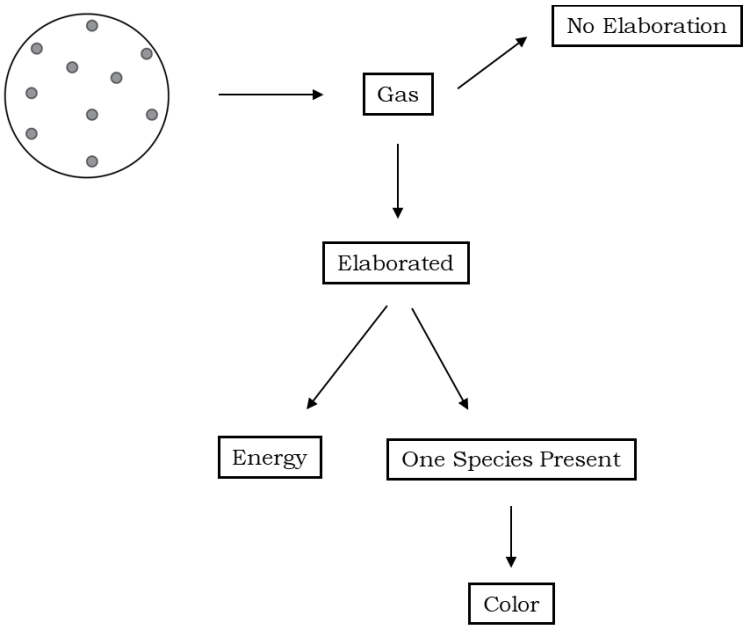
Prompt 1C



- **Liquid** = identifies substance as a liquid
    - **No Elaboration** = student did not provide more information beyond identifying the state of matter depicted
    - **Elaborated** = student provided more information beyond identifying the state of matter depicted
        - **Saturation** = discusses saturation of liquid depicted (correct or misconception)
        - **Classification of Matter** = uses words such as "mixture, solution, aqueous etc." (correct or misconception)
    - **2 Different Species**
        - **Color** = references color of particles

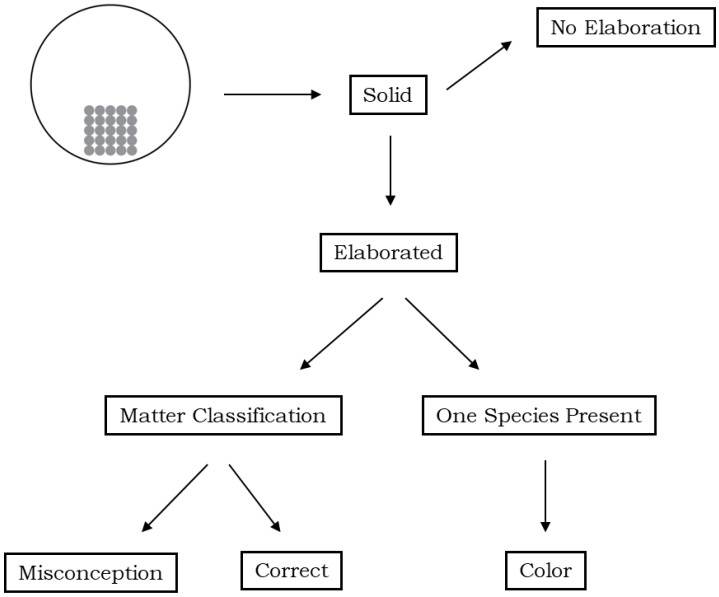
- **Not a liquid** = does not identify substance as a liquid
    - **Gas =** identifies substance as a gas
    - **2 Different Species**
        - **Color** = references color of particles

Prompt 1D



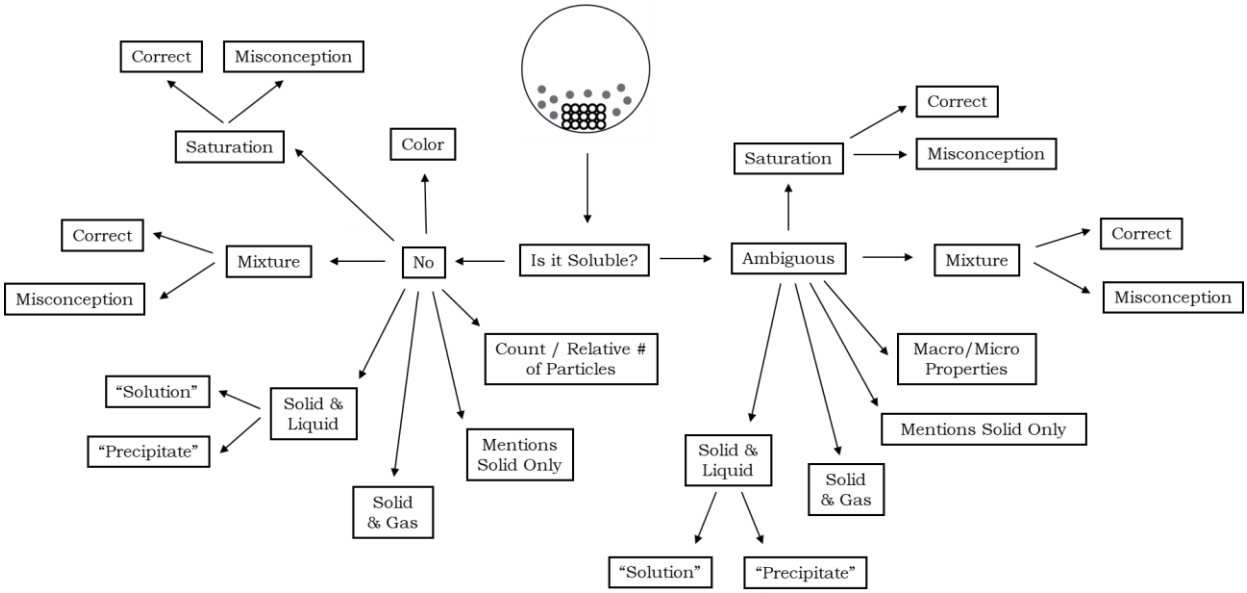
- **Gas =** identifies substance as a gas
    - **Elaborated** = student provided more information beyond identifying the state of matter depicted
        - **Energy =** discusses particles having high energy
        - **One species present**
            - **Color** = discuses color of particles
    - **No elaboration** = student did not provide more information beyond identifying the state of matter depicted

Prompt 1E



- **Solid =** identifies substance as a solid
    - **Elaborated** = student provided more information beyond identifying the state of matter depicted
        - **Classification of Matter** = uses words such as "mixture, solution, aqueous etc." (correct or misconception)
    - **One species present**
        - **Color** = discuses color of particles
    - **No elaboration** = student did not provide more information beyond identifying the state of matter depicted

