Promoting Preservice Elementary Teacher Acquisition of Science and Mathematics Concept Knowledge: Potential of Technological/Engineering Design Based Learning

Mark A. Hainsworth

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John G. Wells, Chair
Brett Jones
Bettibel Kreye
Thomas Williams

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ABSTRACT

(Academic)

Prior research suggests that teachers connect science and mathematics concepts to practical explanations and, when given examples where such concepts can be seen, explanations and applications of the theory are more accurate. Technology and Engineering Design Based Learning (T/E DBL) is uniquely suited for teaching the concepts of science, technology, engineering, and mathematics in an integrative, practical way. However, not yet fully understood is how, when, or the extent to which such conceptual understandings develop while preservice teachers engage in a T/E DBL design challenge and are immersed in the eight design phases.

This research documents how engagement of preservice elementary teachers in T/E DBL promotes their acquisition of complex science and mathematics concept knowledge. Specifically, the research demonstrates the progressions of acquiring science and mathematics concept knowledge among preservice elementary teachers following their engagement in T/E DBL. Participant perceptions of design experiences that support concept knowledge acquisition are also documented.

Results indicate engagement of preservice elementary teachers in T/E DBL design challenges promotes their knowledge progression towards acquisition of targeted science and mathematics concepts and that *Research, Potential Solutions, Solution Evaluation 1 and Solution Evaluation 2* are the most impactful phases of design for promoting conceptual understanding**.** These results provide validation of T/E DBL as an effective pedagogical approach for preparing preservice elementary teachers to teach complex science and mathematics concepts.

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ABSTRACT

(General)

This research demonstrated that Technology and Engineering Design Based Learning (T/E DBL) has the potential to promote preservice elementary teacher acquisition of science and mathematics concept knowledge and that *Research, Potential Solutions, Solution Evaluation 1 and Solution Evaluation 2* are the four most impactful phases of design for promotion of conceptual understanding**.** Participants were asked to solve a design challenge that required science and mathematics concept knowledge to successfully design, build, test and analyze a system for producing freshwater from salt water. Participants were also asked to maintain a Science and Engineering Interactive Notebook (SEIN) throughout the design challenge.

Results from pre/post multi-tiered multiple-choice tests indicated that participants progressed in their science and mathematics concept knowledge after engagement in T/E DBL. Post challenge interviews and SEIN reviews corroborated these findings. The research also suggests that doing background research, brainstorming potential solutions and then evaluating those solutions with testing, analysis, and prototype comparisons helped to promote science and mathematics concept knowledge.

These results validate the use of T/E DBL as a pedagogical approach for instruction of preservice elementary teachers and indicate that special attention to the design phases listed above could enhance learning within those individual.

DEDICATION

This dissertation is dedicated to my wife, Laura. Throughout our life's journey, and my academic journey, you have been my inspiration, my confidant, an interested colleague on our long walks together, and my endless giver of encouragement. Thank you! I love you!

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CHAPTER ONE: INTRODUCTION

Shulman (2005) suggests that there are three dimensions to signature pedagogies: surface structure, which dictates how we physically teach, deep structure, which guides us on how best to teach knowledge within a subject, and implicit structure, that guides our teaching of moral issues encountered within a subject. All three dimensions, experienced by teachers during their PK-12 education and post-secondary training, deeply ingrain into a teacher's belief system ideas about how to best teach the content in their content area. Within the deep structure dimension of a signature pedagogy is the belief that what is being taught is the essential knowledge needed to work as a professional in a field related to the content area. An example of this would be that a science teacher using a signature pedagogy believes that the chosen pedagogy imparts the requisite knowledge of science theory and how to think and perform like a scientist. Factors contributing to this belief are the level and depth of content concept knowledge the teacher possess and their understanding of how content concepts relate to authentic contexts.

Shulman (1987) proposed the need for a greater understanding of the seven categories of teacher knowledge base: content knowledge, general pedagogical knowledge, curricular knowledge, pedagogical content knowledge, knowledge of learners and their characteristics, knowledge of educational contexts, knowledge of ends, purposes and values. While Pedagogical Content Knowledge (PCK) has been a fertile topic of research since Shulman introduced the concept, there is a lack of research on science and mathematics concept knowledge development in preservice elementary teachers using Integrative STEM Education (I-STEM ED) Technology/Engineering Design Based Learning (T/E DBL) pedagogical approaches. This study addresses this gap in teacher content knowledge development, general pedagogical knowledge, and teacher preparation research. The purpose of this study was to better understand the relationship between student preservice teacher engagement in T/E DBL challenges and their

changes in science and mathematics concept knowledge. In addition, this study informs teacher educators on those critical phases and conditions within this pedagogical approach that lead to higher probabilities of impacting science and mathematics concept knowledge within their own preservice elementary student teachers.

Nature of the Problem

Science, technology, engineering, and mathematics (STEM) literacy is critical in today's society not only for a person's ability to use technology that surrounds us but to also enable decision making about wider science and technology related issues. The ability to make informed decisions about funding for science initiatives, personal implementation of disease prevention actions, and the application of clean energy technologies are just a few examples of how STEM literacy is essential to being a responsible and self-reliant citizen in today's society. To maximize the positive effects of technology and manage and maintain control of the non-positive effects of technology, individuals must understand the science and mathematics behind the technology and their historical relationship (National Research Council (U.S.)., 2012; The Royal Society, 1982). The profusion of science and technology in our world has prompted a call for increased STEM education and integrative learning from all corners of our society. Leaders and policy makers in government, education, and industry see value in students and future employees having skills and knowledge born in learning environments where content knowledge is highly connected in real-world contexts (Humphreys, 2005). They have also informed us that integrated science and technology education gives students the cognitive tools to participate in society in an informed manner (National Academy of Engineering, 2002; Organisation for Economic Co-operation and Development et al., 2006).

In order to meet these educational needs of current and future students, the PK-12 and post-secondary education communities are slowly responding. They are recognizing that the task

of developing STEM literacy within students falls squarely on the shoulders of teachers at all levels and that implementation of STEM Education should not wait until students reach the secondary level. Researchers have found that, while elementary students do have the capacity of abstraction (Warren & Cooper, 2009), it is recognized that the teaching of STEM concepts at the elementary level should be taught in a situated contextualized manner (AAAS, 1989; Westbroek et al., 2005). It is not surprising that the development of science and mathematics concepts in situated and contextualized ways should begin with elementary students when use of pedagogical practices using concrete models for concept development are more commonly used (AAAS, 1989). It is also recognized that science and mathematics concepts inform technology while technology provides tools that allow for greater understanding of science and mathematics concepts, therefore, they are inherently tied together. Technology developments occur due to the pursuit of solutions of real world problems. The solution of real world problems requires the understanding of science and mathematics concepts. This interchange between technological advances and increased scientific knowledge supports the assertion that these disciplines should be taught in an integrative manner (AAAS, 1993). If we hope for a society where continued technological developments and improvements are perpetuated, educational environments and approaches must be designed so that science, technology, engineering, and mathematics are taught in an integrative manner using authentic/contextualized problems throughout the K-12 grade levels. As early as 2007, the Netherlands has recognized the need for this integrative approach to science and technology knowledge development for their students. In response, they have supported their teachers by providing professional development opportunities for learning and evolution of "science and technology knowledge, attitudes, and skills in an exploratory and

reflective manner" (Koski, 2014). The theoretical framework that guided what teachers should know so that they could teach science and technology in the classroom included:

1. Teachers should not only know key science and technology concepts but should also acquire key science and technology skills,
2. Teachers should develop more favorable attitudes towards science and technology, and
3. Teachers should develop the instructional skills needed to stimulate inquiry based learning and learning by technical design (Walma van der Molen et al., 2007).

Integrative STEM Education (I-STEM ED) is uniquely suited for the teaching of science, technology, engineering, and mathematics in an integrative way. While separate instruction of science and technology provides students with knowledge that certain phenomena occur under specific environmental conditions and the knowledge of how to physically accomplish a task or acquire more information about phenomena, I-STEM ED is a pedagogical approach that uses the implementation of technology and engineering practices to intentionally teach science and mathematics concepts. The primary goal of this pedagogical approach is the teaching of technology and engineering concepts along with the teaching of concepts within disciplines that are inherent to the design task. Integrative STEM Education is defined in the following manner:

> "Integrative STEM Education is the application of technological/engineering design based pedagogical approaches to *intentionally* teach content and practices of science and mathematics education through the content and practices of technology/engineering education. Integrative STEM Education is equally applicable at the natural intersections of learning within the continuum of content

areas, educational environments, and academic levels" (Wells & Ernst, 2012/2015).

This form of pedagogy is an alternate approach to teaching other than the traditional silo teaching of science and math in non-contextualized ways. It provides students with learning experiences that highly situate and contextualize science and mathematical concept knowledge development and promote problem solution skills sought by the leaders and policy makers in government, education, and industry. Unfortunately, an I-STEM ED T/E DBL curriculum that is not delivered rigorously, energetically and authentically can be as ineffective as any other curriculum (Drake & Burns, 2004). An Integrative STEM ED T/E DBL pedagogical approach can only maximize student learning when teachers have the requisite knowledge of student needs, and science, technology, engineering, and mathematics concepts.

The educational research community is continuing to collect evidence that shows that teachers have an exceedingly strong impact on student learning (Fennema & Franke, 1992; Gersten et al., 2010; Hiebert & Grouws, 2007; Liu et al., 2010; Nye et al., 2004) This outcome has led researchers to begin to try to understand the categories of teacher knowledge that most effect student learning. Shulman proposed that that there are seven categories within a teacher's knowledge base; content knowledge, general pedagogical knowledge, curricular knowledge, pedagogical content knowledge, knowledge of learners and their characteristics, knowledge of educational contexts, knowledge of ends purposes and values. While Shulman (1987) proposed the above listed categories within a teacher's knowledge base, he also identified four sources of a teacher's knowledge base: scholarship in content disciplines, the materials and settings of the institutionalized educational process, educational research, and the wisdom of practice. The facet within a teacher's content knowledge base and the source of this knowledge that will be

investigated in this research is how the underlying learning theories associated with science and mathematics concept development in preservice elementary student teachers relates to I-STEM ED T/E DBL pedagogical approaches.

Concept knowledge is composed of the concepts, theories, and principles within a subject area. Concepts are generalized mental representations of phenomena that are developed over long periods of time and are based on particular instances of observational experiences with a phenomenon. They are mental categories that help the individual to categorize ideas, objects, and events because of shared characteristics (Henze & de Vries, 2021). Conceptual learning is "the search for and listing of attributes that can be used to distinguish examples from non-examples" (Bruner et al., 1967). During conceptual learning, the learner is forming analogies, recognizing regularities, and determining relations related to concepts. Individuals can have pre-conceptions about concepts that are incomplete and formed using insufficient observational experiences. These pre-conceptions are amended and refined when more evidence is experienced and attributes are recognized.

Teachers' levels of concept knowledge have been positively correlated to teaching effectiveness by researchers participating in the Measures of Effective Teaching project (The MET Project, 2013). Teachers who implement I-STEM ED T/E DBL pedagogical approaches face increased difficulties and chaotic teaching environments due to the multiple possible solution pathways students could attempt to use. Those that use this pedagogical approach must possess deep understanding of the related concepts and they must a confident that the design based challenges and the possible solution strategies used by their students will ultimately lead to student understanding of the science and mathematics concept that were intentionally targeted. For instance, if a teacher has created a design challenge that targets gas properties as being the

primary learning objectives the teacher must understand that gases are made of very small elements or molecules, they are compressible, they mix with other gases, they can diffuse through materials, they can be soluble in liquids, and they can displace liquids. They must be capable of recognizing and highlighting examples of these concepts when students encounter them during their design challenge solution efforts. Science concept knowledge is therefore critical for successful teaching of science concepts through I-STEM ED T/E DBL pedagogies. In addition, having a strong understanding of science concepts provides teachers with the basis to design effective T/E DBL lesson plans, critique existing lesson, understand and judge the learning value of student selected solution strategies, identify student misconceptions, and reteach concepts using alternate examples.

Unfortunately, science and mathematics concept knowledge held by elementary teachers is lacking and their confidence in teaching science is low (Appleton, 2003; Fernandez, 2005). Therefore, this could be a reason for hesitancy of teachers to adopt I-STEM ED pedagogical approaches in their classrooms. To further and enhance I-STEM ED T/E DBL teaching in elementary schools we need to prepare teachers in a way that deepens their science and mathematics conceptual understanding and do it in ways that influence their teaching practices towards integrative approaches to teaching.

Rationale of the Study

Studies have shown that elementary teachers (and students) lack a thorough understanding of science concepts such as mass, force, gravity, density, buoyancy, temperature and heat (C. J. Kruger et al., 1990; Bleicher, 2006; Rollnick & Rutherford, 1990). One possible reason for this lack of science concept knowledge is that concepts are abstractions which relate categorical ideas (i.e. tree, fungus, algae) or, more confusingly, they can be theoretical entities that relate ideas about physical phenomena (i.e. buoyancy, air pressure, tensile strength). These

concepts must be experienced rather than solely discussed. We have to experience the common properties of these theoretical entities, in various contexts, in order to fully understand them (Koski, 2014). Likewise, preservice elementary teachers have demonstrated a lack of mathematical concept knowledge. Seaman and Szydlik (2007) found that preservice teachers demonstrated a profound lack of mathematical sophistication and that their lack of mathematical concept knowledge is more than simply deficient procedural knowledge They recommend that in order to correct these deficiencies, preservice teachers need to "create models that have meaning".

If preservice teachers were given the opportunity to experience theory related concepts in tangible ways within an I-STEM ED T/E DBL environment, there might be an improvement in their science and mathematics concept knowledge. In addition, if this pedagogical approach was found to be effective in teaching science and mathematics concept knowledge to preservice teachers then they will be able to, not only, correctly teach these concepts to their future students but they will also be able to teach the concepts in an integrative way due to their familiarity with the I-STEM ED T/E DBL pedagogical approach. This leads to the questions, what does "science and mathematics concept knowledge" mean and why would an I-STEM T/E DBL pedagogical approach to teaching be an appropriate means by which to support concept knowledge growth?

Markman and Rein (2013) inform us that "it is common to use the term category as representing a collection of items that are treated as equivalent" and "a concept is a mental representation of that category" (p. 1). Knowledge of interconnected concepts, otherwise known as conceptual knowledge, can be implicit or explicit, do not have to be verbalized, and is characterized as knowledge that is rich in relationships (Byrnes & Wasik, 1991; Canobi, 2009; Goldin-Meadow et al., 1993; Rittle-Johnson et al., 2001). The aspect of interconnecting concepts

that comprise concept knowledge is thought, by some, to be related to expertise and is therefore subject to evolution over the learning period (Baroody et al., 2007). The source of this evolution in expertise, or rich connectedness amongst concepts, is a product of activity, context, and culture related to when the learning occurs and when the concepts are applied (Brown et al., 1989). In other words, concept development is situated and the situations surrounding the advent of concept development within a learner exert an influence on recall, recognition, categorization, property verification, and property generation (Yeh & Barsalou, 2006). The development of concepts, and therefore concept knowledge, is closely linked to a person's ability to form categories within their memory systems (Markman & Rein, 2013). Categories are collections of items that are treated as equivalent while concepts are the mental representations of categories. According to Markman & Rein (2013) "The information people acquire about category members is strongly influenced by the tasks they perform while the categories are being learned" (p. 2). Understanding the formation and structure of category development within a situated context such as that provided during I-STEM ED T/E DBL experiences begins with understanding concept knowledge development that occurs within that setting. Given the preponderance of evidence (AAAS, 1989; Westbroek et al., 2005; Yeh & Barsalou, 2006) indicating that learning is situated, and that preservice teachers lack thorough understanding of science and mathematics concepts (C. J. Kruger et al., 1990; Bleicher, 2006; Rollnick & Rutherford, 1990; Seaman & Szydlik, 2007), it follows that their science and mathematics experiences likely contained few practical, concrete examples. This lack of experiential learning would then result in reduced acquisition of deep understandings of the science and mathematics concept knowledge, and a lack of rich connections to other disciplinary concepts.

A pedagogical approach such as I-STEM ED DBL provides a highly situated learning environment within which science and mathematics concept development can occur and in which success or failure in the design and testing of technology and engineering principles provides immediate and brutally honest feedback on underlying concept understanding. In other words, an I-STEM ED DBL challenge can be designed so that a successful solution to the challenge requires the student to deeply understand the targeted concepts. If this is not done, then failure of the design will occur and continue to occur until the student understands the concept leading to a redesign that accommodates the new knowledge. Koski (2014), provided evidence that teachers connect science concepts to practical explanations and, when given examples where science concepts can be "seen", explanations and applications of the theory are more accurate. What is not fully understood is how progressions toward acquisition of conceptual understanding occurs when learners are engaged in T/E DBL where they are working with materials, researching, making observations, engaging in discussions with colleagues, testing prototypes, or optimizing designs.

Purpose of the Study

The purpose of this study was to document the progressions of science and mathematics concept knowledge among preservice elementary teachers engaged in T/E DBL challenges and to identify those phases of design they perceived most influenced that progression. To achieve this purpose an exploratory sequential mixed method embedded multiple embedded case study approach was deemed appropriate for assessing and corroborating progressions toward the acquisition of targeted science and mathematics concept knowledge. Results from this research will help to inform teacher educators on critical phases and conditions within I-STEM ED DBL pedagogical approaches that can result in higher probabilities of impacting acquisition of science and mathematics concept knowledge within their own preservice elementary student teachers.