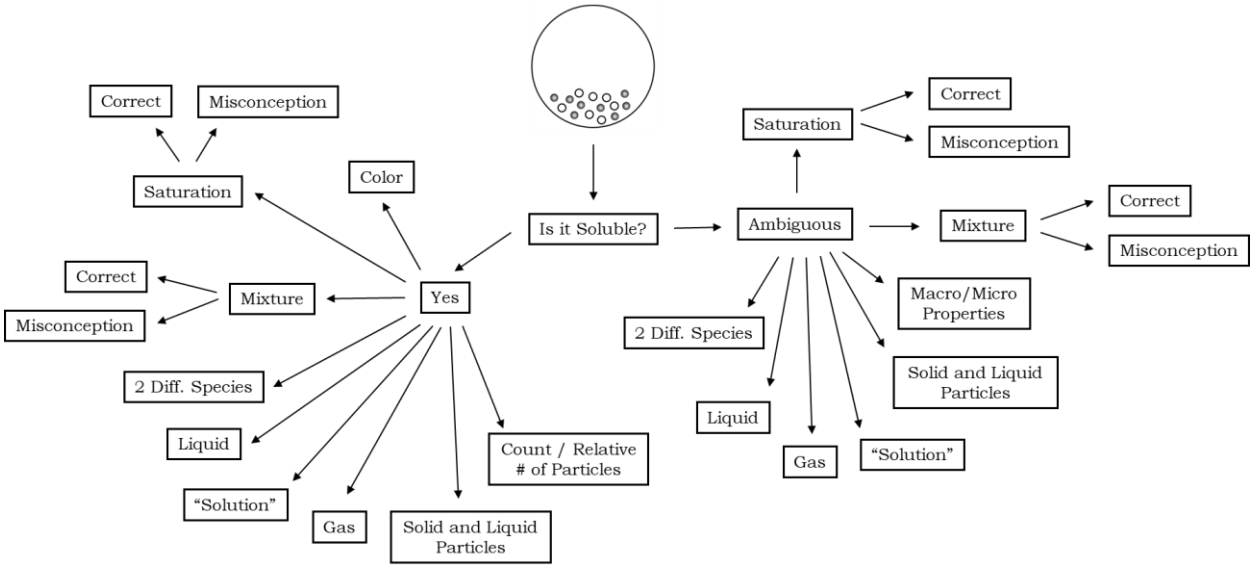
Prompt 2A



- **Is is soluble?**
  - **Ambiguous** = never clearly identified solubility
    - **Mixture** = uses words such as "mixture, homogenous, heterogeneous"
      - **Correct** = correct understanding of concept
      - **Misconception** = an aspect of what was stated was incorrect
    - **Saturation** = discusses saturation of liquid depicted.
      - **Correct** = correct understanding of concept
      - **Misconception** = an aspect of what was stated was incorrect
    - **Macro/Micro properties** = refers to macroscopic or microscopic properties
    - **Mentions solid only**
    - **Solid & Gas** = mentions these states of matter
    - **Solid & Liquid =** mentions these states of matter
      - **Solution** = calls the liquid a solution
      - **Precipitate** = calls solid a precipitate

  - **No =** not soluble
    - **Mixture** = uses words such as "mixture, homogenous, heterogeneous" (correct or misconception)
      - **Saturation** = discusses saturation of liquid depicted (correct or misconception)
    - **Macro/Micro properties** = refers to macroscopic or microscopic properties
    - **Mentions solid only**
    - **Solid & Liquid =** mentions these states of matter
      - **Solution** = calls the liquid a solution
      - **Precipitate** = calls solid a precipitate
    - **Color** = discusses color of particles

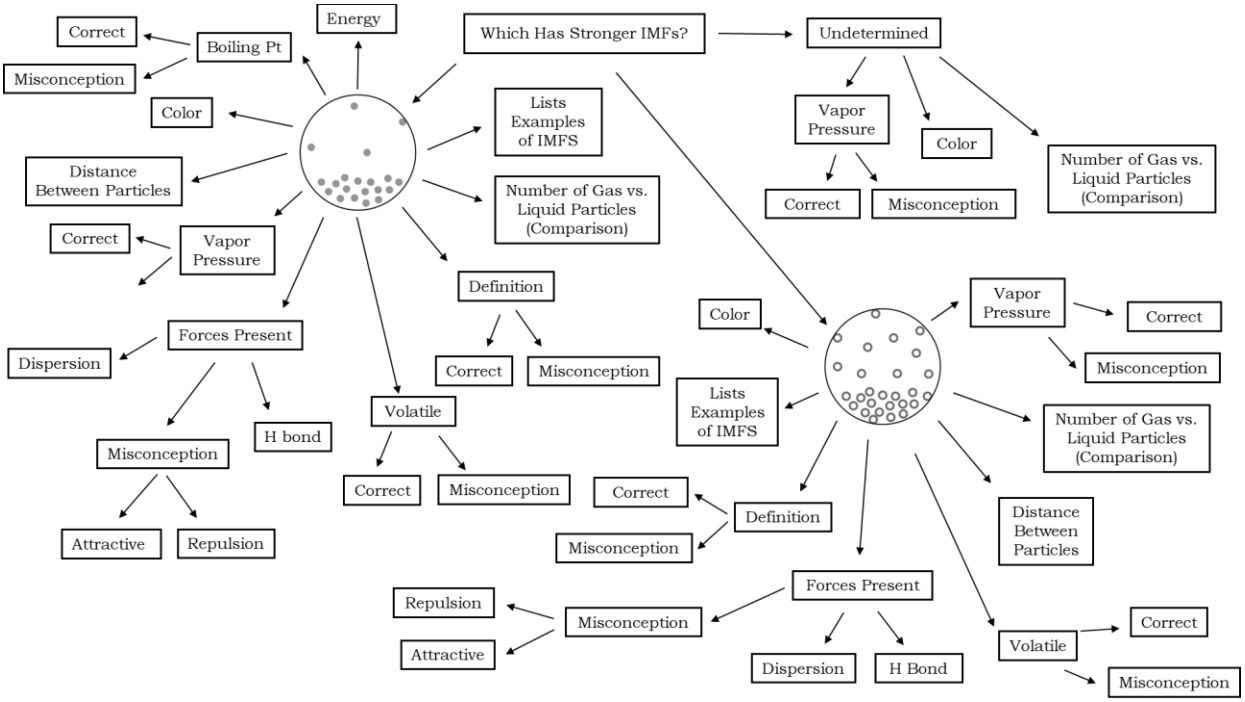
Prompt 2B



- **Yes** = soluble or more soluble
  - **Mixture** = uses words such as "mixture, homogenous, heterogeneous" (correct or misconception)
  - **Saturation** = discusses saturation of liquid depicted (correct or misconception)
  - **Color** = discuses color of particles
  - **Solid & Liquid** = mentions these states of matter
  - **Solution** = calls the liquid a solution
  - **2 diff. species** = identifies two different species
  - **Liquid** = mentions liquid
  - **Gas** = mentions gas
  - **Count / Relative # of particles** = counts the number of particles in different phases and compares between images

- **Ambiguous** = never clearly identified solubility
  - **Mixture** = uses words such as "mixture, homogenous, heterogeneous" (correct or misconception)
  - **Saturation** = discusses saturation of liquid depicted (correct or misconception)
  - **Macro/Micro properties** = refers to macroscopic or microscopic properties
  - **Count / Relative # of particles** = counts the number of particles in different phases and compares between images
  - **Color** = discuses color of particles
  - **Solid & Liquid** = mentions these states of matter
  - **Solution** = calls the liquid a solution
  - **2 diff. species** = identifies two different species
  - **Liquid** = mentions liquid
  - **Gas** = mentions gas