Research Questions

The following research questions were used to guide this study:

When preservice elementary teachers engage in a T/E DBL challenge:

RQ1 - What evidence demonstrates such engagement promotes their knowledge progression towards acquisition of targeted complex science and mathematics concepts compatible with accepted scientific views?

RQ2 – What T/E DBL experiences do they indicate promoted their acquisition of the targeted complex science and mathematics concepts?

CHAPTER TWO: REVIEW OF LITERATURE

The purpose of this chapter is to present the literature relevant to and supportive of the research conducted. The chapter opens by first establishing the theoretical foundations for concept knowledge formation and the characteristics of I-STEM ED T/E DBL pedagogical approaches that are supportive of promoting such knowledge development. Specifically, the underlying concept knowledge formation theories are presented first, followed by the theories of I-STEM ED T/E DBL pedagogy, inclusive of how it can facilitate concept formation in students so as to clearly identify their connections to concept formation theory. The chapter concludes with a discussion of the literature surrounding previous research and methodologies that sought to measure and characterize science and mathematics concept knowledge development in students. These theories and research methodologies provided the basis for the research design followed in conducting this study.

Underlying Theories of Concept Knowledge Development

Category Formation Theory

Individuals encounter innumerable objects, events, and people throughout the course of a single day, each with different features, characteristics, and meanings. The amount of information an individual takes in during every moment of the day is tremendous yet they are not overwhelmed. Why is this? How are individuals able to process this vast amount of information without being stalled in dealing with each piece of information on a singular basis? According to Bruner et al. (1956), the answer lies in the ability of humans to categorize items or events into groups that share similar characteristics, functions, or meaning. These groups of items or events can then be dealt with in a generalized way. This ability to categorize allows individuals to bring their full attention and specialized powers of discernment to items or events that are most pressing at a specific moment. Categories of stimuli can be adjusted, narrowed, or broadened

depending on the tasks for which that information is needed. Once categories are learned, individuals do not have to spend time learning them again. They then continue to refine old categories or invent new categories based on subsequent experiences with the item or event. Throughout every stage of life, individuals can be taught or encounter items or events that can be perceived and categorized. For small children, teachers who are able to "translate ideas" in forms that are meaningful to them at their developmental age help them categorize and create abstract concepts for the newly formed categories. These categories and concept abstractions can and will be modified throughout a person's life due to subsequent exposure and experience with the previously formed categories (Bruner, 1960). Markman and Rein (2013) inform us that "it is common to use the term category as representing a collection of items that are treated as equivalent" and "a concept is a mental representation of that category" (Markman & Rein, 2013, p. 1). These two terms, category and concept, are intertwined, for as we shall see you must have one to have the other.

Bruner et al. (1956) tells us that there are several reasons why we categorize items or events. We categorize because grouping equivalent items and events reduces the complexity of handling an immense amount of information on a constant basis. It provides a means by which we identify things as being exact, or nearly equivalent, based on past experiences. The act of categorization also reduces the need for constant learning and provides us with the ability to anticipate actions or reactions of objects and events that we encounter. Markman and Rein (2013) state that categorization "helps us make predictions about new events and to communicate with others about those events, as well as being central to our ability to make effective decisions" (p. 1). The ability to categorize vast amounts of information is complex and is dependent on numerous variables. The nature of the characteristics that lead to categorization,

the individual's awareness of these characteristics, and their categorizing responses vary between individuals and incidences. In fact, Bruner et al. (1956) noted that "these categories do not have to be verbalized" (p. 2). This means that individuals may not be able to tell someone how the items or events are connected within a category but they know that they are related in a meaningful way based on the specific details of the stimuli.

Category Formation Responses

There are several types of category formation responses to stimuli including; Feature-Based, Similarity-Based, Goal-Derived, Relational, Role-Governed and Thematic. (Markman & Rein, 2013; Smith & Medin, 1981).

A Feature-Based category is formed in response to recognition by an individual that the characteristics of a newly experienced item or event indicates that it is the same as other items or events within a previously learned category (Markman & Rein, 2013). These properties can include necessary and sufficient characteristics that govern category membership. For example, a student might recognize that a necessary property of an algebraic equation is that it must contain at least one variable, one number, and one equals sign. Sufficient properties could include features such as the existence of operations, fractions or inequalities within the algebraic equation. A Similarity-Based category is closely related to Feature-Based categories. Similarity-Based categories are formed based on the recognition that, even though some characteristics of an item or event are different or have changed, they are still equivalent.

Goal-derived categories are formed around some type of goal or task. In the science classroom an example might be a category formed around the concept of distillation or other separation techniques. These categories are rather flexible and there is evidence that they can be formed quickly around goals that have not been experienced before.

Similarly, thematic categories include members that you would expect to experience in a single setting such as *woodworking*. In this setting, category members might include drills, saws, saw dust, and sandpaper. The difference between goal-derived and thematic categories is that every member in a thematic category does not have to be used to complete a goal or task. According to Markman and Hutchinson (1984), children appear to use and relate to thematic categorizations more than other forms of categorization type (as cited by Markman and Reins, 2013).

Relational and role-governed categories are similar categories that relate the relationships between items or events. In an example of a relational category, a science student might categorize materials as compressible, meaning that the volume of material they are examining can be changed as external force is applied. Materials that are compressible only share this one relationship and no other characteristic is required for category membership. Pillows, foam, snow and gasses could be categorized as compressible but their other characteristics need not be similar. A special type of relational category is an event category. It relates individuals or items that are experienced during an event. Students participating in a I-STEM ED T/E DBL challenge might develop event categories that correspond to tasks they encounter within the challenge such as building or testing of design artifacts. An example of this would be a student that is participating in the testing of the speed of a newly built model dragster. She might categorize prototype preparation, starting lights, starter, track, timer, observing teacher, and end line video as being designated as part of a testing event. Notice that the members of the event category *testing* include intrinsic (characteristics directly required for testing; e.g. starter lights, timer) and extrinsic (characteristics on the periphery of testing; e.g. observing teacher) members as well as event or feature-based categories.

The role-governed category is similar to a relational category in that it categorizes individuals or items that are associated with an event and serve a specific function. Student understanding of these roles develops over time beginning with more feature-based categorization and then developing into more of a role-specific categorization. A student in a technology and engineering class might first categorize the role of engineer with members that solely include white men, only later realizing that an engineer is a person who designs and is identified by that role and that other characteristics such as sex, race, and age are not required for category membership.

While some people use different methods of forming categories such as the use of explicitly defined characteristics of objects or events, or categorizing using abstract or affective attributes (Hanfmann, 1937, Kasanin, 1942), the basic processes are the same in all individuals (as cited in Bruner et al., 1956). Categorizations of items or events can occur, in general, in one of two ways, perceptually or conceptually. An individual categorizing items or events perceptually will have immediate stimuli, presented in forms that can be detected by the five senses by which they are used to best "fit" them into an appropriate category. An individual who is categorizing in a conceptual manner may be aligning characteristics of an object or event to category parameters but it is being done in a manner that requires the individual to search for connectedness and explanations of category connectedness, while the immediate physical stimulus is not typically present (Bruner et al., 1956). An example of this would be if a student was asked to find the length of the missing side of a right triangle when he is only given the other two sides of the triangle verbally (no diagram of the triangle is provided). The student would recognize that triangle side length is an attribute of the concept related to Pythagorean's Theorem and would evaluate the appropriateness of applying the theorem to the problem solution. In this

instance, immediate stimuli such as a picture or physical model of a triangle need not be present. This requires the individual to search for category connectedness and member affiliation.

Perceptual and conceptual formation of categories represent two extremes for the process of categorization but there is a continuum of ways by which individuals can categorize items or events. An example would be the individual who, through extensive experience, can recognize a structural design that will not withstand significant force loads, simply by observing the structure or design plans. This individual has efficiently reduced the concepts of balance, rigidity, material strength, compression and torsion into visual stimulus clues. We can see that as individuals gain experience with categories and membership affiliation properties, the processes of concept categorization become more fluent and efficient (Bruner et al., 1956). This increase in the efficiency of categorization is related to memory systems and how they function.

Memory and Category Formation

Markman and Rein (2013) inform us that memory and category formation are closely linked. Our explicit memory systems provide us the ability to recall specific facts about an item or event. An example of this would be an individual's recollection that a test tube is clear, slender, and open at one end. Implicit memory systems provide us the ability to recalled linked stimulus-response relations that have been learned over time. An example of this is when we heat a liquid and see that liquid is being converted to vapor, we infer that it will be hot and that we should avoid touching it. This is because we have witnessed steam production many times while cooking and have experienced pain if we touched surfaces in close contact with it. "This implicit memory system appears to be independent of conscious awareness and perceptual learning" (p. 2). The explicit memory system seeks out rules that the individuals can apply to examples. If an example item, or event, is encountered that does not fit the rules of a category then the category can be modified to fit the new example. This system is highly adaptable and we see its use when

students are classifying biological organisms such as invertebrates or birds. Students first encountering the elements in a chemistry course are using explicit memory systems and are aided by the Periodic Table which serves as a graphic organizer. Implicit memory systems adapt to change much more slowly than explicit memory systems. The implicit system links stimulus and response events together through the perceptual capabilities of the individual and therefore must be experienced a number of times to develop recognition of the stable stimulus-response relationships. If a stimulus-response relationship is experienced consistently over time, the implicit system will dominate the responses required based on detected stimuli. This informs us that more experience with specific categories and category formation can result in the subsequent concept formation within the memory system.

Anticipatory and Exploratory Qualities of Category Formation

There are also anticipatory and exploratory qualities in the way we categorize information. A majority of categorizing efforts consist of trying to fit perceptual cues to an anticipated outcome. For example, a person who sees clouds outside that are dark and menacing and feels the temperature dropping would most likely prepare for rain based on past experience when these weather characteristics were categorized as signs of inclement weather. Likewise, a student might see a loose wire connection in a circuit that they are building. Having experienced failure of circuits due to loose wires in the past, this student would tighten the connection in anticipation that action would result in a working circuit. As Bruner et al. (1956) offers "Anticipatory categorizing then, provides lead time for adjusting one's response to objects or events with which one must cope" (p. 14).

An extension of the above anticipatory quality in categorization is the realization that individuals can attribute cues and characteristics to what Bruner et al. refer to as an *empty category*. These exploratory categories are fictional groupings of characteristics that represent,

for the individual, a *what could happen* type scenario. The empty category represents new learning and new concept formation that goes beyond the experiences of the individual (Bruner et al., 1956). Previously unexperienced configurations of items and events can be seen as relevant new categories or solutions to encountered problems. The realization that a potential change could occur, represents the formation of an "empty category" that can be resolved and refined with further exploration and experience. More recently, Yeh and Barsalou (2006) refer to this process as the abstraction of information for a category, and regard it as an essential part of how individuals transfer knowledge from previously learned concepts to novel concepts.

Category Validation

There are four ways that individuals can decide on whether their efforts of categorization are valid. They include; recourse to an ultimate criterion, test by consistency, test by consensus, and test by affective congruence (Bruner et al., 1956). Recourse to an ultimate criterion refers to category formation that will be tested in a way that provides evidence that the category was correctly formed or not. A student that has categorized all the characteristics of a successfully designed tower could then test that design by building it. If the tower remained standing and was stable, then the ultimate criterion would be met and the student's category of successful tower design characteristics would be deemed trustworthy and could be used and modified based on future experiences. If the tower collapsed, then immediate modification of the category characteristics would occur. Test by consistency occurs, in general, when a category is defined well enough that others would find similar categorical outcomes if they were to simply follow directions. The use of a grading rubric is similar to this test of consistency. Certain characteristics or cues have to be present for the object or event to be placed into the category. The test by consensus is achieved when a reference group or ideal object or event is compared with a category and its members. A test by consensus for a successful launch of a student-

designed rocket would have the flight characteristics of the types of stable launches that we witness NASA accomplishing (on a much smaller scale of course). Test by affective congruence is an augmented case of the test by consistency. It can include elements of equivalent affective response of individual subjective judgements. An example of this would be if a student examined the design of chairs and defined their critical characteristics as providing support for the human body, back rests, elevation off the ground, and leg and arm supports. That student might then inspect the design of a bean bag chair and assign it to the category of chairs due to a subjective judgement in addition to loose connections to the established or well-defined characteristics of the classical category of a chair.

As stated above, "it is common to use the term category as representing a collection of items that are treated as equivalent" and "a concept is a mental representation of that category" (Markman & Rein, 2013, p. 1). At this stage it is important that we begin to connect category formation theory to concept formation and concept attainment theory.

Concept Formation and Concept Attainment Theory

Bruner et al. (1956) informs us that concept formation, which precedes concept attainment, is the preliminary mental awareness of common attributes of a category. These efforts are often not well defined and require many experiences or encountered instances in order for concept attainment to occur. Bourne, Ekstrand, and Dominowski (1971) define concept learning as "acquiring an understanding of a formerly unrecognized regularity" (p. 177). Bruner et al. (1956) similarly defines concept learning thusly, "Concept attainment refers to the process of finding predictive defining attributes that distinguish exemplars from non-exemplars of the class one seeks to discriminate" (p. 22). With an eye towards the stages of concept learning, Bruner et al., continues:

> To say, as Graham Wallas (1926) did a generation ago, that thinking or invention is divided into four stages of "preparation," "incubation," "illumination," and "verification" is helpful only in so far as it serves to indicate that while the experience of "grasping" (illumination or insight) is sudden, it is imbedded in a longer process [which categorization, continued experiences, and category refinement are part of] (p. 50).

Upon realization of concept attainment in an individual, the memory vestiges of the pre-attainment thought regarding the concept are masked or hidden. It is often perceived as if the concept had always been known and the transition cannot be easily verbalized by the individual (Bruner et al., 1956).

Bruner (1960) refers to students needing to understand the structure of subjects when he states "Grasping the "structure" of a subject is understanding it in a way that that permits many other things to be related to it meaningfully. To learn "structure", in short, is to learn how things are related" (p. 7). Categorization leading to concept formation, the focus of Bruner's earlier work, is in essence an exercise in learning the interconnected structure of ideas within a subject. This interconnect structure needs to be a focus of instruction in a subject so that students can apply and transfer their knowledge to the situations they will encounter outside of the classroom. It is up to the instructor to present students with not just facts and techniques, but opportunities for their students to use materials, skills and knowledge that they have gained.

Situated Nature of Concept Knowledge Formation

Background situations related to category formation play a significant part in concept knowledge formation. Vygotsky (1991) stresses the importance of situations or "actual clashes between the organism and its environment, and from the living adaptation to the environment" as being a critical component in the process of development of a child. Background situations help

to constrain and direct concept formation processes, and can act as markers for future memory reference and retrieval (Yeh & Barsalou, 2006). Early concept formation theorists thought that as category formation became increasingly rich and detailed, individuals were able to extract the most meaningful attributes of a concept from background situations and combined the with other categories to form novel concepts. According to Yeh and Barsalou (2006), more modern theorists believe that instead of being stripped away, situational information is being stored and used to help with concept transfer and abstraction. Barsalou (2003) introduced the notion of a simulator, "a neural re-enactment of modality-specific states underlying the conceptual system", as being the connective cognitive process that binds relevant categories in specific situations (p. 1180). For instance, if a student is learning about the concept of distillation in a chemistry class, neurons will fire within the brain to represent *distillation* category members such as a heat source, a solution, a distillation column, and a condensing tube. Background information will also be perceived and neurons will fire that represent odors, sounds, textures of the glassware, as well as a myriad of other environmental characteristics. This creates a pattern, or constellation, of neuron activations that represent the category. During re-call, a simulator will re-enact a simulation subset of these category members that match the requirements of given situation. The richness of the subset is dependent on the current goal or task and is influenced by perception inefficiencies and biases. Yeh and Barsalou (2006) contend that background situations tend to bind themselves strongly with concepts and that one activates the other.

Synthesis of Categorization and Concept Formation/Attainment Theory

What emerges from the literature and our past explanations of categorization theory is that concept attainment is achieved through a series of stages that include initial exposure to an item or event, perceptual gathering of feature information about the item or event, memory system activation (record keeping) related to category development, repeated experience with the

item or event, and testing of inferences of category membership when novel items or events are encountered. In addition, individuals must make decisions about when they believe that they have a true understanding of a concept. Some individuals will repeatedly test their understanding of the concept, time and again, while others will believe that have attained concept attainment relatively quickly. This occurs at different rates for individuals (Bruner et al., 1956). The first stage, initial exposure to an item or event, can occur independently or during formal instruction, and the item or event can be physically experienced or explained to us by peers or instructors (Bourne et al., 1971).

Integrative STEM Education

The Foundations for Integrative STEM Education

Bybee (2010) introduced us to the meanings of STEM education which were highly varied and dependent on the user, and informed us of its National Science Foundation inception in the 1990s. The STEM acronym is typically thought to mean science and mathematics with little connection to technology and engineering. He proposed that "STEM education is for all students to learn to apply basic content and practices of the STEM disciplines *(science, technology, engineering, and mathematics)*[emphasis added] to situations they encounter in life (Bybee, 2013, p. 5). Humphries (2005) explains that integrative learning is important, and is being called for by leaders in government, education and industry because the modern world requires individuals who can connect disparate facts and theories, and adapt skills from one situation to another. Accordingly, those individuals can no longer be taught in a fragmented learning environment.