Prompt 3

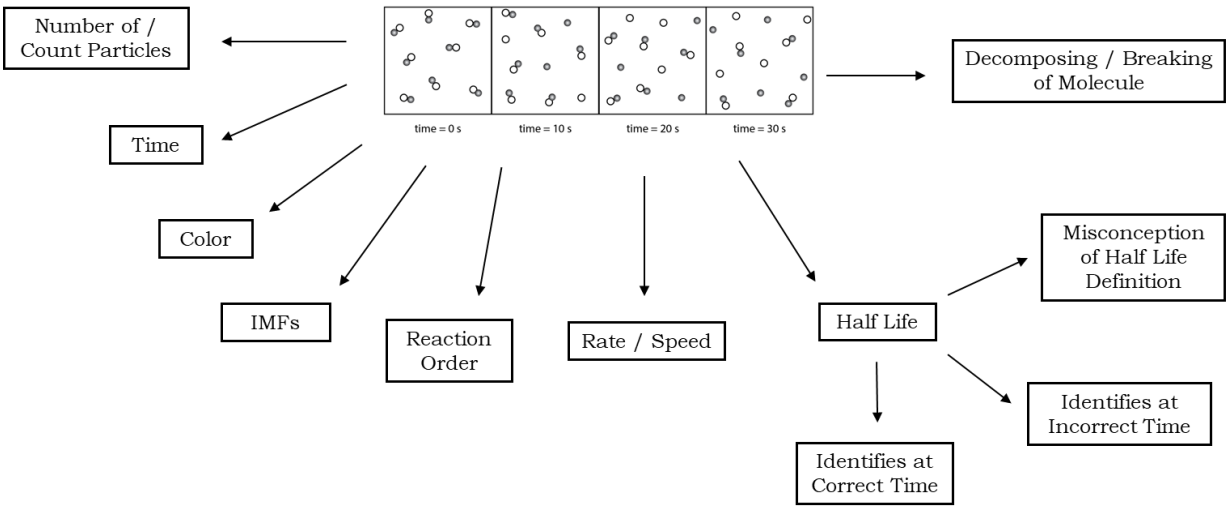


- **3A stronger** = image to the left has stronger IMFs
    - **Vapor Pressure** = conjectures about solution's vapor pressure (correctly or misconception)
    - **Boiling point** = conjectures about solution's bp (correctly or misconception)
    - **Vapor Pressure** = conjectures about solution's vapor pressure (correctly or misconception)
    - **Volatile** = conjectures about solution's volatility (correctly or misconception)
    - **Distance between particles** = describes distance between particles (large vs. small distances)
    - **Number of gas vs. liquid particles (comparison)** = compares the number of gaseous (top) particles to liquid particles (bottom).
    - **Color** = speaks to the color of particles
    - **Definition** = provides an UNPROMPTED definition of IMFs with either a correct or misconception.
    - **List**= provides a list of IMFs but doesn't say if they are necessarily present
    - **Forces Present** = mentions forces they believe are present - Dispersion, H-bonding, misconception = attractive or repulsive forces
    - **Energy** = discusses energy of particles

- **3B stronger** = image to the right has stronger IMFs
    - **Vapor Pressure** = conjectures about solution's vapor pressure (correctly or misconception)
    - **Boiling point** = conjectures about solution's bp (correctly or misconception)
    - **Vapor Pressure** = conjectures about solution's vapor pressure (correctly or misconception)
    - **Volatile** = conjectures about solution's volatility (correctly or misconception)
    - **Distance between particles** = describes distance between particles (large vs. small distances)
    - **Number of gas vs. liquid particles (comparison)** = compares the number of gaseous (top) particles to liquid particles (bottom).
    - **Color** = speaks to the color of particles
    - **Definition** = provides an UNPROMPTED definition of IMFs with either a correct or misconception.
    - **List**= provides a list of IMFs but doesn't say if they are necessarily present
    - **Forces Present** = mentions forces they believe are present - Dispersion, H-bonding, misconception = attractive or repulsive forces

- **Undetermined** = does not articulate which image has stronger IMFs.
    - **Number of gas vs. liquid particles (comparison)** = compares the number of gaseous (top) particles to liquid particles (bottom).
    - **Color** = speaks to the color of particles
    - **Vapor Pressure** = conjectures about solution's vapor pressure (correctly or misconception)

Prompt 4



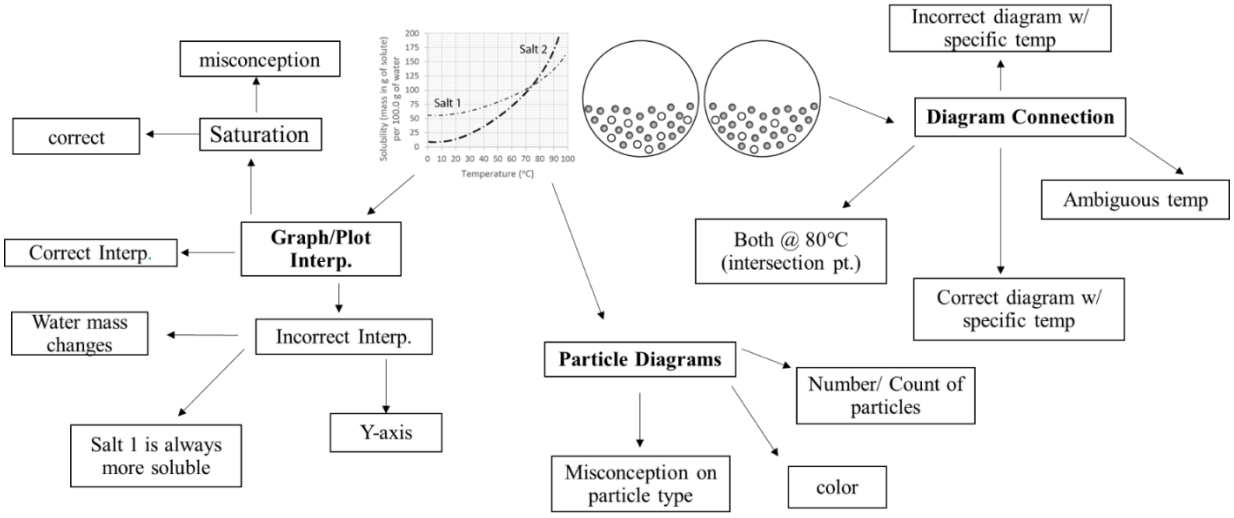
- **Number / count particles:** students counted particles / compared # of particles
- **Time =** students mention these changes are occurring over time
- **Color** = verbalizes color of species
- **Reaction Order** = discusses reaction order
- **Rate/speed** = discusses speed /rate or reaction
- **IMFs =** discusses IMFs
- **Decomposing/ breaking** = students describe reaction as something decomposing, breaking or splitting
- **Half-life =** mentions half life
    - **1** = identifies the half-life in diagram at 30 seconds
    - **2** = incorrect identification of half-life from diagrams
    - **M** = misconception of half-life definition

Prompt 8

If a student's response incorporated any of the following descriptions, a check mark with marked in the corresponding box.

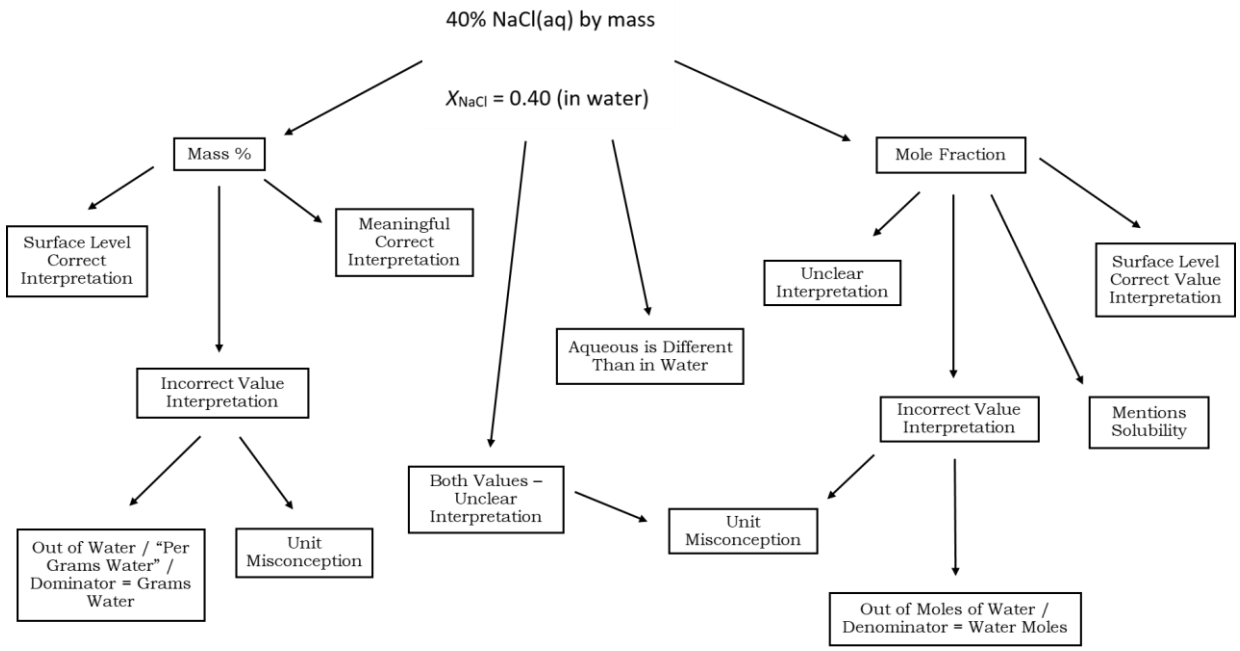
What is E_k?		***Graph Interpretation***		***Curve 1 Interpretation***		***Curve 2 Interpretation***		***Other Features / Vocab***	
Kinetic energy		X axis treated as time		Slower rate / speed		Slower rate / speed		Describes shape/ trend of curves	
Rate		Molecules at diff energies		Faster rate / speed		Faster rate / speed		Recalls shaded portion of curves	
Energy (general)		Represent activation energy – incorrect		Higher energy		Higher energy		Area under the curve	
Activation energy		Represents different rates		Low energy		Low energy		Average kinetic energy	
Unsure		Represents a reaction (react vs. produced)		Higher activation energy / needs more energy		Higher temp		Temperature	
		Energy diagram		Uses energy		Lower activation energy		Distribution	
		2 different compounds represented		Reactants		Products			
		# molecules impact x-axis		High temp		Needs more energy/ higher activation energy			
		X-axis impacts # of molecules		Reaches equilibrium faster		Cooler temp			
		Represent activation energy – correct		Larger molar mass		Longer duration			
				Cooler temp		More molecules			
				More molecules		Less molecules			
				Required more molecules					
				Less molecules					