Integrative STEM Education (I-STEM ED) is an integrative approach to intentional teaching of science and mathematics during the teaching and learning of technology and engineering content and skills within a design based learning environment. Mathematics and science content

are encountered and learned while students are in the process of solving real life contextualized problems. The primary goal of this pedagogical approach is the teaching of technology and engineering concepts along with the teaching of concepts within disciplines that are inherent to the design task. Integrative STEM Education is defined in the following manner:

> "Integrative STEM Education is the application of technological/engineering design based pedagogical approaches to *intentionally* teach content and practices of science and mathematics education through the content and practices of technology/engineering education. Integrative STEM Education is equally applicable at the natural intersections of learning within the continuum of content areas, educational environments, and academic levels" (Wells & Ernst, 2012/2015).

Integrative STEM Education is uniquely suited for the teaching of science, technology, engineering, and mathematics in an integrative way. While separate instruction of science and mathematics provides students with knowledge that certain phenomena occur under specific constrained and often inauthentic conditions, I-STEM ED is a pedagogical approach that integrates content knowledge and technology and engineering skills and concepts in a highly contextualized and situated manner. Students organically encounter targeted science and math concepts while gaining knowledge of how to physically accomplish design challenge tasks.

A Design Model for Classroom Implementation

A conceptual/pedagogical framework for I-STEM ED T/E DBL is the P.I.R.P.O.S.A.L. Model (Appendix A). This pedagogical model characterizes the type of teaching and learning that occurs within the following eight phases of technological/engineering design: Problem Identification, Ideation, Research, Potential Solutions, Optimization, Solution Evaluation, Alterations, and Learned Outcomes (Wells, 2016a, 2016b, 2016c). Each phase of this

pedagogical model reflects the focus of student engagement throughout their design of a viable technological/engineering solution:

- Problem Identification: During this phase, students are presented with a problem related to a human want or need that requires and engineering solution, asked to operationally define the problem, and then required to formulate a concise statement of the problem and constraints.
- Ideation: Student designers are required to review the design criteria, brainstorm and generate possible/plausible uninformed technological/engineering solutions.
- Research: This research engagement phase often overlaps the ideation phase and it is when student designers consider information that they lack and must look to fill those gaps. They explore the topic, investigate prior solutions, and examine the science and mathematics content that is required for a successful engineering solution
- Potential Solutions: Student designers analyze specific elements of the design, visualize and sketch their solutions, and select the solution(s) that will be the focus of their prototyping efforts.
- Optimization: This phase requires designers to experiment with design components, revisit previous ideas and plans that were made, and begin prototype construction.
- Solution Evaluation: This phase is when prototypes are tested, performance data is collected, and interpretations are made regarding attributes of the current design.
- Alterations: Base on the results of the solution evaluation phase possible design changes are identified, prototypes are redesigned and retested.

- Learned Outcomes: Student designers participate in discussions about their prototype and learning iterations where they are required to justify their decisions made during the design process.

Compatibility of T/E DBL with Science and Mathematics Concept Knowledge Development

Within I-STEM ED T/E DBL challenge environments, students are presented with an authentic problem wherein the instructor has intentionally imbedded science or math concepts as learning outcomes that students demonstrate understanding of and can correctly apply to reach a design solution. Explicitly alerting the students to these targeted concepts, for example asking "What do you know about evaporation and condensation?", can affect concept attainment. This forewarning, or definition of task, can lead to increase alertness by the learner to be sensitive to detecting attributes of exemplars and non-exemplars of the targeted concepts (Bruner et al., 1956). The frequency and nature of encounters with exemplar concepts also contributes to concept attainment. Exemplar concepts should be encountered regularly in forms that are recognizable to the learning in order to promote concept learning. If students only briefly or randomly encounter exemplars of a targeted concept, or if those exemplars are completely unrecognizable, then concept attainment might suffer as compared to a design challenge that provides authentic exemplars of targeted concepts in a regular, orderly, and discernable way. As discussed previously, functional categorizing responses occur when group members are present in a category due to a common functional purpose (e.g., microscope, magnifying glasses, and a jeweler's loop). In I-STEM ED T/E DBL challenges, students are provided the opportunity to frequently categorize tools, materials, and problem-solving techniques that they deem are functionally equivalent. Students are also continually faced with making predictions about the outcomes of design actions based on materials or construction techniques they have not

encountered or tried before. In order to do this, students use the features of a category and the category label to help them make connections to the identified need or goal (Yamauchi & Markman, 2000).

The nature of the validation of the student's concept knowledge was also previously discussed as a factor in concept knowledge development. If students are allowed to test their categorization rules immediately after categorization has occurred, and if validation results are clear, then concept attainment can be positively affected. Imagine a student who is designing a vessel to collect a gas that is evolved from a chemical reaction. The concept of gas behavior that must be learned and understood in the immediate challenge is that gas molecules move rapidly and can exit vessels through very small openings. A student who has mis-categorized the ability of a gas to exit through small holes in a vessel may fail to make the collection vessel air tight. The validation of this concept understanding would be immediate and unambiguous. The consequences of categorization and the nature of imposed restrictions can also influence concept attainment. A student's perception of the value of categorization efforts influences concept attainment. In a T/E DBL challenge, students have the ultimate goal of creating a design that functions in a successful way. Student perceive that categorization efforts are valuable to achieving that goal and may increase their efforts of perception of category attributes and the testing of those attributes.

It was presented earlier that the situated nature of concept knowledge development is also important. According to Yeh and Barsalou (2006), situational information is being stored and used to help with concept transfer and abstraction. Students focusing on one aspect of an event are still perceiving the background situation surrounding the event. While students in a teacher centered learning environment may be didactically focused through instruction that directly

teaches a concept description, they are still perceiving the instructional context inclusive of the teacher, classroom environment, and additional learning aids that surround and are part of the lesson. Students participating in a T/E DBL challenge environment are given the opportunity to not only perceive all of the above information but also are witnessing the physical connections the concept plays within the design. Yeh and Barsalou also contend that background situations tend to bind themselves strongly with concepts, and that one activates the other. This notion is supportive of the pedagogical approach within T/E DBL challenges where conceptualizing efforts are situated in richly textured environments where students are not simply listening but are physically manipulating materials, testing hypotheses, and evaluating design outcomes. They are also creating drawings, producing schematics, and building prototypes that incorporate their understanding of the concepts they are learning. Wells (2021) informs us that Bantock (1967) and De Bono (1967) acknowledge that the use of symbolry, to organize the various facets of the environment around an individual, gives them the ability to express their concept understanding in multiple ways. The symbolry found in T/E DBL, such as diagrams, schematics, and physical models, provides the I-STEM ED student with multiple ways to convey their understanding of concepts (Henze & Vries, 2021).

Wells (2021) contends that design and the building of technological artifacts is often "thought of as requiring lower ordered thinking skills (procedural and declarative)" but in reality, "unlike other methods of learning, T/E DBL naturally imposes on the learner a full spectrum of cognitive demands, from concrete to abstract, and requires them to communicated that thinking through the symbolry of design knowledge" (Henze & Vries, 2021, Chapter 11, p. 230).

In I-STEM ED T/E DBL, students progress through design phases that require them to use their prior knowledge and to ask questions as well as formulate possible answers to these

questions in an attempt to solve an engineering problem (Wells, 2016a). This need-to-know learning environment requires students to examine past categorical information that they have acquired and to determine if the new problems or questions they are facing are similar or share exemplar category attributes to those categories. If no, they are then motivated to attribute cues and characteristics of this previously un-encountered problem to an "empty category" that Bruner referred to. This is the beginning of concept formation or is an instance that contributes to concept attainment. Students within the T/E DBL environment can then test their proposed solution, required by the hands-on physical nature of the design process. The design process fits well with the proposal that the invention of concepts is divided into stages that include preparation, incubation, illumination, and verification (Graham Wallas, 1926).

Synthesis of I-STEM ED T/E DBL and Concept Knowledge Formation

The literature is rife with examples of how an I-STEM ED DBL pedagogical approach can support category formation and therefore concept knowledge development. The areas where this pedagogical approach potentially excels over more teacher centered pedagogical approaches is in goal-derived and role-governed categorization processes, perceptual and conceptual categorization processes, abstraction of category requirements, and validation of categorization efforts. Goal-driven categories are formed around some type of goal or task, which are flexible categories that can be abstracted fairly easily. A T/E DBL challenge is by definition a goal-driven undertaking requiring them to recall information from previously learned categories and combine it or infer new categories that relate to novel requirements within the design challenge. A T/E DBL challenge necessitates that students physically manipulate materials and test design prototypes. This compels them to rely on perceptual categorization processes more than if they were to encounter concept information in a lecture style pedagogical approach where conceptualization categorizing processes are the only means by which categorizing can occur.

Engagement in T/E DBL challenges imposes on students the need to demonstrate each of the four knowledge types: declarative, procedural, schematic and procedural knowledge. As Wells (2021) informs us, “Simply stated, the various forms of knowledge afford the individual characteristically unique ways in which to structure and understand their world experiences” (Henze & Vries, 2021, p. 229).

Research and Assessment of Concept Knowledge Development

According to Novak (1965) we can consider a discipline being made up of major concepts which provide the overall structure of the discipline. If we wish our students to deeply understand a discipline, we must know that they understand much more than simple facts. “Understanding a discipline requires more than just memorization of statements summarizing concepts in an area; a student must discover how concepts are derived and elaborated in order to understand the concepts and to grasp the structure of the discipline” (Novak, 1965, p. 72). The key to assessing conceptual knowledge requires a model of concept attainment evidencing when a student perceives input information, that information is processed and stored as cognitive information (category formation), and affective information within the brain. The output of this model, recall of stored information, occurs when behavior is needed such as problem solving or the creation of new category relationships (Novak, 1965). Based on this model, we begin to see how concept knowledge might be assessed. We must first assess the level of targeted concept knowledge an individual has prior to the initial inputs that are the focus of study. Once students have been provided with the information inputs that we wish them to perceive, then it becomes a matter of assessing three components of the above learning model, that is, the cognitive information that has been stored, the affective information (attitude) that has been stored in relation to the concept, and the measurement of problem solving ability that the individual now has (Novak, 1965).

Tests requiring students to remember facts, definitions, and diagrams have utility in helping to assess the cognitive information that has been stored by an individual as it relates to a specific concept of interest. A score on such a test could serve as a partial measurement of the concept knowledge an individual possesses. The score should relate the level of recall of all relevant information about the concept that has been provided but we cannot be sure what the individual has regarded as relevant. In addition, there are inefficiencies/inaccuracies in the way information inputs are provided to students and the structure of questions that are designed to measure student knowledge of a concept. As stated above, this would be considered an incomplete estimate of student concept knowledge when relying only on this one type of assessment strategy.

Science Concept Knowledge Assessment

In research studies that investigate science concept knowledge, authors are careful to distinguish between science content knowledge, science concept knowledge, and science skill development. Cotabish, Dailey, Robinson, and Hughes (Cotabish 2013) define science content as facts and understandings while science concepts are the overarching ideas that connect those facts. Others define conceptual understanding as "a knowledge base of substantive concepts such as the laws of motion, solubility or respiration which are underpinned by scientific fact" (Gott & Duggan, 2002, p. 186). They stress that science content and concept knowledge cannot be fully realized/conceptualized without knowledge of science practices (science skills). Accordingly, they recommend that students should be developing experiments, measuring and interpreting results and forming conclusions rather than learning content and concepts from reading or lectures (Cotabish et al., 2013). It follows then that research is necessary for examining the connections between student engagement in T/E DBL and the promotion of their knowledge progression toward acquisition of targeted science and mathematics concepts.

Specifically, needed are studies investigating this gap in the research and empirically documenting such connections.

Großschedl and Harms (2013) define concept knowledge as "networked knowledge that is composed of key concepts and their interrelations" (p. 71). They inform us that concept maps, similar to the nodes and edges in mathematical graph theory, can be used to understand this concept knowledge where concepts occupy the nodes of the graph and ideas that represent the interrelations between concepts are the edges or interconnecting lines in the graph. These visual models help student prioritize the most relevant information and assists in concept recall (Hilbert & Renkl, 2008). Difficulties have been reported in the use of concept mapping related to the need for prior training before participants in a study have the skills to produce concept maps that are meaningful. Moreover, there are instances where participants will confuse conceptual mapping and simple organization of ideas where limited connections occur (Reader & Hammond, 1994).

Cotabish et al. (2013) used "pre-post embedded curriculum based assessments" that measured "science concepts, concepts that connect STEM fields (i.e. patterns of change, cause and effect), as well as critical thinking skills, and creativity and interest in science" (p. 220). The aim of their study was to determine if content, concept, and science process scores increased due to specifically targeted and sustained teacher professional development focusing on improving teachers' science inquiry and process skills. Similarly, Robinson, Dailey, Hughes, and Cotabish (2014) reported using pre-post embedded curriculum based assessments to assess science concept knowledge. Their report indicated that these assessments utilized open-ended short answer and concept mapping type questions. They also reported that one of the limitations of

their study was that there was no external achievement test used with which to compare their results.

Multiple choice questions can be used to assess concept knowledge, which allows researchers to assess many concepts in a more consistent way as compared to essay questions. Walstad and Becker (1994) recognized that a major consideration in the development of a multiple choice questions was that a great deal of expertise is needed to create an assessment that is both valid and reliable (as cited in Großschedl & Harms, 2013). In addition, single stage multiple choice questions do not allow the researcher to see individual participants conceptual mental representations and whether they are convergent, well defined ideas or loosely related descriptions (Chiu et al., 2007). Niaz and Robinson (1992) investigated the relationships between algorithmic knowledge of gas behavior (the ability to solve ideal gas law related problems through algebraic manipulation) and conceptual gestalt knowledge of gases (the ability to recognize gas behavior patterns), measured student knowledge with multiple choice and open ended logic and reasoning questions. Measures of logical thinking, mental capacity, and disembedding ability (the ability to recognize patterns in confusing data or backgrounds) were correlated with multiple choice item results to determine factors that influenced algorithmic and concept gestalt type knowledge.

In an effort to identify science misconceptions related to Global Warming and Greenhouse Effect, Arslan et al. (2012) developed a Three Tiered Multiple Choice (TTMC) diagnostic test. This multi-tiered multiple-choice assessment instrument is comprised of items that test concept knowledge. Within each item are multiple tiers. Tier 1 requires students to answer a concept related question that is that is very similar to a common multiple-choice question. The Tier 2 multiple choice question requires the student to select a response that

explains their reason for the Tier 1 question. This tier can provide information on misconceptions that are held by the student. The Tier 3 question asks students to rate their confidence in their answers to the previous two tiers. The combination of responses to this type of diagnostic assessment can provide information that allows a researcher to differentiate between responses that indicate lack of knowledge and guessing to concept knowledge acquisition. Multiple studies using TTMC Diagnostic Tests to investigate science concept knowledge were reviewed (Anti Kolonial Prodjosantoso et al., 2019; Banawi et al., 2019; Romine et al., 2015; Siswaningsih et al., 2019) yet were fairly limited in number.

Essay questions can also be used to assess concept knowledge. A valuable aspect of using this type of assessment is that it provides a window into the logical thinking of the student in a way that reduces the biases that can be present it standard multiple-choice curriculum based questions. Unfortunately, essay questions require students to utilize high level and differentiated intellectual effort and writing skills, which therefore limits the number of concepts that can be tested in one question (Großschedl & Harms, 2013). It can also magnify student disadvantages that are unrelated related to their knowledge of the concepts. Disparities in student ability to write and their knowledge of concept related vocabulary can also cause inaccuracies in concept assessment using essay questions. According to Chase (1968), students with poor handwriting can be unfairly assessed using essay type assessment formats (as cited in Großschedl & Harms, 2013).

Gopal, Kleinsmidt, Case, and Musonge (2004) set out to study the alternate conceptions of evaporation and condensation held by third year chemical engineering students. Data was collected in this study through interviews with students where diagrams of different evaporation and condensation scenarios were shown to each participant and they were allowed to explain

their understandings of what would happen in each scenario. Guiding questions associated with each scenario were provided to the participants as well. The authors found that interviewing with diagrams and guiding questions required students to focus their reasoning skills on particular concepts and provide rich descriptions of their understandings. This in turn allowed the researchers to understand student alternate conceptions. In addition, the authors felt that the interviewing process created opportunities for enhancing student conceptual change in that the students were required to look closely at their conceptual understanding when answering a question and explicitly work through their reasoning verbally.

Multiple studies have shown that elementary teachers lack understanding of basic facts and scientific ideas such as the properties of matter, differences between chemical and physical changes and the particulate nature of matter (Bulunuz & Jarrett, 2010; Cox & Carpenter, 1989; Kruse et al., 2020; Tuttle et al., 2016). This is obviously a fundamental problem for instruction in our public schools. Kruse et al. (2020) investigated how in-service elementary teachers' concept knowledge of property of matter changed as a result of engagement in professional development that utilized active learning pedagogical approaches. They did so by implementing a qualitative case study that used pre/post assessments with open ended questions related to NGSS properties of matter performance expectations. Their results provide evidence that professional development utilizing active learning pedagogies increase teacher conceptions of matter that aligned with performance expectations.

Concept Knowledge Assessment and Technology Design

Kolodner (1996) describes conceptual change within students participating in technology design as following a constructivist model in that students will construct new concepts based on the experiences that they have, giving new meaning to older concepts (as cited in van Breukelen, de Vries, et al., 2017). According to van Breukelen, de Vries, and Schure (2017), technology

(design) supports student conceptual learning by creating situations where students are forced to examine their resident knowledge of specific concepts and then challenge them when building prototypes and then conducting prototype testing. The processes surrounding design, such as collaboration, reflection, contextual learning, applying what is learned, learning from failures and iteration, and connecting skills, practices and concepts, support conceptual learning and can lead to transfer of learning between experiential environments (Bransford et al., 1999).