Prompt 9



- **Graph/Plot Interpretation**
    - **Correct Interpretation** = states general trend of solubility of the salts increasing with increasing temperature; salt 1 is more soluble at low temperatures; salt 2 is more soluble at high temperatures
    - **Saturation** = saturation of solutions and how it connects to the solubility curve is discussed (correct or misconception)
    - **Incorrect Interpretation**
        - Water mass is not constant
        - Salt 1 is always more soluble
        - Misconception of what the Y-axis presents
- **Particle Diagrams**
    - **Number / Count of particles** = students count and compare particles to determine which image is more soluble
        - Discusses color of particles (solute = white, solvent = grey)
            - Misconception (solute= grey, solvent = white)
- **Diagram and Plot Connection**
    - Connects the correct diagram with a corresponding temperature
    - Incorrectly connects the diagram to a corresponding temperature
    - **Ambiguous** = no temperature mentioned; connection to diagrams ambiguous
    - Both diagrams depict where solubility is equal at approximately 80-90°C

Prompt 10



Mass Percent (%)

- **Meaningful correct interpretation** = students describe the value as 40 grams of NaCl in 100 grams of solution
- **Surface level interpretation** = articulates the mass of NaCl (40 grams) but no mention of mass of solution etc.
- **Incorrect interpretation**
    - Percentage is based on mass of water / solvent present
    - Incorrect units

Unclear Interpretation for Both Values

- Unit misconception

Aqueous is Different Than Water

- Does not connect that aqueous means in solution / NaCl is dissolved in solution

Mole Fraction

- **Meaningful correct interpretation** = students describe 0.4 moles of NaCl over total moles of solution
- **Surface level interpretation** = 0.4 moles of NaCl and 0.6 moles of water / no mention of total moles of solution
- **Incorrect interpretation**
    - Percentage is based on mass of water / solvent present
    - Incorrect units
- **Unclear Interpretation**
- **Mentions solubility** = value provides information about the solubility of NaCl

Prompt 12

If a student's response incorporated any of the following descriptions, a check mark with marked in the corresponding box.

X-Axis (E_k)		***Diagram to Distribution Connection***		***Diagrams' Features***		***Vocabulary***		***Curve 1 Interpretation***		***Curve 2 Interpretation***	
Kinetic energy		Curve 1 = A ; Curve 2 = B		Particles show motion /speed		"Average"		Using energy quickly		Smaller E_a	
Energy		Curve 1 = B; Curve 2 = A		Particles show kinetic energy		"Distribution		High kinetic energy		High kinetic energy	
Kelvin		No connection		Gas		"Temperature "		Low kinetic energy		Low kinetic energy	
Rate		Intersection point		# of particles comparison/ count		"Collision"		Larger EA		Faster	
Unsure/ ambiguous				B is faster / more speed / greater rate				Slower		Low energy	
Equilibrium				B has more energy / excited				More molecules		More molecules	
Speed				X axis treated as time				High energy		Slower	
				Particles show energy (general)				Faster		Larger k value / rate	
				B has more molecules				Smaller rate			
				B = higher temp				Larger rate			
								Requires more energy			

Prompt 14A

If a student's response incorporated any of the following descriptions, a check mark with marked in the corresponding box.

Code	Check
Soluble	
Insoluble	
Conducts electricity = electrolytes	
Draws generic species for electrolyte (no dissociation)	
Draws generic ions (charge w/ dissociation)	
Draws ions (specifically NaCl dissociated)	
Na/Cl particles dissociated (no charge)	
1:1 ratio for NaCl for dissociation	
Na ion only (discussed and/or drawn)	
Cl ion only (discussed and/or drawn)	
Electrons = electrolytes	
Salt/charge/ionic	
Draws other species type for electrolyte	
No drawing	
Omits water	
Draws more water than electrolytic species	
Draws equal water and electrolytic species	
Draws less water than electrolytic species	
Draws gas and liquid phase	

Prompt 14B-D

If a student's response incorporated any of the following descriptions, a check mark with marked in the corresponding box.

	Check
Meaning/ Interpretation of Volatility	
Volatile = evaporates / changes phase quickly	
Nonvolatile = no phase change / stays in solution	
Volatility = reactivity	
Incorrect def. of volatility	
Volatile connects with LOW vapor pressure	
Volatile connects with HIGH vapor pressure	
Correct examples of volatile / nonvolatile substances	
Incorrect examples of volatile / nonvolatile substances	
Relates to boiling / melting point	
Drawing Connection	
Correct Definition - Correct Drawing	
14B	
14C	
14D	
Incorrect Definition - Correct Drawing	
14B	
14C	
14D	
Incorrect Definition - Incorrect Drawing	
14B	
14C	
14D	
No drawings provided	

Prompt 15

If a student's response incorporated any of the following descriptions, a check mark with marked in the corresponding box.

Establishing Scenario	**Check**
X- Axis	
Selects temperature (unprompted)	
Selects temperature (prompted)	
Defines sample size (mass of solute)	
Y- Axis	
Mass of water varies	
Solubility Representation - Drawing A	**Check**
Correct solubility depicted	
Draws / discusses diagram in context of saturation	
Draws diagram at saturation point	
More/ same solvent particles drawn	
Shows dissociation of ions	
Solid phase / ppt included	
Solvent Omitted /water line drawn	
Incorrect or unclear solubility depicted	
Solubility Representation - Drawing B	**Check**
Correct solubility depicted	
Draws / discusses diagram in context of saturation	
Draws diagram at saturation point	
More /same solvent particles drawn	
Shows dissociation of ions	
Solid phase / ppt included	
Solvent Omitted /water line drawn	
Incorrect or unclear solubility depicted	
Solubility Representation - Drawings in General	**Check**
Correct relative ratio of solute drawn between A&B	
Selected Scenario Depiction	**Check**
Both salts at the same temp	
One salt at different temperatures	
Salts at intersection point	
One salt, different masses	
Both salts at different temperatures	
Unclear	

Level of Understanding	**Check**
Relative solubility understanding	
Basic level of saturation understanding	
Advanced level of saturation understanding /mass	
Unclear	
Second Temperature (If Prompted…)	**Check**
Incorrect verbal explanation given only (stop here)	
Correct verbal explaination given only (stop here)	
Drawings (continue down chart)	
Solubility Representation - Drawing A	**Check**
Correct solubility depicted	
Draws / discusses diagram in context of saturation	
Draws diagram at saturation point	
More/ same solvent particles drawn	
Shows dissociation of ions	
Solid phase / ppt included	
Solvent Omitted /water line drawn	
Incorrect or unclear solubility depicted	
Solubility Representation - Drawing B	**Check**
Correct solubility depicted	
Draws / discusses diagram in context of saturation	
Draws diagram at saturation point	
More /same solvent particles drawn	
Shows dissociation of ions	
Solid phase / ppt included	
Solvent Omitted /water line drawn	
Incorrect or unclear solubility depicted	

Prompt 16

If a student's response incorporated any of the following descriptions, the letter of the relevant code was added to the selection box for that section.