In an effort to measure science conceptual knowledge change in students participating in a T/E DBL challenge and identify what might be impeding conceptual knowledge growth, van Breukelen et al (2017) employed pre- and post- multiple-choice tests and qualitative interviews. The multiple-choice tests were comprised of 20 questions where each concept was measured using two pairs of questions. One question pair was designed to measured concepts with contexts similar to what students encountered in the T/E DBL challenge, while the other paired asked the same concept questions with different contextual scenarios in order to measure knowledge transfer. Written qualitative questions were open ended and were based on the Situation, Task, Action, Result and Reflection (STARR) questioning method framework. These questions required students to relate instances within the challenge that stimulated learning. In addition, post design challenge interviews were conducted using student design artifacts as the basis for more specific examination of how science concepts were used within the design process.

Other researchers have utilized formative peer assessment accompanied with feedback or reflection as both a pedagogical approach to student content knowledge development and assessment (Potter et al., 2017). Bartholomew, Mentzer, Jones, Sherman, and Baniya (2020) coupled formative peer assessment with adaptive comparative judgement (ACJ) to determine if a learning by evaluation (LbE) pedagogical approach would result in greater knowledge gains. The

ACJ assessment procedures consisted of student use of *RMCompare* software that allowed for the randomized comparison of student artifacts and encouraged student comments on why they made their comparison judgements. The benefits of using this ACJ assessment was that it provided the researchers with ranked order of student produced artifacts, software generated parameter values, judgement times, and judgement comments. In order to determine if students' judgements are correct and based on logical reasoning, experts have to also participate in the ACJ assessment procedures. Adaptive comparison judgement results generated by students can then be correlated with results generated by the experts as a means for establishing the validity of judgements students are making.

Concept Knowledge Assessment and Engineering Design

In the field of engineering education, conceptual knowledge is thought of as a combination of facts and the underlying connections between those facts (Baroody et al., 2007; Watson et al., 2016). Conceptual knowledge then cannot be attained through memorization of facts but must be developed through use of the facts. Montfort, Brown and Pollock (2009) speak of conceptual knowledge being more "intuition like" in that "you don't remember something you understand conceptually, it is just true" (p. 111). They further recognize that conceptual knowledge develops over time and that it only becomes transferable when it is internalized by the student through events that make the concept understandable and useful. This definition of conceptual knowledge growth connects quite nicely to the benefits associated with classroom based design and engineering pedagogies. Fortus et al (2004) informs us that scientific concept knowledge is considered to be constructed knowledge based on past experiences and if the constructed knowledge is sufficient, meaning it explains physical environments and actions, it can be transferred to different contexts.

Methods used to assess scientific concept knowledge gains associated with design based learning challenges include pre- and post- multiple choice and written tests, drawings of designs, and three dimensional models. Analysis of the written examinations is accomplished by use of an answer key while open ended questions are graded by multiple raters who have been trained to grade answers using a rubric (Fortus et al., 2004). Inter-rater reliability is achieved by training raters on samples of tests, with discussion of the application and modification of rubrics. Models and posters (or drawings) of designs are also assessed using rubrics that are designed to measure engineering and science concept knowledge development. In the Fortus et al (2004) study, "early" and "late" models that were built at different times within the design build stages (initial design and re-design) were assessed and compared to each other to determine if concept knowledge growth had occurred. Concept mapping has also been used to assess concept knowledge in addition to measuring novelty and systems thinking (Lavi et al., 2021).

An alternate method for assessing concept knowledge is the use of qualitative interviews that focus on several interconnected concepts. Participants within the study are asked to think aloud when solving problems and to rank and explain their knowledge of interconnected concepts. If participant responses are unclear, further clarifying questions are asked (Montfort et al., 2009). An example of the ranking requirements within this type of qualitative interview would be if participants were asked to rank designs that would most efficiently complete a design task.

Fan and Yu (2017) conducted a quasi-experimental study to analyze the differences in student science and mathematics conceptual knowledge development, higher-ordered thinking and engineering design based on their participation in a STEM engineering module or a technology education module. Their data collection methods included a mechanical conceptual

knowledge assessment that included science and math conceptual knowledge questions, a design project artifact, a higher-order thinking skills test, a semi-structured interview, and informal observations. Benefits of this approach were that a comparison between two pedagogical approaches could be conducted, and that multiple aspects of the learning benefits could be analyzed. The difficulties in this approach included the requirements to develop the instruments and rubrics in valid and reliable ways.

Mathematics Concept Knowledge Assessment

According to Cole (1990), Webb & Romberg (1992), and Wilson (1992), knowledge in mathematics is "conceived as a system of relations among mathematical symbols, concepts, operations, activities, and situations" (as cited in Niemi, 1996, p. 351). In addition, mathematical researchers commonly define concepts as ideas, and relations between those ideas, that are specific and critical to a given mathematical domain (Lenz et al., 2020). In Crooks and Alibali's (2014) literature review of 4282 academics sources revealed that there were six major types of definitions of mathematical conceptual knowledge within the mathematics literature. These include definitions that describe conceptual knowledge as; connections between ideas and/or numbers within a domain, knowledge of general principles, knowledge of principles underlying procedures, categorical knowledge, awareness of the meaning of symbols, and the knowledge of the structure of a mathematical domain.

Assessing mathematics concept knowledge typically entails a wide variety of methods ranging from hands-on use of manipulatives for explaining understanding, to explicit written explanations/justifications for solution strategies. What is evident is that researchers tend to use multifaceted assessment strategies so as to try to illuminate deep connections between broad ranges of concepts rather than focus on singular tasks or types of problem solving strategies (Niemi, 1996). A multifaceted assessment approach, such as examining students' use of

graphical representation of concepts and also their problem solving, symbol usage, and written explanation assessments allows the researcher to examine the relationships between graphical representation knowledge of a concept and mathematical skills. This in turn can help educators determine effective representations that should be used during classroom instruction and assessment.

Niemi (1996) asserts that a characteristic of concept knowledge is that as an individual deepens their understanding and improves their skill related to a concept, a greater organization of information around an abstract ideal of the concept occurs, rather than around facts and algorithmic procedures. The organized extent of information as it relates to a concept can therefore be looked at as a measure of conceptual knowledge held by an individual. The goal of the mathematics researcher should then be to select targeted relations related to the concepts that are to be assessed, and determine the extent of a student's ability to provide multiple representations or those relations. It should be noted that conceptual knowledge can be expressed implicitly or explicitly and that as age increases, knowledge expression shifts from implicit to explicit, most likely due to developing language skills within students (Crooks & Alibali, 2014). Based on this, it could be assumed that students of all ages would experience a transition from implicit understanding of a concept to being able to explicitly convey the meaning of a concept to others. This transition would be based on the individual's level of experience with the concept and their language skill level.

Ke (2014) conducted a mixed method case study that examined student mathematics concept learning and attitudes towards mathematics through design of computer math games. Data was collected using video recording of design activities, analysis of artifacts, semi structured interviewing and implementation of an "Attitudes towards Math Inventory" (Tapia &

Marsh, 2004) instrument that was given to the students (Ke, 2014). Group conversations were videotaped and the recordings were coded for relevant design and math content actions as well as student discussions. The artifact analysis was focused on observations of design specific outcomes that indicated math concept understanding. These data were triangulated with results from the semi-structured interviews where questions such as "What do you want your players to learn from this game?" or "What do you think this game will teach?" (p. 30). According to the author the use of a mixed method approach allowed for analysis of the relations that existed between design of a math game and math learning, the relationship between computer programming and math learning, as well as the relationships between math game computer design and math learning. The limitations of this study were that the "findings are generally descriptive in nature, and hence lack power to be generalized to a broader population" (p. 38).

Integrative STEM Concept Knowledge Assessment

It should be noted that when looking at STEM within the context of a transdisciplinary approach to integrating domain knowledge, the idea of competence of students in STEM is commonly discussed. According to the National Governors Associations Center for Best Practices & Council of Chief State School Officers (2010), National Research Council (2012), Ng (2008), and Pellegrino (2014), competence can be thought of as the "knowledge, skills, and abilities (KSAs) from one or more disciplines to solve problems across a wide range of authentic contexts" (as cited in Douglas et al., 2020, p. 234). These competencies should require knowledge and application of connected concepts needed to creatively solve problems. Typically, concept inventories, which utilize multiple choice assessments and open-ended prompts to gain insight into a student's understanding of a small number of key concepts are used assess concept knowledge development. Sometimes these inventory questions can be designed such that distractor answer options are provided that offer common or plausible

alternative conceptions that are theorized to exist by the researcher. Multidimensional STEM competencies can be assessed by combining conceptual assessments and STEM practices assessment in multistage questions. These questions would not only ask conceptual type questions, but also require students to explain how a concept could be shown or modeled. As an added validation of results, the implementation of an external achievement test should be considered to compare student concept knowledge (Robinson et al., 2014).

Gott and Duggan (2002) introduce a term they refer to as "concepts of evidence" which includes the reasoning that leads to procedural actions. They feel that this body of knowledge is represented by cognitive elements such as a student's decisions on what tools to use for specific tasks, how many samples to take, and what measurements to make. Basic skills are a component of this knowledge and need to be coupled with the concepts of evidence knowledge for solutions of problems. Typically, assessment of "concepts of evidence" might come from observation by instructors or written descriptions by students in design/engineering notebooks. These can introduce biases and inaccuracies in assessment due to poorly defined criteria for expected skill outcomes or uneven writing abilities of students. Efforts to alleviate these biases focus on rubric development and notebook report writing training for students.

Gott and Duggan (2002) have offered assessment tasks, in addition to the ones listed above, that could be used to help determine conceptual understanding. Tasks may include; requiring parts of investigations to be conducted, asking students to design an experiment that would indicate concept understanding, or using computer-based partial simulations.

The assertion that I-STEM T/E DBL challenges can provide high-level cognitive demand type tasks for deep conceptual knowledge formation needs to be evaluated on a much greater basis than what is presented in the literature. Diego-Mantecon et al (2021) inform us that the

level of research that evaluates Science, Technology, Engineering, Arts, and Mathematics STE(A)M-PBL pedagogical approaches in relation to mathematics is “rather low” and is insufficient in answering fundamental questions about the efficacy T/E DBL approaches on math conceptual knowledge development (Diego-Mantecon et al., 2021). Suggested ways to increase understanding of the efficacy of T/E DBL would be to determine if factors associated with the maintenance of high-level cognitive demand task were being provided to students during the T/E DBL challenge and if students are engaged in them. Examples of two of these factors would be that students are given the means and engage in monitoring their own progress and students are required to reflect on their prior knowledge. Estrella et al (2019) conducted a study on how teachers implemented high-level cognitive demand tasks within a lesson. The researchers utilized video recordings of the lesson and then transcribed and coded what factors for implementing high level cognitive demand tasks were exhibit by the teachers (in the case of potential research conducted by the author of this question response, this could be done with attention being placed on the exhibition of students’ efforts in engaging with these factors). Frequencies of exhibited factors were then recorded as well as qualitative reflections, written by the teachers who implemented the lessons, were analyzed and related to the factor frequencies (Estrella et al., 2020).

Typically, most of these mathematical tasks, either ones that are self-realized or instructor imposed, are ones in which the student has already learned the required mathematical concepts for solution of the task. Lasa, Abaurrea, and Iribas’s (2020) review of STEM activities within resources curated by Spanish Federation of Mathematic Teachers Association (FESPM) and the Mathematics Teachers (Portuguese) Association (APM) found that mathematical content was “basic and utilitarian, mostly related to measuring magnitudes and using fundamental

geometrical language". In addition, they found that STEM projects took place after students had previously learned the math that they would need in the STEM activity. It is rare to see students engaging in a DBL challenge where mathematical concept knowledge is being learned of encountered for the first time. This is not an uncommon finding. Diego-Mantecon et al (2021) found that out of 41 STE(A)M-PBL projects that were studied, only 25 had any type of mathematical content, and out of those 25 math containing projects, only 15 included medium to high cognitive demand activities. This indicates that there is a need to investigate mathematics concept knowledge development related to I-STEM ED T/E DBL engagement.

Synthesis of the Literature Review

This study was guided by the results of the literature review that have shown that I-STEM ED T/E DBL is a viable pedagogical approach for promoting concept knowledge development. Within I-STEM ED T/E DBL challenge environments, students are presented with an authentic problem wherein the instructor has intentionally imbedded science or math concepts as learning outcomes that students demonstrate understanding of and can correctly apply to reach a design solution. The clear definition of task and highly situated nature of the conditions and environment in which concepts are encountered helps to promote concept formation by increasing learner sensitivity in detecting attributes of exemplars and non-exemplars of the targeted concepts. The need-to-know learning environment requires students to examine past categorical information that they have acquired and to determine if the new problems or questions they are facing are similar or share exemplar category attributes to those categories. This necessitates that students make predictions regarding design outcomes during the T/E DBL challenge, forcing students to use the features of a category and the category labels to help them make connections to the identified need or goal. When students are allowed to test their categorization rules during the design phases and immediately after categorization has occurred,

and if validation results are clear, then concept attainment can be positively affected. In addition, the use of diagrams, schematics, and physical models required in T/E DBL challenges provides the I-STEM ED student with multiple ways to convey their understanding of concepts. Finally, a student's perception of the value of categorization efforts influences concept attainment. In a T/E DBL challenge, students have the ultimate goal of creating a design that functions in a successful way. Students perceive that categorization efforts are valuable to achieving that goal and may increase their efforts of perception of category attributes and the testing of those attributes, ultimately promoting concept development. Establishing that T/E DBL pedagogical approaches could viably promote concept knowledge development led to the search for methods of assessing this knowledge.

The literature review results also guided the decisions for how to best assess concept knowledge development. Multiple studies were found that used pre/post diagnostic assessments and/or semi-structured interviews for assessing science and mathematics concepts. Multi-tiered multiple choice diagnostics were identified that required students to answer questions about concepts then provide reasoning for their answers, and finally indicate their confidence in their answers. Advantages to this form of diagnostic test is that the combination of responses to this type of diagnostic assessment can provide information that allows a researcher to differentiate between responses that indicate lack of knowledge and guessing to concept knowledge acquisition. The use of semi-structured interviews to corroborate diagnostic responses and provide details and texture to students' concept knowledge development were also reviewed and found to be applicable to the conditions of this study. These mixed method (quantitative, and qualitative) approaches also allowed for analysis of the relations that existed between design and concept learning.

The above results and learned conclusions have resulted in the research design and assessment methods chosen to investigate T/E DBL as a viable pedagogical strategy for promoting concept knowledge development in preservice elementary teachers. The following chapter provides the research method and procedures used for data collection necessary for answering the research questions.

CHAPTER THREE: RESEARCH METHOD

This chapter presents the research method adhered to in conducting this study. The details regarding the method chosen are provided in the following sections: research design, participants, instrumentation, procedures, and data analysis (quantitative, qualitative, and mixed). This mixed method approach was employed in acquiring data to answer the following research questions:

Research Questions

The following research questions were used to guide this study:

When preservice elementary teachers engage in a T/E DBL challenge:

RQ1 - What evidence demonstrates such engagement promotes their knowledge progression towards acquisition of targeted complex science and mathematics concepts compatible with accepted scientific views?

RQ2 – What T/E DBL experiences do they indicate promoted their acquistion of the targeted complex science and mathematics concepts?

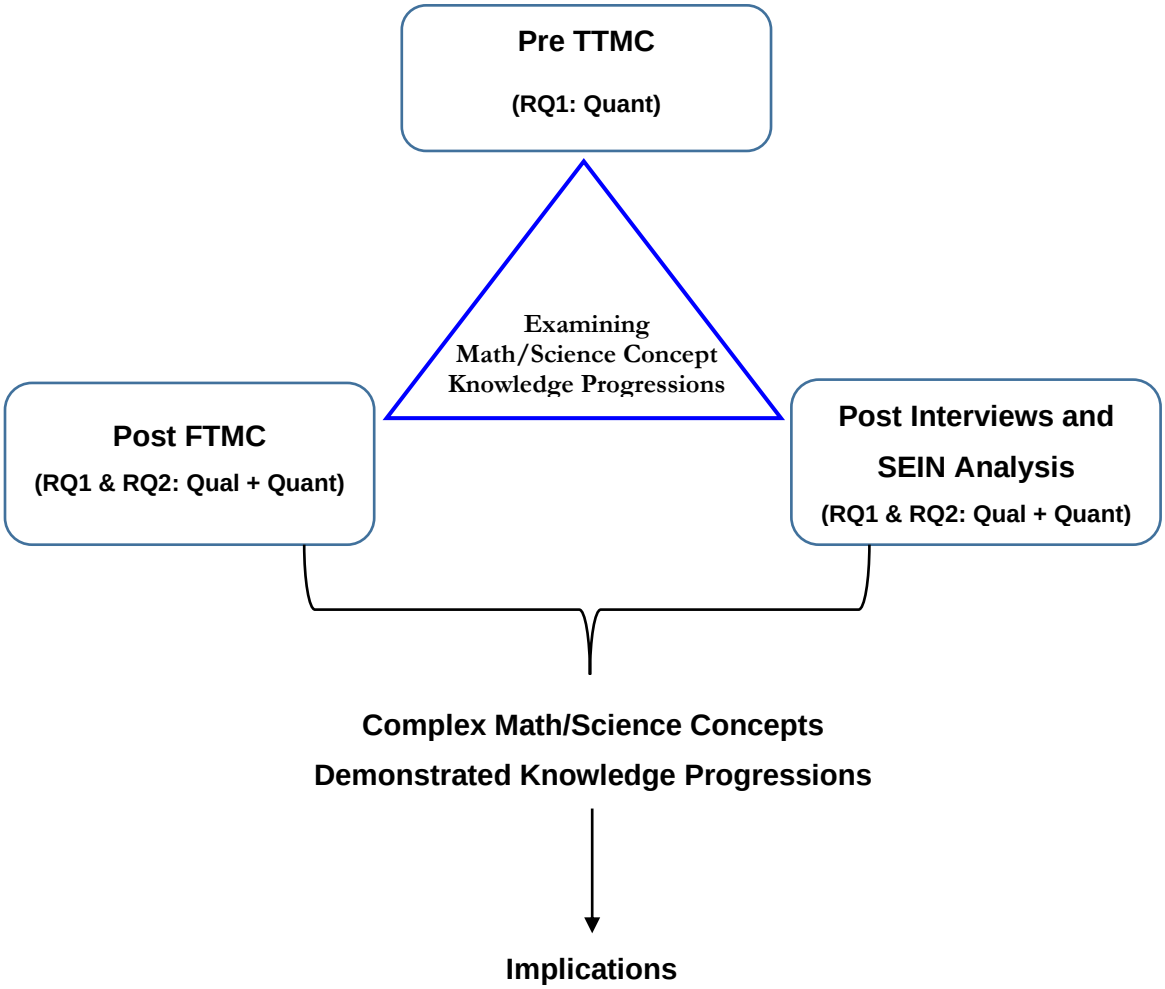
Research Design

The research questions guiding this study were answered through analyses of data collected during an exploratory sequential mixed method embedded multiple case study (Teddlie & Tasshakori, 2006) intended to assess changes in science and mathematics concept knowledge. The mixed method approach was deemed appropriate given the exploratory nature of the problem and the need to incorporate both quantitative and qualitative data in order to infer relationships between variables (Teddlie & Tasshakori, 2006). The selection of an exploratory sequential mixed method embedded multiple case study was also supported by Stake (1995) and Creswell (2009) who posit case studies are used to investigate events, or processes (such as a design challenge) involving one or more individuals and which involves the collection of

quantitative and qualitative data that can be merged to provide an in-depth assessment of the study's results (as cited in Creswell, 2009). As a sequential mixed method embedded multiple case study, triangulation of data collected (Fig. 1) is critical in answering the stated research questions. This method was used to facilitate triangulation of data gathered in the first phase through pre/post diagnostic testing, with data gathered through semi-structured interviews and Science and Engineering Interactive Notebooks (SEIN) in the second phase in an effort to confirm or disconfirm the findings from the first phase (Teddlie & Tashakkori, 2006).

Figure 1

Triangulation of Data



The model in Figure 1 represents the ways in which triangulation of the data occurred. As seen above, testing of participant preconceptions of complex science and mathematics concepts was assessed using a Three-Tiered Multiple Choice (TTMC) diagnostic instrument. This was done prior to implementation of the study's intervention, a T/E DBL challenge. After all participants had completed the intervention, a Four-Tiered Multiple Choice (FTMC) diagnostic instrument was used to assess their changes in conceptions of complex science and mathematics concepts and to identify what T/E DBL experiences they felt promoted their understanding of the targeted concepts. Semi-structured interviews were then conducted with a select group of participants so as to provide corroboration of the pre/post assessment results and clarification of the perceptions of targeted science and mathematics concepts participants held after the T/E DBL challenge. In addition, content analysis of participant SEINs was conducted to generate corroborative evidence of progressions toward concept knowledge acquisition. To strengthen the internal validity of the study, triangulation of quantitative diagnostic pre/post testing data with qualitative data gathered through semi-structured interviews, and content analysis of science and mathematics sub-concept knowledge development revealed by SEIN entries (annotated/labeled design drawings and written descriptions) were used to corroborate emergent findings. Pre/post diagnostic testing revealed participants' changes in science and mathematics concept knowledge related to their participation in the intervention and provided insight into what T/E DBL experiences they perceived as promoting their acquisition of the targeted concepts. This data supported answers to research questions RQ1 and RQ2. The semi-structured interview questions, designed to corroborate and enhance understanding of participant's responses on the pre/post diagnostic tests, were developed based on the diagnostic test item responses. They were structured so as to provide elaboration of student understanding of specific science and

mathematics concepts and to answer the proposed research questions listed above. Science and Engineering Interactive Notebook (SEIN) entries were also analyzed for evidence of concept knowledge development that corroborated the pre/post diagnostic tests.

Table 1 presents the alignment of research questions, data sources, and data analyses.

Table 1

Alignment of Research Questions with Data Sources and Analyses

Research Question	Data Source	Data Analysis
RQ1- When preservice elementary teachers engage in a T/E DBL challenge, what evidence demonstrates such engagement promotes their knowledge progression towards acquisition of targeted complex science and mathematics concepts compatible with accepted scientific views?	Quantitative/Qualitative Science and Math Concept Three-Tiered Multiple Choice (TTMC) and Four-Tiered Multiple Choice (FTMC) Diagnostic Tests Qualitative Semi-structured Interviews SEIN Analysis	QUANT: Matched Pair *t*-test QUAL: Thematic and Corroborative Analysis
RQ2 – When preservice elementary teachers are engaged in a T/E DBL challenge, what T/E DBL experiences do they indicate promoted their acquisition of the targeted complex science and mathematics concepts?	Qualitative Science and Math Concept Four Tiered Multiple Choice (FTMC) Diagnostic Test (Specifically, the fourth-tier question) Semi-structured Interviews SEIN Analysis	QUAL: Thematic and Corroborative Analysis

As shown in Table 1, data used to answer RQ1 were collected from the Science and Math Concept Three Tiered Multiple Choice (TTMC) Diagnostic Test, the Four Tiered Multiple Choice (FTMC) Diagnostic Test, semi-structured interviews, and SEIN content analysis. The data generated from these instruments, questions, and SEIN entries were analyzed using item analysis, matched pair *t*-tests, and thematic and corroborative content analysis. Research question

two (RQ2) was answered using data from the fourth tier of the Science and Math Concept Four Tiered Multiple Choice (FTMC) Diagnostic Test, together with data derived from the semi-structured interview and SEIN content analysis. An item, thematic, and corroborative analysis approach was used to triangulate the data for this research question.

Participants

Recruitment of participants was conducted following Institutional Review Board (IRB) approval from both Virginia Tech and the institution where the study was conducted (Appendix B). Participants were recruited from a convenience sample of preservice elementary and middle school (K-8) teachers enrolled in a science and mathematics pedagogy course at a liberal arts college in the rural southeast region of the United States. All participants were in their sophomore or junior year of college and seeking an endorsement in elementary education while pursuing interdisciplinary degrees in mathematics, social studies, or English. Participant sample size was 13, with 85 % (ratio) female and 15% (ratio) male.

Instrumentation

Three instruments were created to collect the needed data to answer the above listed research questions: Three-Tiered Multiple Choice Diagnostics, Four-Tiered Multiple Choice Diagnostics, and Semi-Structured Interview Protocol. Included in this Instrumentation section are brief descriptions of the data collection instruments used in this study. The procedures followed in creating these instruments are presented afterwards in the Instrument Development section.

Tiered Multiple-Choice Science and Mathematics Concept Diagnostics

The tiered multiple choice diagnostics instruments developed for this research were modelled after those used in prior studies for assessing the science and mathematics concept knowledge of high school students, undergraduate science students, and preservice teachers

(Arslan et al., 2012; Aydeniz et al., 2017; Canpolat, 2006; Chang, 1999; Coştu et al., 2012; Gopal et al., 2004; Kirbulut & Geban, 2014). The tiered multiple choice diagnostics instruments and their test items used in these prior studies were validated by those researchers using various methods. The development and validation methods employed in these prior studies guided the development and validation of the tiered multiple-choice diagnostic instruments used in this study.

Three-Tiered Multiple-Choice Diagnostics

As a targeted pre-assessment of resident science and mathematics concept knowledge, a Three-Tiered Multiple-Choice (TTMC) diagnostics instrument was created to investigate the science and mathematics concept knowledge of participants prior to their engagement in the T/E DBL intervention specifically addressing concepts related to evaporation, condensation, areas of irregular shapes, rates of production, and slopes of production rate data. Each TTMC item is comprised of three tiers of multiple choice questions designed to investigate the level of concept knowledge held by the participant. The first multiple-choice question is Tier 1 and assesses the participant's knowledge of a concept by presenting them with four possible answers from which they are to choose the correct one. The second multiple choice question, Tier 2, assesses the participant's reasoning for the response they selected in the Tier 1 question. Tier 3, the third multiple-choice question, assesses the participant's confidence in their responses to the Tier 1 and Tier 2 diagnostic items.

Four-Tiered Multiple-Choice Diagnostics

In order to assess science and mathematics concept knowledge development following participant engagement in the T/E DBL intervention, a Four-Tiered Multiple-Choice (FTMC) diagnostics instrument was created as a post assessment of the same science and mathematics concepts as in the TTMC, plus a question targeting the T/E DBL experience. Specifically, the

first three tiers of each FTMC item in the post diagnostic instrument were identical to the TTMC items used to investigate the same science and mathematics concept knowledge targeted in the pre-assessment of science and mathematics concepts. The fourth question, Tier 4, for each FTMC item was an open-ended question asking the participant to indicate during which phase of the T/E DBL design process did they perceive their concept knowledge changed.

Semi-Structured Interview Protocol

A post intervention Semi-Structured Interview Protocol was developed to corroborate the findings of the pre/post diagnostic assessments and clarify participant progression in concept knowledge development as a result of engagement in the T/E DBL design challenge. The protocol was a mixture of predetermined structured questions developed from participant responses on the pre/post TTMC and FTMC diagnostic tests, and unscripted follow-up questions based on responses within the interviews themselves. The predetermine structured questions allowed for consistent comparison between participants while the unscripted questions allowed flexibility for additional clarification questions of participant interview responses.

Instrument Development Procedures

The following is a detailed description of the procedures used in development of the Three and Four-Tiered Science and Mathematics Concept Multiple-Choice Diagnostic Tests, and the Post Intervention Semi-Structured Interview Protocol.

Three-Tiered Multiple-Choice (TTMC) Diagnostic Test

As reported in the Chapter 2 literature review, there are many concepts that teachers of science and mathematics struggle to correctly understand. In light of this, the T/E DBL intervention was designed to intentionally impose the need to know a targeted sub-set of these concepts in order to achieve a successful design solution. Though a myriad of concepts and practices K-8 teachers would be expected to know are addressed by the T/E DBL intervention,

for this research the intervention was developed to specifically target the following science and mathematics concepts: evaporation, condensation, rate of condensate production per unit area, area of irregular shapes, and slope and rate of change. To assess preservice teacher concept knowledge development as a result of their participation in the intervention, an instrument was needed that assessed the concepts listed above. The instrument developed to assess these concepts is the Three-Tiered Multiple Choice (TTMC) diagnostics test. The following sections outline the procedures that guided the instrument development.

Targeted Science and Mathematics Concepts

The T/E DBL intervention was designed such that participants needed a deep understanding of the above listed science and mathematics concepts to successfully design, analyze, and report on their solution to the proposed challenge. The challenge within the T/E DBL intervention, which will be discussed in detail in the Procedures section below, required participants to design and build a technological solution to produce fresh water from salt water using the process of solar distillation. The essential concepts targeted within this design challenge are those of evaporation and condensation which are essential to designing and building an effective and efficient technological solution to this challenge. Furthermore, given that the challenge requires participants to understand the concepts of determining the area of irregular shapes, rate of condensate production per unit area, and slope and rate of change in order to successfully analyze, compare and report on their designed solutions, they were also identified as targeted concepts. With targeted science and mathematics concepts identified, the next step was generation of propositional knowledge statements.

Generating Propositional Knowledge Statements

Five targeted science and math concepts were intentionally imbedded as learning outcomes for the selected T/E DBL intervention challenge. Accepted definitions of the targeted

science and math concepts, as well as essential sub-concepts were found in published research articles, textbooks, and internet resources and used in generating a first draft of the science and math learning outcomes for the T/E DBL intervention challenge. The following are definitions of accepted science and mathematics concepts/sub-concepts from the literature that later served as the basis for the formation of the targeted propositional knowledge statements.

Concept/Sub-Concepts: Accepted Definitions

Science Concept 1: Evaporation – the process by which molecules in the liquid phase are converted to molecules in the gas phase.

Sub-Concepts:

Evap-A: evaporation occurs at the liquid-gaseous interface when liquid molecules absorb enough kinetic energy to move from the liquid phase to the gaseous phase

Evap-B: the energy absorbed by liquid water molecules moving into the gaseous phase is known as the heat of evaporation and removing this energy from the liquid causes evaporative cooling

Evap-C: during evaporation of a solvent (water) and dissolved solute (salt) mixture, the solvent will evaporate leaving the solute behind

Evap-D: while the evaporation rate of a solvent is dependent on temperature of the liquid, the evaporative production rate increases proportionally with the surface area of the solvent

Science Concept 2: Condensation – the process by which molecules in the gaseous phase are converted to molecules in the liquid phase.

Sub-Concepts:

Cond-A: condensation occurs in the gaseous-liquid phase and occurs due to absorption into a liquid phase or adsorption onto a solid phase

Cond-B: condensation results in the collision of vaporized water molecules where heat is released, often referred to as the heat of condensation

Cond-C: in a closed system, the rate of condensation will equal the rate of evaporation after a period of time, it is effect by vapor pressure and temperature.

Mathematics Concepts 1: Rate of Condensate Production Per Unit Area – is the amount vapor that is changed to a liquid through the exothermic process of condensation in a given amount of time per unit of condensation area.

Sub-Concepts:

RateCond-A: rates of condensate production include changing condensate quantities over time

RateCond-B: changing quantities can be averaged over an effective unit area

Math Concepts 2: Area of Irregular Shapes – is the measurement of the region within the perimeter of an irregular figure in square units.

Sub-Concepts:

Area-A: irregular shapes can be divided into regular shaped regions

Area-B: as the number of rectangles inscribed or circumscribed within and irregular shape increase to infinity, the area estimate of the irregular shape, using the sum of those rectangles, becomes more accurate

Math Concepts 3: Slope and Rate of Change – the slope of a of a linear function of two variable is equal to the rate of change of those variables.

Sub-Concepts:

Slope-A: the slope of a linear function can be calculated based on production versus time data

Slope-B: the slope of a linear function that models production data is the same as the rate of change

The above established science and mathematics concept definitions were used in creating initial drafts of the targeted propositional knowledge statements. Table 2 presents a sample of targeted propositional knowledge statements related to evaporation derived from the above established science and mathematics concept learning outcomes. A complete list of all targeted propositional knowledge statements can be found in Appendix C

Table 2

Example: Targeted Propositional Knowledge Statements Related to Evaporation

Sub-Concepts	Learning Outcome Categories	Targeted Propositional Knowledge Statements
Evap-A	Heat of Evaporation	Liquid molecules, located near the surface of a liquid, with sufficient kinetic energy to overcome liquid-phase intermolecular forces, will leave the liquid phase and enter the vapor phase.
Evap-B	Heat of Evaporation	Liquid molecules with enough kinetic energy to overcome liquid-phase intermolecular forces will leave the liquid–phase and enter the vapor phase. This loss of high-kinetic energy molecules to the gas phase lowers the average kinetic energy of the liquid resulting in cooling of the liquid.
Evap-C	Residuals of Evaporation	Solutes do not evaporate along with the solvent during evaporation. They will remain in the evaporation container unless they are also volatile.

Establishing Statement Face Validity

Expert Panel

An expert panel of five individuals was assembled to aid in various phases of development, refinement, and validation of the propositional knowledge statements and diagnostic items. Panel members were selected based on their academic credentials and research experience that met at least three of the four following criteria:

- Candidates must hold a terminal degree in one of the following disciplines; chemistry, mathematics, or physics,

- Candidates must have at least five years of experience teaching at the undergraduate level,
- Candidates must have experience with assessment of content concepts at the undergraduate level,
- Candidates must have experience developing diagnostic items for standardized science or mathematics assessment instruments.

Members of the expert panel were assembled and asked to review, for concept accuracy and wording, all propositional knowledge statement items. Through a succession of arbitrations, an iterative process of statement revision was conducted until a consensus of 80% or greater on each was achieved. What follows is a description of the process followed in reaching consensus.

Achieving Consensus

The initial propositional knowledge statements were provided to all panelist to review for accuracy and readability using a Propositional Knowledge Statement (PKS) Expert Panelist Review Form. Figure 2 presents a sample of this form, with the complete form in Appendix D.

Figure 2

Sample: Propositional Knowledge Statement Expert Panelist Review Form

Concept	Sub-concept	Current PKS	Do you wish to make an editorial change?	Revised PKS
Evaporation		Evaporation is the process by which molecules in the liquid phase are converted to molecules in the gas phase.	Yes/No	
	Heat of Evaporation	Liquid molecules, located near the surface of a liquid, with sufficient kinetic energy to overcome liquid-phase intermolecular forces, will leave the liquid phase and enter the vapor phase.	Yes/No	

Note: PKS = Propositional Knowledge Statement

Using the review form provided, panelists entered their editorial comments and then returned the form to the researcher. Through each stage of arbitration, panelist feedback was compiled in a Response Summary Review Rubric. Figure 3 presents a portion of the rubric, with the complete version found in Appendix E

Figure 3

Response Example Summary Review Rubric

Propositional Knowledge Statement	Proposed Changes	Refined Propositional Knowledge Statement
1) Evaporation is the process by which a liquid molecule is converted to a gaseous molecule (or vapor molecule)	PM-1* Evaporation is the process by which molecules in the liquid phase are converted to molecules in the gas phase. PM-2 A** PM-3 A PM-4 A PM-5 A	Evaporation is the process by which molecules in the liquid phase are converted to molecules in the gas phase.
2) Liquid molecules, located near the surface of a liquid, with sufficient kinetic energy to overcome liquid-phase intermolecular forces, will leave the liquid phase and enter the vapor phase.	PM-1 A PM-2 A PM-3 A PM-4 A PM-5 A	Statement Accepted

*PM-1 = Expert Panel Member #1; **A = Propositional Knowledge Statement Accepted as Written

In successive rounds of arbitration, panelists addressed newly refined propositional knowledge statements until at least 80% consensus regarding the accuracy of each statement was achieved. The complete set of results from these successive rounds of arbitration is found in Appendix F.