1) Representation: Drawing		
Symbolic = S	Generic particulate / shapes = G	Meaningful particulate = MP
Code for Section 1		
2) Representation: Solute vs. Solvent		
Solvent only = 1	Solute only = 2	Both solute & solvent = 3
Code for Section 2		
3) Representation: Dissociation		
No dissociation = N	Dissociation = D	
Code for Section 3		
4) Ratio Depiction		
Incorrect ratio = I	Correct ratio = C	Partially correct ratio = PC
Code for Section 4		
5) Dialogue – Drawing Connection		
Matches = M	No match = N	Partially match = PM
Code for Section 5		
6) Dialogue – Number Sense (Units)		
Ambiguous = A	Moles = N Molecules = m	Grams = g mL/L = L
Code for Section 6		
Comments		

Section 1

- Symbolic = students use symbols in drawing
- Generic particulate / shapes = students use circles or other basic shapes to represent particles
- Meaningful particulate = students include water or show charged particles

Section 2

- Solvent only = only includes solvent particles in drawing
- Solute only = only includes solute particles in drawing
- Both solute and solvent = includes both solvent particles and solute particles

Section 3

- No dissociation = no dissociation of NaCl
- Dissociation = draws NaCl dissociation

Section 4

- Correct ratio
    - 4 NaCl (undissociated) and 6 water particles
    - 2 of each dissociated ion and 6 water particles
- Partially Correct
    - 4 NaCl (undissociated) particles with 10 water particles
- Incorrect ratio
    - Any other combination of solute and solvent particles

Section 5

- Matches = student's dialogue matches their drawing
- No Match = student's dialogue does not match their drawing
- Partial match = student's dialogue partially matches their drawing

Section 6

- Ambiguous = students make no reference to units in mole fraction
- Moles = denominator units → moles
- Molecules = denominator units → molecules
- Grams = denominator units → grams
- Volume = denominator units → mL or L

Prompt 17

If a student's response incorporated any of the following descriptions, the letter of the relevant code was added to the selection box for that section.

Prompt 17	
Time 0s	
A shown - even #	
A shown - odd #	
B shown	
Time 40s	
Verbal Articulation	
Graph description explicit	
"Halved"	
"Half - Life"	
Drawing (Based on Time 0s)	
A halved - results in even #	
A halved - results in odd #	
A "halved" - encounters odd #	
Odd # resolution, drawing	
Odd #, rounds # of particles	
A decreasing (not by half)	
B present	
A:B stoich correct	
Time 80s	
Verbal Articulation	
"Halved"	
"Half - Life"	
Drawing (Based on Time 40s)	
A halved	
A "halved" - encounters odd #	
Odd # resolution, drawing	
Odd #, rounds # of particles	
A decreasing (not by half)	
B increased	
A:B stoich correct	

Drawing at Time = 0s

- A species shown only – even number drawn
- A species shown only– odd number drawn
- B species shown

Time = 40s

- Verbal Articulation
    - Describes plot explicitly (decreasing over time)
    - States A is “halved”
    - States “half-life”
- Drawing at 40s (based on 0s drawing)
    - A species halved – results in even number of species
    - A species halved - results in odd number of species
    - A species halved – encounters an odd number of species from previous drawing at t=0s
        - Rounds number of particles
        - Adds additional particles to t=0s to avoid odd number of particles
    - A species decreasing (not by half)
    - B species is present
        - A:B stoichiometry correctly drawn

Time = 80s

- Verbal Articulation
    - Describes plot explicitly (decreasing over time)
    - States A is “halved”
    - States “half-life”
- Drawing at 80s (based on 40s drawing)
    - A species halved – results in even number of species
    - A species halved - results in odd number of species
    - A species halved – encounters an odd number of species from previous drawing at t=0s
        - Rounds number of particles
        - Adds additional particles to t=0s / t= 40s to avoid odd number of particles
    - A species decreasing (not by half)
    - B species increasing
        - A:B stoichiometry correctly drawn

Appendix E

E.1. Science Motivation Questionnaire (SMQ II)

E.1A. Science Motivation Questionnaire II (SMQ-II) Glynn, et al., 2011

In order to better understand what you think and how you feel about your science courses, please respond to each of the following statements from the perspective of "When I am in a science course…"

[Response scale: ○ Never ○ Rarely ○ Sometimes ○ Always]

01. The science I learn is relevant to my life.
02. I like to do better than other students on science tests.
03. Learning science is interesting.
04. Getting a good science grade is important to me.
05. I put enough effort into learning science.
06. I use strategies to learn science well.
07. Learning science will help me get a good job.
08. It is important that I get an "A" in science
09. I am confident I will do well on science tests.
10. Knowing science will give me a career advantage.
11. I spend a lot of time learning science.
12. Learning science makes my life more meaningful.
13. Understanding science will benefit me in my career.
14. I am confident I will do well on science labs and projects.
15. I believe I can master science knowledge and skills.
16. I prepare well for science tests and labs.
17. I am curious about discoveries in science.
18. I believe I can earn a grade of "A" in science.
19. I enjoy learning science.
20. I think about the grade I will get in science.
21. I am sure I can understand science.
22. I study hard to learn science.
23. My career will involve science.
24. Scoring high on science tests and labs matters to me.
25. I will use science problem-solving skills in my career.

End. Thank you.

E.1B. SMQ-II items by motivation subscale

Items	Motivation Subscale
01. The science I learn is relevant to my life. 03. Learning science is interesting. 12. Learning science makes my life more meaningful. 17. I am curious about discoveries in science. 19. I enjoy learning science.	Intrinsic Motivation
09. I am confident I will do well on science tests. 14. I am confident I will do well on science labs and projects. 15. I believe I can master science knowledge and skills. 18. I believe I can earn a grade of "A" in science. 21. I am sure I can understand science.	Self-Efficacy
05. I put enough effort into learning science. 06. I use strategies to learn science well. 11. I spend a lot of time learning science. 16. I prepare well for science tests and labs. 22. I study hard to learn science.	Self-Determination
02. I like to do better than other students on science tests. 04. Getting a good science grade is important to me. 08. It is important that I get an "A" in science. 20. I think about the grade I will get in science. 24. Scoring high on science tests and labs matters to me.	Grade Motivation
07. Learning science will help me get a good job. 10. Knowing science will give me a career advantage. 13. Understanding science will benefit me in my career. 23. My career will involve science. 25. I will use science problem-solving skills in my career.	Career Motivation

E.2. Academic Motivation Survey – Chemistry (AMS-Chemistry)

E.2A. AMS-Chemistry Liu et al.,2017

Using the scale below, indicate to what extent each of the following items presently corresponds to one of the reasons why you are enrolled in this chemistry course.

Does not correspond at all	Corresponds a little	Corresponds moderately	Corresponds a lot	Corresponds exactly
1	**2 3**	**4**	**5 6**	**7**

Why are you enrolled in this chemistry course?