Arbitration results were compiled in a Review Response Summary table demonstrating the progression of each propositional knowledge statement toward meeting the 80% consensus

threshold. Table 3 presents a portion of the Review Response Summary, with the complete summary found in Appendix G.

Table 3

Example: Review Response Summary:

PKS[a]	PM-1[b]	PM-2	PM-3	PM-4	PM-5	% Agreement
1	A[c]	A	A	A	A	100
2	A	A	A	A	A	100
3	A	A	A	A	A	100

[a]PKS = Propositional Knowledge Statement; [b]PM-1 = Expert Panel Member #1
[c] A = Accepted Statement; [d]D = Did Not Accept Statement

The panel's editorial efforts resulted in the final list of propositional knowledge statements (Appendix H), which were then used as the basis for developing the individual Tier 1 and Tier 2 Science and Mathematics diagnostic test items as discussed in detail below.

Development of Diagnostic Test Items

The items in both the TTMC and FTMC instruments requiring development were only Tier 1 and Tier 2 items. Initial diagnostic item development was guided by prior studies using multi-tiered diagnostic tests that reliably assessed the same science and mathematics concept knowledge of high school, undergraduate science, and preservice teaching students (Arslan et al., 2012; Aydeniz et al., 2017; Canpolat, 2006; Chang, 1999; Coştu et al., 2012; Gopal et al., 2004; Kirbulut & Geban, 2014). As conducted in other studies, the item development approach used in this study was as follows: identify previously developed test items, edit to address translation and readability issues, generate additional items, and establish face validity. The procedures followed in each of these steps is presented below.

Previously reported assessment items that focused on the same propositional knowledge statements as in this research were identified and minimally edited by the researcher in the first stage of the diagnostic item development sequence. A sample of these instrument items and their subsequent modification can be seen in Table 4. The entire list of modifications to prior study Multi-Tiered Multiple Choice (MTMC) test items can be seen in Appendix I.

Table 4

Samples: Modification to Prior Study MTMC Test Items

Item Source	Original Item Excerpt	Modified Excerpt
Aydeniz et al., 2017	At room temperature (25^{o}C), there is an open plastic bottle half-filled with water. If this bottle were left for several days in this room, what would happen to the level of water in the bottle? (Note: The humidity in the air should be considered too little).	At room temperature (25^{o}C), there is an open plastic bottle half-filled with water. If this bottle were left for several days in this room, what would happen to the level of water in the bottle? (Note: The humidity in the air should be thought of as not having any effect).
Canpolat, 2006	At a constant temperature, the below open containers A and B contain 100ml of pure water. Compare the evaporation rate of the water in the containers. Explain your answers as best as you can.	At a constant temperature, the below open containers A and B contain 100ml of pure water. Compare the evaporation rate of the water in the containers. a) The water in container A will evaporate faster than container B. b) The water in container A will evaporate slower than container B. c) The water in both containers will evaporate at the same rate.

Additional diagnostic items were created by the researcher for propositional knowledge statements that had not been addressed by items from previous studies. All of the diagnostic items were then compiled in a Diagnostic Item Review Rubric. This rubric was then used to direct the expert panel members in their face validity efforts as described in detail below.

Face Validity of Diagnostic Test Items

The Diagnostic Review Rubric was distributed to the previous expert panel for evaluation of the test items following the same process used for establishing face validity of the propositional knowledge statements. A sample of the rubric is provided in Figure 4 and the full rubric is found in Appendix J.

Figure 4

Sample: Diagnostic Item Review Rubric

ITEM #1 (Targeted Propositional Knowledge Statement (PKS) 1a and 1c.)
Tier 1: At room temperature (25^{o}C), there is an open plastic bottle half-filled with water. If this bottle were left for several days in this room, what would happen to the level of water in the bottle? (Note: The humidity in the air should be thought of as not having any effect). A) The level of water decreases. B) The level of water stays the same. C) The level of water increases
Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐ If yes, please provide revisions in the text box below.
Tier 1 Revisions:
Tier 2: Which of the following best describes the reason for your answer for the previous question?

a) In order for evaporation to take place, temperature has to be increased.

b) Water evaporates with its own energy at every temperature.

c) Water evaporates at or above its boiling point which is 100^{o}C.

d) In order for evaporation to take place, a liquid has to take heat from its environment.

e) Hot air condenses in the bottle.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions in the text box below.

Tier 2 Revisions:

Edits received were entered into a Diagnostic Item Round 1 Review Results table. Table 5 presents a sample of the results table, and the complete table can be found in Appendix K. The Review Results table was used in comparing suggested revisions. Based on suggestions, the items were refined and incorporated into subsequent rounds of review. This was done for each item until at least 80% consensus was reached.

Table 5

Sample: Diagnostic Item Round 1 Review Results

Item	Tier	Current Diagnostic Item	Proposed Revisions	Refined Question
Item 1	Tier 1	At room temperature (25°C), there is an open plastic bottle half-filled with water. If this bottle were left for several days in this room, what would happen to the level of water in the bottle? (Note: The humidity in the air should be thought of as not having any effect). A) The level of water decreases. B) The level of water stays the same. C) The level of water increases	PM-1* A** PM-2 A PM-3 A PM-4 A PM-5 A	Current Question Accepted
Item 1	Tier 2	Which of the following best describes the reason for your answer for the previous question? a) In order for evaporation to take place, temperature has to be increased. b) Water evaporates with its own energy at every temperature. c) Water evaporates at or above its boiling point which is 100°C. d) In order for evaporation to take place, a liquid has to take heat from its environment. e) Hot air condenses in the bottle.	PM-1 A PM-2 Choice C should be "Water evaporates at or above its boiling point which is 100° C=212 °F. (add space before C) PM-3 A PM-4 A PM-5 A	Which of the following best describes the reason for your answer for the previous question? a) In order for evaporation to take place, temperature has to be increased. b) Water evaporates with its own energy at every temperature. c) Water evaporates at or above its boiling point which is 100°C = 212°F. d) In order for evaporation to take place, a liquid has to take heat from its environment. *e)* Hot air condenses in the bottle.

*PM-1 = Panel Member #1; **A = Current Diagnostic Item Was Accepted

An Arbitration Results Summary table was developed to document consensus on each diagnostic item. Table 6 shows a sample of this summary. The complete summary can be found in Appendix L.

Table 6

Sample: Arbitration Results Summary

Item[a]	Tier	PM-1[b]	PM-2	PM-3	PM-4	PM-5	% Agreement
1	1	A[c]	A	A	A	A	100
1	2	A	D[d]	A	A	A	80
2	1	D	A	A	A	A	80
2	2	A	A	A	A	A	100

[a]Item = Diagnostic Item; [b]PM-1 = Expert Panel Member #1; [c] A = Accepted the Diagnostic Item as Written; [d]D = Did Not Accept Diagnostic Item as written

The arbitration process resulted in development of the Tier 1 and 2 assessment items for both the TTMC and FTMC. It is important to note that the Tier 1, 2, and 3 items used in the FTMC Diagnostic Instrument were the same as those on the TTMC Diagnostic Instrument administered as the pre-intervention assessment. Creation of the FTMC entailed including an additional question that inquired about what specific experience the participant had during the intervention that they considered significant in helping them progress in their knowledge about the targeted concept. This fourth question constitutes the Tier 4 item which asks participants "What T/E DBL experience do you think promoted your understanding of the concept discussed in Tier 1 and 2 of this question?"

Post Intervention Semi-Structured Interview Protocol

The post intervention semi-structured interview protocol was a mixture of predetermined structured questions derived from responses on the pre/post TTMC and FTMC diagnostic tests, and open-ended follow-up prompts to be used during the interviews when necessary for gaining

further clarifications. The derivation of structured questions required first reviewing the analyses of pre/post responses to identify those participants reflecting polar extremes in progressing toward concept knowledge development – clear vs. poor progression. As such, described first in this section are the purposeful sampling procedures used in determining interview participants, followed by the procedures used in developing the structured questions and open-ended follow-up prompts.

Interview Participants: Purposeful Selection

Purposeful selection was used to identify six participants for the semi-structured interviews who reflected polar extremes in progressing toward concept knowledge development. Selection was based on the gains in their pre/post Tier 1 and Tier 2 total scores to determine three participants demonstrating clear progressions in concept knowledge development and three participants demonstrating poor progressions in concept knowledge development. Specifically, three participants demonstrating the greatest gains in pre/post Tier 1 and Tier 2 scores were selected, and three participants demonstrating the least gains in pre/post Tier 1 and Tier 2 scores were selected for interviews. Selection of participants using criteria of the latter case was based on an expectation that they would exhibit anomalous concept knowledge reasoning and retention of misconceptions despite participation in the T/E DBL intervention.

Structured Interview Questions

Questions developed for the semi-structured interview focused the level of conceptual understanding the interviewee possessed for each of the five targeted math and science concepts: evaporation, condensation, areas of irregular shapes, rates of production, and slopes of production rate data. Particular pre/post TTMC and FTMC responses of interest that were the subject of these questions were incidences where students showed evidence of learning a new concept over the course of the intervention but still retained some misconception about the

concept. This was evidenced by participants responding incorrectly to a Tier 1 item on the pre-assessment and then responding correctly to the same Tier 1 item on the post assessment but incorrectly answered the Tier 2 reasoning multiple choice question. In addition, questions requiring participants to elaborate on their perceptions about what phase of the design process or T/E DBL experience most influenced their conceptual learning of the above targeted items were also developed.

Concept responses were used to draft interview questions designed to corroborate participant concept knowledge progression (addressing RQ1). In addition, evidence for what T/E DBL experiences they thought promoted their acquisition of the science and mathematics concepts was corroborated using questions related to participant responses on Tier 4 for each targeted concept (addressing RQ2). Follow up anticipatory questions were asked as a result of interesting or anomalous response phenomena during the interviews in order to clarify participant thinking related to persistent misconceptions. The following lists the science and mathematics concepts which were the subject of the interview questions and provides example questions and probes that could be used.

Science Concept 1: Evaporation. Interview questions on evaporation targeting RQ1 would ask about the degree of concept knowledge progression.

Example Question: Tell me about your understanding of evaporation and how this understanding may have changed over the course of the recent design challenge?

Potential Probes:

1. Tell me about what is happening with the water molecules at surface of the liquid.
2. Where does the energy for evaporation come from?
3. What happens to the salt molecules during evaporation?

Interview questions on evaporation targeting RQ2 ask about the perceived experiential conditions leading to knowledge progression.

Example Question: Was there a particular design experience during the challenge that helped to change your understanding of evaporation?

Potential Probes:

1. What was it about that particular design experience that helped change your understanding of evaporation?

2. Were there any other experiences beyond the challenge itself that helped you better understand the concept of evaporation?

Science Concept 2: Condensation. Interview questions on condensation targeting RQ1 would ask about the degree of concept knowledge progression.

Example Question: Tell me about your understanding of condensation and how this understanding may have changed over the course of the recent design challenge?

Potential Probes:

1. Can you explain more about what was happening to the water molecules in the vapor state when condensation occurs?
2. Tell me a little more about where the energy goes when water molecules in the vapor phase condense to form liquid?

Interview questions on condensation targeting RQ2 would ask about the perceived experiential conditions leading to knowledge progression.

Example Question: Were there any particular design experiences during the challenge that helped change your understanding of condensation?

1. What was it about that particular design experience that helped change your understanding of condensation?
2. Were there any other experiences beyond the challenge itself that helped you better understand the concept of condensation?

Mathematics Concept 1: Areas of Irregular Shapes. Interview questions on areas of irregular shapes targeting RQ1 would ask about the degree of concept knowledge progression.

Example Question: What did you come away with from our design challenge about determining the area of the 2-dimensional irregular shapes?

Potential Probes:

1. How has your approach to finding the area of irregular shapes changed over the course of the challenge?
2. Do you feel you are better at determining the area estimate of a 2-dimensional irregular shape? Can you explain why?

Interview questions on areas of irregular shapes targeting RQ2 would ask about the perceived experiential conditions leading to knowledge progression.

Example Question: Were there any particular design experiences during the challenge that helped change your understanding of how to find the area or irregular shapes?

Potential Probes:

1. What was it about that particular design experience that helped change your understanding of how to determine the area of irregular shapes?
2. Were there any other experiences beyond the challenge itself that helped you better understand the concept of determining the area of irregular shapes?

Mathematics Concept 2: Rates of Condensate Production Per Unit Area. Interview questions on rates of condensate production per unit area targeting RQ1 would ask about the degree of concept knowledge progression.

Example Questions: Tell me about your understanding of how best to estimate the rate of condensation per unit area and how this understanding may have changed over the course of the recent design challenge.

Potential Probes:

1. What is your understanding of how the rate of condensation for different systems can be compared?
2. Can you tell me more about what the production rate per unit area tells you about a given system design? (more efficient, less efficient)

Interview questions on areas of irregular shapes targeting RQ2 would ask about the perceived experiential conditions leading to knowledge progression.

Example Question: Were there any particular design experiences during the challenge that helped change your understanding of how to find the condensation production rate per unit area?

Potential Probes:

1. What was it about that particular design experience that helped change your understanding of how to determine the condensation production rate per unit area?
2. Were there any other experiences beyond the challenge itself that helped you better understand the concept of determining the condensation production rate per unit area?

Mathematics Concept 3: Slopes of Condensate Production Rate Data. Interview questions on slope of production rate data targeting RQ1 would ask about the degree of concept knowledge progression.

Example Question: Tell me about your understanding of the slope of the condensate production data and the rate of change of condensate production.

Potential Probes:

1. How would you explain to another student how you could find the condensate production rate from the slope of your production versus time graph? Can you explain in more detail how you knew these to values were the same?
2. Tell me about what you know about rate of change? Is it related to slope of the production versus time graph somehow? Explain what you mean.

Interview questions on slopes of condensate production rate data targeting RQ2 would ask about the perceived experiential conditions leading to knowledge progression.

Example Question: Were there any particular design experience during the challenge that helped you better understand the rate of change in condensate production?

Potential Probes:

1. What was it about that particular design experience that helped change your understanding of how to determine rates of change?
2. How did this design experience clear up any confusion you might have had about slope and how it relates to the rate of change with the slope of your production data?

The predetermined questions were organized and listed in tabular form (Table 7), which would serve as the protocol to be followed in each individual interview. The entire protocol can be found in Appendix M.

Table 7

Sample: Predetermined Structured Interview Questions and Follow-Up Prompts

Question	Predetermined Structured Interview Questions	Targeted RQ
1a	Tell me about your understanding of evaporation and how this understanding may have changed over the course of the recent design challenge? Potential Probes: 1. Tell me about what is happening with the water molecules at surface of the liquid. 2. Where does the energy for evaporation come from? 3. What happens to the salt molecules during evaporation?	RQ1
1b	Was there a particular design experience during the challenge that helped to change your understanding of evaporation?	RQ2
1b	Potential Probes: 1. What was it about that particular design experience that helped change your understanding of evaporation? 2. Were there any other experiences beyond the challenge itself that helped you better understand the concept of evaporation?	
2a	What did you come away with from our design challenge about determining the area of the 2-dimensional irregular shapes? Potential Probes: 1. How has your approach to finding the area of irregular shapes changed over the course of the challenge? 2. Do you feel you are better at determining the area estimate of a 2-dimensional irregular shape? Can you explain why?	RQ1
2b	Were there any particular design experiences during the challenge that helped change your understanding of how to find the area or irregular shapes? Potential Probes: 1. What was it about that particular design experience that helped change your understanding of how to determine the area of irregular shapes? 2. Were there any other experiences beyond the challenge itself that helped you better understand the concept of determining the area of irregular shapes?	RQ2

Note: RQ = research question

Intervention

This section describes the T/E DBL intervention that was employed in this research during week eight of the science and math pedagogy course. The T/E DBL intervention that was developed for this research challenged participants to design, build, test, analyze, and report on a technological system that produced fresh water from salt water using the process of solar distillation. The design challenge (Appendix N) was crafted such that it required participants to deeply understand the targeted concepts listed above in order for successful completion of all intervention requirements. The instructional duration of the intervention required 6-8 days of one hour and twenty-minute class periods. The intended daily intervention plans were delineated and developed to correspond to specific design phases as described in the P.I.R.P.O.S.A.L. Model (Appendix A). This model, described in detail in chapter 2, is a conceptual/pedagogical framework for I-STEM ED that includes the following design phases: Problem Identification, Ideation, Research, Potential Solutions, Optimization, Solution Evaluation, Alterations, and Learned Outcomes (Wells, 2016a, 2016b, 2016c). The I-STEM ED T/E DBL Intervention Instructional Plan (Appendix O) provides a detailed description of daily teaching strategies and concurrent student engagements. A brief overview of the daily Intervention Instructional Plan is as follows:

Day 1 Problem Identification and Ideation

1. Participants were introduced to the problem of worldwide impoverished coastal communities' need for access to fresh water.
2. Each participant was tasked with preparing an uninformed design sketch of a potential T/E prototype solution that could extract fresh water from the abundant saltwater resources available to these communities using a solar distillation process.