1. Because without having taken chemistry I would not find a high-paying job later on.	1	2	3	4	5	6	7
2. Because I experience pleasure and satisfaction while learning new things.	1	2	3	4	5	6	7
3. Because I think that chemistry courses will help me better prepare for the career I have chosen.	1	2	3	4	5	6	7
4. For the feelings I experience when I am communicating chemistry ideas to others.	1	2	3	4	5	6	7
5. Honestly, I don't know; I really feel that I am wasting my time taking chemistry courses.	1	2	3	4	5	6	7

6. For the satisfaction I experience while improving my understanding of chemistry.	1	2	3	4	5	6	7
7. To prove to myself that I am capable of succeeding in chemistry.	1	2	3	4	5	6	7
8. In order to obtain a better job later on.	1	2	3	4	5	6	7
9. For the pleasure I experience when I learn new things about chemistry.	1	2	3	4	5	6	7
10. Because taking chemistry will enable me to enter the job market in a field that I like.	1	2	3	4	5	6	7
11. For the pleasure that I experience when I perform chemistry experiments.	1	2	3	4	5	6	7
12. I once had good reasons for taking chemistry courses; however, now I wonder whether I should continue.	1	2	3	4	5	6	7
13. For the satisfaction I experience while succeeding in chemistry.	1	2	3	4	5	6	7
14. Because when I succeed in chemistry I feel smart.	1	2	3	4	5	6	7
15. Because I want to have a well-paying career.	1	2	3	4	5	6	7
16. For the pleasure that I experience in broadening my knowledge about chemistry.	1	2	3	4	5	6	7
17. Because taking chemistry courses will help me make more informed choices about my career options.	1	2	3	4	5	6	7
18. For the enjoyment I experience when I think about the world in terms of atoms and molecules.	1	2	3	4	5	6	7
19. I don't know why I take chemistry courses, I couldn't care less about them.	1	2	3	4	5	6	7
20. For the satisfaction I feel as I work toward an understanding of chemistry.	1	2	3	4	5	6	7
21. To show myself that I am an intelligent person.	1	2	3	4	5	6	7
22. In order to have a better salary later on.	1	2	3	4	5	6	7
23. Because studying chemistry allows me to continue to learn about things that interest me.	1	2	3	4	5	6	7
24. Because I believe that chemistry courses will improve my skills in my chosen career.	1	2	3	4	5	6	7
25. For the satisfaction I experience while learning about various chemistry topics.	1	2	3	4	5	6	7
26. I don't know; I can't understand what I am doing taking chemistry courses.	1	2	3	4	5	6	7
27. Because chemistry courses allow me to experience satisfaction in my quest for knowledge.	1	2	3	4	5	6	7
28. Because I want to show myself that I can succeed in studying chemistry.	1	2	3	4	5	6	7

E.2B. AMS – Chemistry items by motivation subscale

Items	**Motivation Subscale**
1. Because without having taken chemistry I would not find a high-paying job later on. 8. In order to obtain a better job later on. 15. Because I want to have a well-paying career. 22. In order to have a better salary later on.	External Regulation
2. Because I experience pleasure and satisfaction while learning new things. 9. For the pleasure I experience when I learn new things about chemistry. 16. For the pleasure that I experience in broadening my knowledge about chemistry. 23. Because studying chemistry allows me to continue to learn about things that interest me.	To Know

3. Because I think that chemistry courses will help me better prepare for the career I have chosen. 10. Because taking chemistry will enable me to enter the job market in a field that I like. 17. Because taking chemistry courses will help me make more informed choices about my career options. 24. Because I believe that chemistry courses will improve my skills in my chosen career.	Identified Regulation
4. For the feelings I experience when I am communicating chemistry ideas to others. 11. For the pleasure that I experience when I perform chemistry experiments. 18. For the enjoyment I experience when I think about the world in terms of atoms and molecules. 25. For the satisfaction I experience while learning about various chemistry topics.	To Experience
5. Honestly, I don't know; I really feel that I am wasting my time taking chemistry courses. 12. I once had good reasons for taking chemistry courses; however, now I wonder whether I should continue. 19. I don't know why I take chemistry courses; I couldn't care less about them. 26. I don't know; I can't understand what I am doing taking chemistry courses.	Amotivation
6. For the satisfaction I experience while improving my understanding of chemistry. 13. For the satisfaction I experience while succeeding in chemistry. 20. For the satisfaction I feel as I work toward an understanding of chemistry. 27. Because chemistry courses allow me to experience satisfaction in my quest for knowledge.	To Accomplish
7. To prove to myself that I am capable of succeeding in chemistry. 14. Because when I succeed in chemistry I feel smart. 21. To show myself that I am an intelligent person. 28. Because I want to show myself that I can succeed in studying chemistry.	Introjected Regulation

E.3. Modified Motivation Survey

Using the scale below, indicate to what extent each of the following items presently corresponds to one of the reasons why you are enrolled in this chemistry course.

Does not correspond at all	Corresponds a little	Corresponds moderately	Corresponds a lot	Corresponds exactly
1	**2 3**	**4**	**5 6**	**7**

Why are you enrolled in this chemistry course?

1. Because without having taken chemistry I would not find a high-paying job later on.	1	2	3	4	5	6	7
2. Because I experience pleasure and satisfaction while learning new things.	1	2	3	4	5	6	7
3. Because I think that chemistry courses will help me better prepare for the career I have chosen.	1	2	3	4	5	6	7
4. For the feelings I experience when I am communicating chemistry ideas to others.	1	2	3	4	5	6	7
5. Honestly, I don't know; I really feel that I am wasting my time taking chemistry courses.	1	2	3	4	5	6	7
6. For the satisfaction I experience while improving my understanding of chemistry.	1	2	3	4	5	6	7
7. To prove to myself that I am capable of succeeding in chemistry.	1	2	3	4	5	6	7
8. In order to obtain a better job later on.	1	2	3	4	5	6	7
9. For the pleasure I experience when I learn new things about chemistry.	1	2	3	4	5	6	7
10. Because taking chemistry will enable me to enter the job market in a field that I like.	1	2	3	4	5	6	7

11. For the pleasure that I experience when I perform chemistry experiments.	1	2	3	4	5	6	7
12. I once had good reasons for taking chemistry courses; however, now I wonder whether I should continue.	1	2	3	4	5	6	7
13. For the satisfaction I experience while succeeding in chemistry.	1	2	3	4	5	6	7
14. Because when I succeed in chemistry I feel smart.	1	2	3	4	5	6	7
15. Because I want to have a well-paying career.	1	2	3	4	5	6	7
16. For the pleasure that I experience in broadening my knowledge about chemistry.	1	2	3	4	5	6	7
17. Because taking chemistry courses will help me make more informed choices about my career options.	1	2	3	4	5	6	7
18. For the enjoyment I experience when I think about the world in terms of atoms and molecules.	1	2	3	4	5	6	7
19. I don't know why I take chemistry courses, I couldn't care less about them.	1	2	3	4	5	6	7
20. For the satisfaction I feel as I work toward an understanding of chemistry.	1	2	3	4	5	6	7
21. To show myself that I am an intelligent person.	1	2	3	4	5	6	7
22. In order to have a better salary later on.	1	2	3	4	5	6	7
23. Because studying chemistry allows me to continue to learn about things that interest me.	1	2	3	4	5	6	7
24. Because I believe that chemistry courses will improve my skills in my chosen career.	1	2	3	4	5	6	7
25. For the satisfaction I experience while learning about various chemistry topics.	1	2	3	4	5	6	7
26. I don't know; I can't understand what I am doing taking chemistry courses.	1	2	3	4	5	6	7
27. Because chemistry courses allow me to experience satisfaction in my quest for knowledge.	1	2	3	4	5	6	7
28. Because I want to show myself that I can succeed in studying chemistry.	1	2	3	4	5	6	7

In order to better understand what you think and how you feel about your science courses, please respond to each of the following statements from the perspective of "When I am in a chemistry course…"

	Never	***Rarely***	***Sometimes***	***Often***	***Always***
	0	***1***	***2***	***3***	***4***
I like to do better than other students on chemistry tests	***0***	***1***	***2***	***3***	***4***
Getting a good chemistry grade is important to me	***0***	***1***	***2***	***3***	***4***
I put enough effort into learning chemistry	***0***	***1***	***2***	***3***	***4***
I use strategies to learn chemistry well	***0***	***1***	***2***	***3***	***4***
It is important that I get an "A" in chemistry	***0***	***1***	***2***	***3***	***4***
I spend a lot of time learning chemistry	***0***	***1***	***2***	***3***	***4***
I prepare well for chemistry tests and labs	***0***	***1***	***2***	***3***	***4***
I think about the grade I will get in chemistry	***0***	***1***	***2***	***3***	***4***
I study hard to learn chemistry	***0***	***1***	***2***	***3***	***4***
Scoring high on chemistry tests and labs matters to me	***0***	***1***	***2***	***3***	***4***