3. Participants were then placed into a two-person design dyad and asked to discuss their individual designs and complete a dyad potential design solution.

Day 2 Ideation and Research

1. Participant dyad design groups conducted small group and whole class discussions of possible process solutions to the design challenge.
2. Design groups researched solar distillation, evaporation, condensation, and solute-solution relationships during evaporation in order to more fully understand the concepts underpinning technological solution options.
3. Whole-class preliminary design drawing gallery walks and discussions were held during this class.

Day 3 Potential Solutions

1. Prior to building prototypes, each design group participated in a gallery walk of all the groups' designs and materials lists.
2. Any/All additional design options revealed during the gallery walk are recorded in the IEJs of each member of the dyad as "potential alternative designs"
3. Dyads consider alternative designs and generate a number of additional detailed sketches of any potential prototype sub-systems.
4. The generation of 3 or 4 additional sketches and drawings, inclusive of notes and dimensions, allows for envisioning of new design options and ideas leading to the preparation of construction details.

Day 4 Optimization

1. In this phase "specific elements" of potential designs generated in the previous phase were tested. Based on these assessments the most efficient ones were selected for use in the design of their working solar distillation prototype.

2. Design groups developed and submitted a bill of materials need for their designs and assembled all the necessary materials and supplies.
3. Design groups began construction of their solar distillation prototypes.
4. Design groups finished the construction of their group's solar distillation prototype and calculated an estimate of the effective condensation area using Riemann sum techniques.
5. Design groups decided how they would evaluate their prototype's performance at producing fresh water from salt water.
6. Whole class discussions were held related to calculating condensation production rates per effective condensation areas in order for groups to compare their overall production efficiencies.

Day 5 and 6 Solution Evaluation 1 and Alterations

1. Over the next two class periods, participants evaluated their prototype's performance at producing fresh water from salt water.
2. Participants recorded condensation collection volumes over time. They plotted fresh water production data versus time and analyzed the slope of the freshwater production versus time plot to determine an overall hourly production rate.
3. Conductivity measurements of the condensate were conducted at this time to show participants that the solute (NaCl) was not present in the collected condensate.
4. Designs were assessed to determine if alterations could be made to increase production.

Day 7 Alterations

1. Design groups identified points of design weaknesses, and made alterations as needed to their designs
2. Redesigned prototypes were retested, new performance data collected, and design iterations reevaluated for their rates of change/rates of condensate production.

3. Iterations continued until such time as design teams achieved a design solution that met or exceeded the system criteria.

Day 8 Solution Evaluation 2

1. Design groups prepared final reports based on IEJ entries, and developed presentations to be used for discussing their rates of change/rates of condensate production with other design groups.
2. Design group presentations of their working solar distillation prototype performances, and included discussion of how their solution addressed the design criteria.
3. Whole class discussions of design group learned outcomes concluded the design challenge.

Data Collection Procedures

This section describes the reasoning, context, and schedule for collection of the following data types: pre-intervention diagnostics (TTMC), post-intervention diagnostics (FTMC), and semi-structured interview questions as well as the collection of science and engineering interactive notebooks (SEINs). The science and mathematics pedagogy class that was the setting for the study is a one semester course lasting fifteen weeks. On the first day of class, study participants were informed about the nature of the research that was to be conducted. Institutional Review Board (IRB) protocols were followed when informing students within the course about their rights and responsibilities if they chose to participate. All students in the course participated in the intervention, though only data from those who submitted signed consent forms (Appendix P) were used in the study.

Pre-Intervention Diagnostics (TTMC)

On day two of class the pre-intervention diagnostic instrument (TTMC) was administered to all students enrolled in the course. Students were provided paper copies of the instrument and

given 50 minutes to complete the TTMC test. Responses from study participants were entered into an SPSS spreadsheet for later analyses.

Post Intervention Diagnostics (FTMC)

During the next class meeting following participant completion of the design challenge, participants were asked to complete the FTMC post-intervention diagnostics instrument. This assessment, administered on paper, was completed in class, without notes or other external information sources. Response data were recorded into an SPSS spreadsheet for later analyses.

Semi-Structured Interview

Individual semi-structured interviews with each of the six purposefully selected participants were conducted within five days of they having completed the design challenge. Interviews were audio recorded and transcribed using transcription software. These data were stored in a secured location for later analyses

SEIN Entries

Prior to the start of the intervention, participants were instructed to keep a SEIN (composition notebook) in which they would make entries as they progressed through the design challenge such as notes, design ideas, design sketches, prototype testing data, and calculations. All entries were to be dated and as detailed as possible. Following completion of the intervention, all SEINs were collected and stored in a secured location for later analysis.

Data Analysis

Data from the pre-assessment (TTMC), post-assessment (FTMC), Semi-Structured Interviews, and SEINs were collected and analyzed in such a way as to answer the proposed research questions. Specifically, collected data were analyzed to provide “evidence demonstrating that engagement in the T/E design challenge promoted knowledge progression toward acquisition of targeted concepts” (RQ1) and “student indications of what intervention

experiences most promoted their acquisition of targeted concepts" (RQ2). Data from both the pre and post assessments were used to provide insight into the extent to which participants progressed in their science and mathematics concept knowledge development. A total of 10 distinct variables were examined: *Tier-1 Scores (T1), Tier-1 Total Scores (T1-total), Item Success Scores (IS), Mean Instrument Success Score (MInstr-S), Tier1&2 Score (T1/2), Tier 1&2 Total Score (T1/2-total), Certainty Scores* (*C*), *Certainty Total Scores (C-total), Knowledge Score (K), and Knowledge Total Score (K-total).* These scores were calculated as described by Arslan et al (2012), Caleon and Subramaniam (2010), and Pesman and Eryilmaz (2010), and were calculated in the same manner for both the pre and post assessment. The variables are discussed in detail below.

Pre-Assessment

In the pre-assessment (TTMC) instrument 10 variables were used to measure science or mathematics conceptual knowledge and participant "certainty" perceptions of their knowledge for each item on the TTMC instrument. Each item included a set of three tiered questions. As described above, Tier 1 questions were multiple choice concept questions similar to what would be found on a standard multiple-choice test. Tier 2 questions were multiple choice questions asking participants for the scientific or mathematical reasoning that guided their selection of the response to Tier 1 questions. The Tier 3 questions asked participants to indicate their level of certainty for the Tier 1 and 2 responses (certain, uncertain) they provided. For every item on the TTMC, data gained from each tier within a set were analyzed per tier as described in the following paragraphs.

Tier 1

Data gathered from the Tier 1 questions for each test item were used to calculate *Tier-1 Scores* (T1). A T1 score was produced by coding the first tier responses for each item from each

participant with a "1" if the correct response was chosen and a "0" when otherwise. A *Tier-1 Total Score* (*T1-total*) was then calculated by summing all of the *T1* scores for each participant. This provided a score similar to what would be calculated in a common multiple-choice assessment and it provided a snapshot of overall participant understanding of the targeted concepts. An *Item Success* (*IS)* score for each item was produce by determining the proportion of participants that answered each Tier 1 questions correctly. The purpose for calculating this score was to determine if item success increased as a response to intervention engagement. The *Mean Instrument Success* (MIS) score was found by calculating the mean of the *IS* scores. It was expected that MIS scores would increase in response to intervention engagement.

An example of scores produced from Tier 1 data is shown below in Table 8.

Table 8

Tier 1 Data Scores Example

Participant	**Item 1**	**Item 2**	**…**	**Item 25**	**T1-total**
	T1[a]	**T1**		**T1**	
1	1	0	…	1	11
2	0	1	…	1	9
…	…	…	…	…	…
n[b]	1	1	…	1	16
Total Correct	6	8	…	15	
IS[c]	6/n	8/n	…	15/n	

[a]T1 = Tier 1 Score; [b]n = Total Number of Participants; [c]IS = Item Success Score

It should be noted that, when appropriate for the above variables, overall descriptive statistics such as means, standard deviations, and maximum and minimum values were calculated.

Tier 2

Data from Tier 2 questions for each test item were used to calculate *Tier 1&2 scores* (*T1/2*). A T1/2 score was produced by coding the first and second tier responses for each item a "1" if they were both correct and a "0" if otherwise. A *Tier 1&2 Total Score* (*T1/2-total*) was then calculated by summing all of the *T1/2* scores for each item for each participant. This provided a measure of how well a participant knew the concepts and the reasoning behind them. These variables also provided measurement of concept knowledge development that was more reliable than simple *T1* and *T1-total* scores that could be a result of guessing.

Tier 3

The Tier 3 question allowed for the assessment of the level of confidence a participant had when responding to Tier 1 and 2 questions for each item, and was thought of as a certainty score for that item. Previous studies have indicated that students have difficulty discriminating between what they know and what they don't know (conceptual understanding and misconceptions) (Caleon & Subramaniam, 2010). Data from this tier were used to help identify those instances where students were sure about their correct understanding of concepts, instances when they firmly believed in their misconceptions, and instances where participants lacked conceptual knowledge. This was done through the calculation of the four "certainty" related scores which include: *Certainty Scores (C), Certainty Total Score (C-total), Knowledge Score (K), Knowledge Total Score (K-total).* A detailed discussion of each of the above listed variables is provided below.

Certainty and Certainty Total Scores. *Certainty Scores (C)* were coded with a "1" if the participant responded "certain" to the Tier 3 question for each item and "0" if otherwise. The item certainty scores for each item were summed to provide the *C-total* score for each participant. The C-total score provided a measure of participant confidence in their Tier 1 and

Tier 2 responses. The *C* and *C-total* scores were expected to increase in response to the engagement in the intervention. The item certainty scores for each item were summed to provide the *C-total* score for each participant.

Knowledge Score and Knowledge Total Score. The *Knowledge Score* (*K)* was produced by examining the Tier 1, 2, and 3 responses for an item and coding a "1" if responses to Tier 1 and 2 were correct and the response to Tier 3 was "Certain". This case (correct, correct, certain) is indicative of a participant that correctly and confidently understands the targeted science or mathematics concept. A code of "0" was used for any incorrect or uncertain responses. The *Knowledge Total Score* (*K-total*) was produced by summing the *K* score for all items for each participant. This variable provided a measure of a participant's confident understanding of the target concepts across the instrument.

Post Diagnostic (FTMC) Analysis

The post-diagnostic (FTMC) instrument was identical to the pre-diagnostic (TTMC) instrument with the exception of the inclusion of the Tier 4 question. This tier asked participants to indicate what T/E DBL experience they thought promoted their acquisition of the particular science and mathematics concept in question.

Tiers 1, 2, and 3

The analyses of the data collected in Tiers 1, 2, and 3 were conducted using the same methodologies as those used for the pre-diagnostic instrument discussed above. Variables were identified in similar ways but were assigned a "post" prefix designation (p) in their variable ID coding (example: *p-T1* signifying *Post Tier-1 Score*).

Tier 4

The analysis of data collected from Tier 4 questions helped to answer RQ2 and required a qualitative analysis method. Each item on the post-diagnostic FTMC instrument was related to

one of five science and mathematics concepts. Responses to Tier 4 questions for each item where participants demonstrated conceptual understanding were examined for emerging themes as to what T/E DBL experiences most helped the participants gain knowledge of the items' targeted concepts. Frequencies and relative frequencies of these thematic T/E DBL experiences were calculated and recorded.

Pre/Post Diagnostic Comparison

In order to answer RQ1, pre/post paired data was examined to find evidence that engagement in a T/E DBL challenge promoted the participants' knowledge progression towards acquisition of the targeted science and mathematics concepts. Matched paired *t*-tests were used to examine the relationships between paired variables from the pre/post diagnostic instruments. All data were entered into the statistical software SPSS which was subsequently used for data analysis. Variable distributions were checked for normality using the Shapiro-Wilks test, and matched pair *t*-tests were used if normality was achieved. Otherwise, the nonparametric Wilcoxon matched-pairs signed-rank test was used. All data generated were assumed to be independent in nature and in each of the hypothesis tests the null hypothesis of "no difference" was used. The paired variables for each tier are discussed in detail below.

Tier 1

The Tier 1 paired variables from the pre/post diagnostic instruments were the *Tier-1 Total Score (T1-total* and *p-T1-total)*, and *Mean Instrument Success Scores* (*MInstr-S* and p-*MInstr-S)*.

Tier 2

The Tier 2 paired variables that were investigated included the *Tier 1&2 Total Score (T1/2-total* and *p-T1/2-total).*

Tier 3

Tier 3 variables that were analyzed using matched pair *t*-tests included the Certainty Total Score *(C-total and p-C-total),* and *Knowledge Total Scores (K-total* and *p-K-total).*

Participant Interviews

Transcribed participant interviews were thoroughly reviewed for corroborative evidence of progression toward concept knowledge acquisition previously indicated in the pre/post diagnostics (RQ1) and indications of T/E DBL experiences that most helped the participants gain knowledge of targeted concepts (RQ2). Notes were taken on participant responses where phrases and sentences indicating accurate (or inaccurate) knowledge of the targeted science and mathematics concepts was provided. These instances were labeled using *a priori* codes indicating knowledge progression of science or mathematics concepts in response to intervention engagement or impactful concept knowledge related T/E DBL experience. Coding schemes (Table 9) were manually assigned that organized evidence into meaningful groupings that could be combined into emergent themes.

Table 9

Semi-Structured Interview Evidence Statements, Codes and Emergent Themes

Evidence Statements	Codes	Emergent Themes
Science Concepts Pre Post	 Pre-Evap & Pre-Cond Post-Evap & Post-Cond	Concept Knowledge Progression (RQ1)
Math Concepts Pre Post	 Pre-Area, Pre-Rate, Pre-Slope Post-Area, Post-Rate, Post-Slope	
Phases of design experiences supporting progression of concept knowledge development.	DExp-Prob DExp-Idea DExp-Rsrch DExp-ProbSoln DExp-Opt DExp-SolEval DExp-Alt DExp-Lrnd (P.I.R.P.O.S.A.L. Phases)	T/E DBL Experiences That Promoted Science and Math Concept Development (RQ2)

The coded data was then analyzed using content and thematic qualitative methods. Illustrative quotes were selected to show participant knowledge and perceptions in relation to the stated research questions.

SEIN Content Analysis

Content analysis of the Science and Engineering Interactive Notebooks (SEINs) from all participants were thoroughly analyzed by the co-coders to discern corroborative evidence of progressions toward concept knowledge acquisition as previously indicated in the pre/post diagnostics (RQ1), inclusive of FTMC T4 responses indicating T/E DBL experiences that most helped the participants gain knowledge of targeted concepts (RQ2). Content analysis included recording/labeling the dates and phases of design during which entries were made. Indications of science and mathematics sub-concept knowledge development were coded along with clarifying notes made to provide interpretive detail for targeted design drawings or participant written statements. Coded data were then analyzed using content and thematic qualitative analysis methods. Both the participant interviews and SEIN data also assisted in corroborating the triangulation efforts detailed below.

Triangulation

Triangulation of pre/post diagnostic, semi-structured interview data, and SEIN data was conducted to enhance the validity and reliability of the study's findings. The pre/post diagnostic instruments as well as the semi-structured interviews and SEIN analyses included quantitative and qualitative items that allowed for corroboration of participants' responses and identification of strengths and weaknesses in the instrumentation and intervention. A detailed description of the data analysis methods used between the multiple data sources is discussed below.

Pre/Post Diagnostic Quantitative Results

Data generated from the pre/post diagnostic instruments, specifically Tier 1 and 2 questions for each item, were compared using descriptive and inferential statistical analysis methods. This was achieved through the use of SPSS and provided insight into participants' conceptual knowledge progression from the conceptions they held prior to the intervention and the change (or lack of change) in the science or mathematics conceptual knowledge of the participants after the intervention (RQ1).

Pre-Diagnostic and Semi-Structured Interview Quantitative and Qualitative Results

The semi-structured interview data allowed for corroboration of science and mathematics concept knowledge progression. Concept specific interview responses were compared to pre-diagnostic responses for alignment (RQ1).

Post Diagnostic, Semi-Structured Interview, and SEIN Quantitative and Qualitative Results

The semi-structured interview and SEIN data allowed for corroboration of science and mathematics concept knowledge progression post intervention. Detailed descriptive data obtained through the interviews and SEIN entries related to current science and mathematics conceptual knowledge was compared to post diagnostic responses to provide a deeper understanding of participant conceptual understanding and alignment. In addition, the interview and SEIN data related to T/E DBL experiences that helped to support conceptual knowledge development were compared to FTMC Tier 4 diagnostic responses for analysis of alignment. This provided a more detailed understanding of relationships between the contextualized learning environment and participant concept knowledge development.

Summary of Research Method

To answer the research questions, the data collected from the pre/post diagnostic instruments as well as the semi-structured interviews and SEIN entries were examined using a combination of descriptive statistics, matched paired *t*-test for testing the significance, content

analyses, and corroborative analyses. These analyses provided evidence of preservice elementary teachers' preconceptions of complex science and mathematics concepts prior to a T/E DBL experience and how their conceptions change based on those experiences. These analyses also shed light on what T/E DBL experiences were perceived by the participants as most supporting their conceptual knowledge growth. The findings of these analysis methods are detailed in Chapter 4.