E.4. Weighted Subscores

Table E.4A GC I motivation (weighted) subscore averages pre to post (*ref.* Table 5.7)

GC I Motivation Pre to Post Comparison (n = 158)				
	Pre	**Post**	***p***	**Effect Size**
Intrinsic Motivation	**2.97**	**2.71**	**0.029**	**0.176**
External Motivation	3.82	3.80	0.888	-----
Self - determination	4.00	3.90	0.265	-----
Grade Motivation	4.44	4.29	0.084	-----
Amotivation	**1.24**	**1.44**	**0.019**	**-0.188**

Table E.4B. Motivation (weighted) subscore average comparisons between GC I and GC II pre to post of the semester (*ref.* Table 5.9)

GC I Student (n = 158) and GC II Student Comparison (n =144)								
	PRE				**POST**			
	GC I	**GC II**	***p***	**Effect Size**	**GC I**	**GC II**	***p***	**Effect Size**
Intrinsic	2.97	2.85	0.395	------	2.71	2.68		------
External	3.82	3.83	0.932	------	3.80	3.80		------
Self - determination	4.00	3.94	0.552	------	3.90	4.05		------
Grade	4.43	4.39	0.649	------	**4.29**	**4.51**	**0.022**	**-0.265**
Amotivation	1.23	1.33	0.262	------	1.44	1.48		------

Table E.4C. GC I male student motivation (weighted) subscore averages pre to post (*ref.* Table 5.10)

GC I Male Pre to Post Comparison (n = 52)				
	Pre	**Post**	***p***	**Effect Size**
Intrinsic Motivation	**3.14**	**2.83**	**0.034**	**0.302**
External Motivation	3.97	3.71	0.114	-----
Self - determination	3.91	3.82	0.188	-----
Grade Motivation	4.28	4.27	0.924	-----
Amotivation	1.40	1.50	0.477	-----

Table E.4D. GC I female student motivation (weighted) subscore averages pre to post (*ref.* Table 5.11)

GC I Female Pre to Post Comparison (n = 106)				
	Pre	**Post**	***p***	**Effect Size**
Intrinsic Motivation	2.88	2.66	0.059	-----
External Motivation	3.74	3.85	0.322	-----
Self - determination	4.05	3.93	0.151	-----
Grade Motivation	**4.52**	**4.30**	**0.001**	**0.328**
Amotivation	**1.15**	**1.41**	**0.002**	**-0.315**

Table E.4E. Motivation (weighted) subscore averages between GC I male and female students pre and post of the semester (*ref.* Table 5.12)

GC I Female Student (n = 106) and Male Student Comparison (n = 52)								
	PRE				**POST**			
	Female	**Male**	***p***	**Effect Size**	**Female**	**Male**	***p***	**Effect Size**
Intrinsic Motivation	2.88	3.14	0.193	------	2.65	2.83	0.375	------
External Motivation	3.74	3.97	0.258[a]	------	3.84	3.71	0.548	------
Self - determination	3.91	4.05	0.351	------	3.94	3.82	0.417	------
Grade Motivation	4.52	4.28	0.071	------	4.30	4.27	0.807	------
Amotivation	1.16	1.40	0.051[a]	------	1.41	1.50	0.601	------
[a] *Equal variance not assumed*								

Table E.4F. GC I male student motivation (weighted) subscore averages pre to post (*ref*. Table 5.14)

GC II Male Pre to Post Comparison (n = 45)				
	Pre	**Post**	***p***	**Effect Size**
Intrinsic Motivation	2.97	2.89	0.622	------
External Motivation	4.02	3.78	0.158	------
Self - determination	3.90	3.80	0.504	------
Grade Motivation	4.35	4.39	0.726	------
Amotivation	1.51	1.68	0.315	------

Table E.4G. Motivation (weighted) subscore averages between GC II male and female students pre and post of the semester (*ref*. Table 5.14)

GC II Female Student (n = 99) and Male Student Comparison (n = 45)								
	PRE				**POST**			
	Female	**Male**	***p***	**Effect Size**	**Female**	**Male**	***p***	**Effect Size**
Intrinsic Motivation	2.79	2.97	0.390[a]	------	2.59	2.89	0.163	------
External Motivation	3.74	4.02	0.272	------	3.80	3.78	0.924	------
Self - determination	3.96	3.89	0.727	------	**4.16**	**3.80**	**0.035**	**0.383**
Grade Motivation	4.42	4.35	0.666	------	4.56	4.39	0.249	------
Amotivation	1.26	1.51	0.109	------	1.39	1.68	0.094	------
[a] *Equal variance not assumed*								

Table E.4H. GC I pre-professional student motivation (weighted) subscore averages pre to post (*ref*. Table 5.17)

GC I Pre - Professional Pre to Post Comparison (n = 53)				
	Pre	**Post**	***p***	**Effect Size**
Intrinsic Motivation	3.10	2.80	0.089	------
External Motivation	4.16	3.98	0.226	------
Self - determination	4.13	3.97	0.106	------
Grade Motivation	**4.66**	**4.43**	**0.006**	**0.391**
Amotivation	1.32	1.53	0.138	------

Table E.4I. Motivation (weighted) subscore averages between GC I science major and pre-professional students pre and post of the semester (*ref*. Table 5.18)

GC I Science Major (n = 86) and Pre – professional Comparison (n = 53)								
	PRE				POST			
	Pre - Professionals	Science Majors	*p*	Effect Size	Pre - Professionals	Science Majors	*p*	Effect Size
Intrinsic Motivation	3.10	2.86	0.257	------	2.80	2.70	0.671	------
External Motivation	**4.16**	**3.72**	**0.039**	**0.350**	3.98	3.84	0.545	------
Self - determination	4.13	3.91	0.170	------	3.97	3.86	0.461	------
Grade Motivation	**4.66**	**4.29**	**0.004**[a]	**0.482**	4.43	4.24	0.183[a]	------
Amotivation	1.32	1.23	0.499	------	1.53	1.40	0.478	------
[a] *Equal variance not assumed*								

Table E.4J. GC II science major student motivation (weighted) subscore averages pre to post (*ref*. Table 5.19)

GC II Science Major Pre to Post Comparison (n = 78)				
	Pre	**Post**	***p***	**Effect Size**
Intrinsic Motivation	**2.76**	**2.54**	**0.027**	**0.255**
External Motivation	3.66	3.61	0.628	------
Self - determination	3.87	4.06	0.055	------
Grade Motivation	4.29	4.37	0.281	------
Amotivation	1.42	1.54	0.200	------

Table E.4K. GC II pre-professional student motivation (weighted) subscore averages pre to post (*ref*. Table 5.20)

GC II Pre - Professional Pre to Post Comparison (n = 53)				
	Pre	**Post**	***p***	**Effect Size**
Intrinsic Motivation	3.06	2.85	0.085	------
External Motivation	4.31	4.27	0.764	------
Self - determination	4.07	4.13	0.639	------
Grade Motivation	**4.61**	**4.82**	**0.027**	**-0.312**
Amotivation	1.18	1.39	0.074	------

Table E.4L. Motivation (weighted) subscore averages between GC II science major and pre-professional students pre and post of the semester (*ref*. Table 5.21)

GC II Science Major (n = 78) and Pre – professional Comparison (n = 53)								
	PRE				POST			
	Pre - Professionals	Science Majors	*p*	Effect Size	Pre - Professionals	Science Majors	*p*	Effect Size
Intrinsic Motivation	3.07	2.76	0.147[a]	------	2.85	2.54	0.174[a]	------
External Motivation	**4.31**	**3.66**	**0.006**	**0.513**	**4.27**	**3.61**	**0.005**	**0.518**
Self - determination	4.07	3.87	0.245	------	4.13	4.06	0.697	------
Grade Motivation	**4.61**	**4.29**	**0.030**	**0.398**	**4.82**	**4.37**	**0.001[a]**	**0.561**
Amotivation	1.18	1.41	0.121	------	1.39	1.54	0.376	------

[a] *Equal variance not assumed*

Table E.4M. GC II positive learning gain group motivation (weighted) subscore averages pre to post (*ref*. Table 5.22)

Positive Learning Gain Group Motivation Pre to Post Comparison (n = 35)				
	Pre	**Post**	***p***	**Effect Size**
Intrinsic Motivation	2.92	2.80	0.251	-----
External Motivation	3.50	3.72	0.206	-----
Self - determination	**3.75**	**4.09**	**0.034**	**-0.373**
Grade Motivation	4.29	4.46	0.156	-----
Amotivation	1.09	1.29	0.155	-----

E.5. Unweighted Subscores

Table E.5A. GC I motivation (unweighted) subscore averages pre to post (*ref*. Table 5.8)

GC II Motivation Pre to Post Comparison (n = 144)				
	Pre	**Post**	***p***	**Effect Size**
Intrinsic Motivation	**3.39**	**3.19**	**0.021**	**0.195**
External Motivation	4.41	4.37	0.619	-----
Self - determination	4.76	4.90	0.114	-----
Grade Motivation	5.56	5.69	0.069	-----
Amotivation	**1.67**	**1.87**	**0.028**	**-0.185**

Table E.5B. GC II female student motivation (unweighted) subscore averages pre to post of the semester (*ref*. Table 5.13)

GC II Female Pre to Post Comparison (n = 99)				
	Pre	**Post**	***p***	**Effect Size**
Intrinsic Motivation	**3.35**	**3.08**	**0.005**	**0.292**
External Motivation	4.35	4.37	0.842	------
Self - determination	**4.80**	**5.03**	**0.022**	**-0.233**
Grade Motivation	5.59	5.76	0.059	------
Amotivation	1.58	1.75	0.098	------

Table E.5C. GC I science major student motivation (unweighted) subscore averages pre to post of the semester (*ref*. Table 5.16)

GC I Science Major Pre to Post Comparison (n = 86)				
	Pre	**Post**	***p***	**Effect Size**
Intrinsic Motivation	3.40	3.22	0.193	------
External Motivation	4.29	4.41	0.385	------
Self – determination	4.73	4.66	0.516	------
Grade Motivation	5.42	5.36	0.454	------
Amotivation	1.56	1.78	0.058	------

Curriculum Vitae

Allison Renee Tomczyk-Schauer

EDUCATION PROFILE

2019 - 2024 **Doctor of Philosophy in Chemistry (Chemical Education)**

Dissertation: *An in-depth investigation into scale literacy: A refinement of a scale-themed curriculum intervention through scaffolding, interviews, and affect*

Advisor: Dr. Kristen L. Murphy

University of Wisconsin – Milwaukee

2018 **Bachelor of Science in Chemistry**

American Chemical Society Approved Emphasis (*magna cum laude*)

Carroll University, Waukesha, WI

AWARDS

2024, 2022 Gloria Moczynski Student Teacher Award

2022 George Keulks Memorial Scholarship and Award

RESEARCH EXPERIENCE

Graduate Research

2020 - 2024 **Graduate Research Assistant – Chemical Education**

Department of Chemistry & Biochemistry • University of Wisconsin – Milwaukee

- Designed curriculum intervention materials for general chemistry II course
    - Emphasis on implementation of scale-themed activities and instructional scaffolding
- Experience in qualitative research methodology
    - Designed 5 unique interview decks
    - Conducted over 50 think-aloud interviews
    - Coding
- Proficient in various statistical methods
    - Exploratory factor analysis (EFA) and confirmatory factor analysis (CFA)
- Experience in survey data collection and analysis

PUBLICATIONS

McAfee, S.C.; **Tomczyk-Schauer, A.R**.; Johnson Kempinski, L.E.; Williamson.; Rodriquez, J-M.G. A graduate course-based chemistry education research experience: Describing a general model and the project outcomes related to investigating chemistry graduate students' perceptions of the imposter phenomenon, *Manuscript in review*

TEACHING EXPERIENCE

Instructor of Record

Fall 2024 **Chemical Science Instructor**

Department of Chemistry & Biochemistry • University of Wisconsin – Milwaukee

Graduate Teaching Assistant

2022 - 2024 **Graduate Teaching Assistant – Supplemental Instruction Leader**

Department of Chemistry & Biochemistry • University of Wisconsin – Milwaukee

2022 – 2023 **Private Chemistry Tutor**

2019 - 2022 **Graduate Teaching Assistant – Lab / Discussion**

Department of Chemistry & Biochemistry • University of Wisconsin – Milwaukee

ORAL PRESENTATIONS

Summer 2024 Biennial Conference for Chemical Education – "The role of affect in learning: Understanding how motivation can impact instructional interventions," *Lexington, KY*

Summer 2024 Biennial Conference for Chemical Education – "The power of scaffolding in instruction: Using multi-mode student interviews to understand learning gains and changes in scale literacy," *Lexington, KY*

Spring 2024	Spring National American Chemical Society Meeting – "Validation and interpretation of the motivation of general chemistry students: The merging of two instruments to study motivation," *New Orlean, LA*
Summer 2022	Biennial Conference for Chemical Education – "Development of semi-structured student interviews for insight into student problem-solving in key general chemistry II content areas," *West Lafayette, IN*
Summer 2022	Biennial Conference for Chemical Education – "Exploring modification to scale-themed instruction in general chemistry II: Determining content area and scale concepts targets," *West Lafayette, IN*
Spring 2021	UW-Milwaukee Department of Chemistry & Biochemistry Annual Symposium – "Exploring modifications to scale-themed instruction in general chemistry II: Determining content area and scale concepts targets," *University of Wisconsin – Milwaukee*

POSTER PRESENTATIONS

Spring 2024	UW-Milwaukee Department of Chemistry & Biochemistry Annual Symposium "Development, transcribing, and coding of extensive qualitative interview responses," *University of Wisconsin – Milwaukee*
Spring 2024	Spring National American Chemical Society Meeting – "Development, transcribing, and coding of extensive qualitative interview responses," *New Orlean, LA*
Spring 2023	UW-Milwaukee Department of Chemistry & Biochemistry Annual Symposium "Qualitative Analysis of general chemistry II students' interview responses: Understanding responses on solutions and kinetics prompts on a continuum of correctness and completeness," *University of Wisconsin – Milwaukee*
Spring 2022	UW-Milwaukee Department of Chemistry & Biochemistry Annual Symposium "Development of semi-structured student interviews for insight into student problem-solving in key general chemistry II content areas," *University of Wisconsin – Milwaukee*
Fall 2021	American Chemical Society: Milwaukee Chapter Poster Session – "Exploring modifications to scale-themed instruction in general chemistry II: Determining content area and scale concepts targets," *Milwaukee, WI*

WORKSHOPS

Winter 2021 — UW-Milwaukee Center of Excellence in Teaching and Learning Annual Symposium – "Helping students get from A to B: Evaluating the need for scaffolding and strategies to implement in the sciences," *University of Wisconsin – Milwaukee*

MENTORING

New Teaching Assistants

Fall 2021 – 2024
- Developed orientation and training activities for newly reconstructed teaching assistant mentoring program
- Led new teaching assistant orientation activities
- Met weekly with new teaching assistants to discuss progress and personal growth
- Conducted teaching evaluations and produced formal feedback on instructional practices

Undergraduate Researchers

Spring 2024
- Mira Beranek

Spring 2023
- Mira Beranek
- Preston Burdett

Fall 2022
- Mira Beranek

Fall 2021
- Jennifer McClanahan

Spring 2020
- Kim Osborn
- Trent Lechleitner

VOLUNTEERING

Winter 2023 — **Science Olympiad Event Supervisor & Judge**