CHAPTER FOUR RESULTS

The purpose of this study was to document the progressions of science and mathematics concept knowledge among preservice elementary teachers engaged in a T/E DBL challenge and to identify those phases of design they perceived most influenced that progression. Evidence was collected from the pre/post diagnostic instruments, semi-structured interviews and science and engineering interactive notebooks (SEINS). These data were examined using descriptive statistics, matched paired *t*-test for determining the level of significance between pre/post outcomes, and thematic and corroborative analysis. As discussed in this chapter, analysis of data collected was used to answer the following research questions (RQs):

When preservice elementary teachers engage in a T/E DBL challenge:

RQ1 - What evidence demonstrates such engagement promotes their knowledge progression towards acquisition of targeted complex science and mathematics concepts compatible with accepted scientific views?

RQ2 – What T/E DBL experiences do they indicate promoted their acquisition of the targeted complex science and mathematics concepts?

Results presented in this chapter are organized by research question. In analyzing data to answer RQ1, presented first are pre/post diagnostic instrument results, followed by results of semi-structured interviews, and finally results of interactive notebooks. Analyses used to answer RQ2 begins by presenting results from Tier Four (*T4*) post diagnostic design experience item, followed by design experience results from post interview and interactive notebooks.

Description of Sample

Thirteen participants were recruited from a convenience sample of preservice elementary and middle school (K-8) teachers enrolled in a 15 week science and mathematics pedagogy course at a liberal arts college in the rural southeast region of the United States. All participants

were in their sophomore or junior year of college and seeking an endorsement in elementary education while pursuing interdisciplinary degrees in mathematics, social studies, or English. The participant sample included 11 female and 2 male students (approximately 85% and 15% respectively).

Research Question 1: Science and Mathematics Knowledge Progression

Research Question 1 (RQ1) asks what evidence demonstrates that teacher engagement in T/E DBL promotes their knowledge progression towards acquisition of targeted complex science and mathematics concepts. Responses to Tier-1 (*T1*) items on the pre Three Tiered Multiple Choice (TTMC) and on the post Four Tiered Multiple Choice (FTMC) diagnostic instrument were used as evidence for assessing preservice teacher progression towards acquisition of targeted concept knowledge.

T1 Items: Pre/Post Analysis

Pre and post Tier-1 (*T1*) item analysis was conducted using a scoring key to code correct answers using a "1" and incorrect answers using a "0". A *Tier-1 Total Score* (*T1-total*) was then calculated for each item by summing all participant *T1* scores. These calculations provided a snapshot of overall participant understanding of the targeted concepts. Examples of these data are provided in Tables 10 and 11. Complete data tables can be found in Appendices Q and R.

Table 10

Pre Tier 1 Data Scores Example

Participant	Item 1 *T1*	Item 2 *T1*	…	Item 25 *T1*	*T1*-total
1	1	1	…	1	21
2	1	1	…	1	16
3	0	1	…	0	18
…	…	…	…	…	…
13	0	1	…	1	13

Table 11

Post Tier 1 Data Scores Example

Participant	Item 1 *T1*	Item 2 *T1*	…	Item 25 *T1*	T1-total
1	1	1	…	1	23
2	1	1	…	1	22
3	1	1	…	1	22
…	…	…	…	…	…
13	1	1	…	0	21

RQ1 can be addressed, in part, through pre/post comparison of *T1* Total Scores which serve as evidence of participant science and mathematics concept progression following T/E DBL engagement. Pre and post *T1* Total Scores were compared and changes calculated by subtracting Pre *T1 Total* Scores from Post *T1-Total* Scores (Table 12).

Table 12

Pre and Post T1 Total Score Comparisons

Participant	Pre T1 total Scores	Post T1 total Scores	Change
1	21	23	+2
2	16	22	+6
3	18	22	+4
4	12	14	+2
5	12	19	+7
6	13	20	+7
7	10	17	+7
8	16	19	+3
9	18	15	-3
10	12	16	+4
11	17	17	0
12	15	18	+3
13	13	21	+8

RQ1 seeks evidence demonstrating preservice elementary teachers progress in their understanding of science and mathematics concepts as a result of engagement in a T/E DBL challenge. Evidence of progression would be reflected by differences in means between pre and

post *T1* Total Scores that are statistically significant. Matched 2-tailed paired *t*-tests, where the null hypothesis states that the mean difference between the paired pre and post *T1* Total Scores is zero, are particularly suited for determining the significance of mean score differences before and after an intervention.

Requirements of a matched paired t-test

Listed below are several assumptions that must be met before a matched paired *t*-test can be reliably performed:

1) Subjects must be independent, meaning that the data collected from one subject do not affect the data collected from another subject.
2) Each paired measurement must be obtained from the same subject.
3) The dependent variable must be continuous.
4) The differences between the paired observations should be approximately normally distributed.

A check to determine if these assumptions were met was performed prior to running the matched paired *t*-test. Since participants completed the pre and post diagnostic instruments independently in a proctored environment it can be assumed that the data collected was produced by independent subjects. Data collection procedures ensured that pre and post diagnostic instrument results were paired to the same participant. The dependent variable, pre and post *T1* Total Scores, were continuous across an interval. Additionally, the Shapiro-Wilk test for normality of the pre and post *T1* Total Score differences provided a significance level of 0.393 which is greater than $\alpha = 0.05$ (Table 13).

Table 13

Pre and Post T1 Total Score: Test for Normality

	Shapiro-Wilk		
	Statistic	*df*	*p*
Post T1 Total – Pre T1 Total	0.935	13	0.393

Pre/Post *T1* Total Score Differences were normally distributed based on Shapiro-Wilk test (p>0.05)

Results from the Shapiro-Wilk test provides evidence that the null hypothesis of distribution normality should not be rejected and that a matched paired *t*-test would be appropriate for comparing the means of pre and post *T1* Total Scores.

Matched Paired t-test Results

The pre and post *T1* Total Scores were compared using a matched 2-tailed paired *t*-test to assess the level of significance between the means. Results (Table 14) indicate significance for pretest/posttest differences in the *T1* Total Scores reflecting concept progression. Furthermore, the practical strength of the mean differences is substantiated by the large effect size as measured by Cohen's d.

Table 14

T1 Total Score: Pretest/Posttest Concept Progression

Total Score	***M***	N	***SD***	***SEM***	***df***	***t***	***p***	***d***
Pre *T1*	14.85	13	3.158	0.876	12	4.36	<0.001*	1.21
Post *T1*	18.69	13	2.840	0.788				

*p <0.05, 2-tailed, paired;

Corroborating Evidence of Concept Knowledge Progression

Eight other variables were examined to provide corroborating evidence of the extent to which participants progressed in their science and mathematics concept knowledge progression: *Item Success Scores (IS), Mean Instrument Success Score (MInstr-S), Tier1&2 Alignment Score (T1&2-A), Tier 1&2 Total Score (T1&2-Total), Certainty Scores* (*C*), *Certainty Total Scores (C-total), Knowledge Score (K), and Knowledge Total Score (K-Total).*

Pre and Post Item Success Scores

An *Item Success* (*IS)* score for each item was produce by determining the total number of participants that answered each *T1* question correctly (Table 15). The purpose for calculating this score was to determine any change in item success between pre and post assessment following intervention engagement and to provide additional evidence for answering RQ1.

Table 15

Pre and Post Item Success Scores Comparison

Item	Pre *IS* Score	Post *IS* Score	Change
1	5	9	+4
2	12	12	0
3	10	9	-1
4	10	13	+3
5	9	12	+3
6	6	9	+3
7	9	12	+3
8	9	6	-3
9	9	10	+1
10	3	9	+6
11	12	10	-2
12	9	11	+2
13	11	12	+1
14	6	11	+5
15	4	6	+2
16	4	1	-3
17	9	13	+4
18	10	11	+1
19	7	12	+5
20	4	5	+1
21	8	12	+4
22	8	11	+3
23	9	13	+4
24	2	6	+4
25	8	8	0

Pre/Post Mean Instrument Success Scores

The *Mean Instrument Success* (*MInst-S*) score was determined by calculating the mean of the *IS* scores. This was done so as to discern any changes in *MInst-S* scores between pre and post

assessment following intervention engagement and provide further evidence of participant concept knowledge progression. Results from the descriptive statistics calculations (Table 16) indicate that the post *MInst-S* score was greater than the pre *MInst-S* score.

Table 16

Pre and Post Mean Instrument Success (MInstr-S) Scores

	M	N	***SD***	***SEM***
Post *MInstr-S*	9.72	25	2.99	.599
Pre *MInstr-S*	7.72	25	2.777	.555

A test of normality was performed on the Pre and Post *MInstr-S* scores and it was found that the post Scores were decidedly not normal (Table 17).

Table 17

Pre/Post MInstr-S: Test for Normality

	Shapiro-Wilk		
	Statistic	*df*	*p*
Post *MInstr-S* – Pre *MInstr-S*	0.873	25	0.005

Pre/Post *T1* Total Score Differences were normally distributed based on Shapiro-Wilk test ($p>0.05$)

This indicated a matched paired *t*-test would not be appropriate for comparing means. Instead, a non-parametric Wilcoxon Signed rank test was selected for comparison of the means of the pre and post *IS* score groups. This test is appropriate for comparing the means of two related groups where the data is not normally distributed. The Wilcoxon Signed rank test (Table 18) revealed a significant difference between the pre *MInstr-S* score and the post *MInstr-S* score.

Table 18

Pre and Post Mean Instrument Success Scores Wilcoxon Signed Rank Test

Variable	Pre *MInstr-S*	Post *MInstr-S*	Test Statistic (z)	*p*
IS Score	7.72	9.72	-3.182	<0.001*

*$\boldsymbol{p}$ <0.05

Tier 1 and Tier 2 Alignment Results

Tier 2 (*T2*) results were used in conjunction with *T1* results to produce a *Tier1&2 Alignment Score (T1&2-A)* for each test item. This provided a measure of how well a participant knew the concepts and the reasoning behind them when both *T1* and *T2* were answered correctly. A *Tier 1&2 Total Score* (*T1&2-Total*) was then calculated by summing all of the *T1&2* scores for each item per participant. These variables also provided a measure of concept knowledge development that was more reliable than simple *T1* and *T1-Total* scores alone, which could be a result of guessing. Table 19 presents the pre and post *T1&2-Total* Scores with corresponding changes, calculated by subtracting pre *T1&2-Total* scores from post *T1&2-Total* scores, for each participant.

Table 19

Pre and Post Tier 1&2 Total Scores

Participant	Pre *T1&2-Total* Scores	Post *T1&2-Total* Scores	Changes
1	20	21	+1
2	9	21	+12
3	13	20	+7
4	6	12	+6
5	8	16	+8
6	7	14	+7
7	8	14	+6
8	12	17	+5
9	13	11	-2
10	6	9	+3
11	14	14	0
12	11	16	+5
13	10	16	+6

Evidence that preservice elementary teachers are progressing in their understanding of science and mathematics concepts as a result of engagement in a T/E DBL challenge would be demonstrated by a statistically significant difference in participant pre and post mean *T1&2-*

Total Scores. Results from the descriptive statistics calculations (Table 20) indicate that the post mean *T1&2-Total* Score was greater that the pre mean *T1&2* Total Score.

Table 20

Pre and Post Tier 1&2 Total Score Descriptive Statistics

	M	N	***SD***	***SEM***
Pre *T1&2-Total*	10.539	13	3.929	1.08967
Post *T1&2-Total*	15.462	13	3.711	1.02916

The Shapiro-Wilk test for normality indicated that pre and post *T1&2-Total* Scores were normally distributed (Table 21).

Table 21

Pre and Post Tier 1&2 Total Score Test of Normality

	Shapiro-Wilk		
	Statistic	***df***	***p***
Pre Tier 1&2 Total Scores	0.914	13	0.207
Post Tier 1&2 Total Scores	0.949	13	0.587

Matched Paired *t*-test Results

Analysis of the pre and post *T1&2-Total* Scores matched 2-tailed paired *t*-test (Table 22) indicates that the difference between the means for the post *T1&2-Total* Score and the pre *T1&2-Total* Score was statistically significant. Furthermore, the practical strength of the mean differences is substantiated by the large effect size as measured by Cohen's d.

Table 22

Pre and Post Tier 1/2 Matched Paired t-test

Score	***M***	N	***SD***	***SEM***	***df***	***t***	***p***	***d***
Pre *T1/2-Total*	10.54	13	3.93	1.09	12	4.82	<0.001*	1.34
Post *T1/2-Total*	15.46	13	3.71	1.03				

*p <0.05, 2-tailed, paired;

Certainty Scores

Data generated from Tier 3 (*T3*) responses were used to help identify those instances where participants were sure about their correct understanding of concepts, instances when they firmly believed in their misconceptions, and instances where participants lacked conceptual knowledge. This was done through the calculation of the two *certainty* related scores which include: *Certainty Scores (C),* and *Certainty Total Score (C-Total).* The item certainty scores for each item were summed to provide the *C-total* score for each participant. The *C-Total Score* provided a measure of participant confidence in their *T1* and *T2* responses. The *C* and *C-Total* Scores were expected to increase in response to the engagement in the intervention. Pre and post *C-Total* Scores along with the change, calculated by subtracting pre *C-Total* scores from post *C-Total* scores, for each participant are presented below in Table 23.

Table 23

Pre and Post Tier 3 Certainty Total Scores

Participant	Pre *C-Total* Scores	Post *C-Total* Scores	Change
1	13	25	+12
2	1	3	+2
3	9	17	+8
4	15	16	+1
5	5	18	+13
6	8	15	+7
7	13	17	+4
8	12	19	+7
9	6	11	+5
10	2	23	+21
11	10	22	+12
12	8	25	+17
13	10	16	+6

The Shapiro-Wilk test for normality indicated that pre and post *C-Total* Scores were normally distributed (Table 24).

Table 24

Pre and Post Certainty Total Score Test of Normality

	Shapiro-Wilk		
	Statistic	***df***	***p***
Pre *C-Total* Scores	0.96	13	0.76
Post *C-Total* Scores	0.91	13	0.19

Matched Paired *t*-test Results

A statistically significant mean difference in summed participant pre and post Certainty Total Scores would provide evidence supporting preservice elementary teachers' progression toward understanding the targeted science and mathematics concepts as a result of engagement in a T/E DBL challenge. Results from the pre and post *C-Total* Scores matched paired *t*-test (Table 25) indicate that the post *C-Total* Score mean was significantly greater than the pre *C-Total* Score mean. Furthermore, the practical strength of the mean differences is substantiated by the large effect size as measured by Cohen's d.

Table 25

Pre and Post Tier 3 C-Total Matched Paired t-test

Score	***M***	N	***SD***	***SEM***	***df***	***t***	***p***	***d***
Pre *C-Total*	8.62	13	4.25	1.18	12	5.43	<0.001*	1.51
Post *C-Total*	17.46	13	5.98	1.66				

****p*** <0.05, 2-tailed, paired;

Knowledge Scores

Participant responses to Tiers 1, 2, and 3 for each item were used in conjunction to produce the *Knowledge Score* (K). The case where a participant correctly responded to *T1* and *T2*, as well as responding that they were "certain" in *T3*, was indicative of a participant that correctly and confidently understands the targeted science or mathematics concept. The *Knowledge Total Score* (*K-Total*) was produced by summing the *K* score for all items for each

participant. This variable provided a measure of a participant's confident understanding of the target concepts across the instrument. Pre and post *K-Total* Scores and change in those scores, which were calculated by subtracting pre *K-Total* Scores from Post *K-Total* Scores, are presented in Table 26.

Table 26

Pre and Post Knowledge Total Scores

Participant	Pre *K-Total* Scores	Post *K-Total* Scores	Change
1	12	22	+10
2	1	3	+2
3	6	17	+11
4	3	11	+8
5	2	13	+11
6	5	10	+5
7	7	12	+5
8	6	14	+8
9	6	6	0
10	1	9	+8
11	6	14	+8
12	6	16	+10
13	9	14	+5

The Shapiro-Wilk test for normality indicated that pre and post *K-Total* Scores were normally distributed (Table 27).

Table 27

Pre and Post Knowledge Total Score Test of Normality

	Shapiro-Wilk		
	Statistic	***df***	***p***
Pre *K-Total* Scores	0.921	13	0.256
Post *K-Total* Scores	0.979	13	0.974

Matched Paired *t*-test Results

Results from the pre and post *K-Total* Scores matched paired *t*-test (Table 28) indicates that the difference between the post *K-Total* Score mean and the pre *K-Total* Score mean was

statistically significant. Furthermore, the practical strength of the mean differences is substantiated by the large effect size as measured by Cohen's d.

Table 28

Pre and Post K-Total Matched Paired t-test

Score	***M***	N	***SD***	***SEM***	***df***	***t***	***p***	***d***
Pre *K-Total*	5.39	13	3.12	0.87	12	7.39	<0.001*	2.05
Post *K-Total*	12.39	13	4.86	1.35				

*p <0.05, 2-tailed, paired;

These results provide evidence supporting a progression toward understanding of the targeted science and mathematics concepts among the preservice elementary teacher participants following their engagement in a T/E DBL challenge.

Post Intervention Interview Analysis

Transcribed interviews of the six purposefully selected participants were thoroughly reviewed by the researcher and co-researcher (co-coders) for corroborative evidence of progression toward concept knowledge acquisition previously indicated in the pre/post diagnostics (RQ1). Notes were taken on participant responses where phrases and sentences indicating accurate (or inaccurate) knowledge of the targeted science and mathematics concepts pre and post intervention was provided. These instances were labeled using *a priori* codes indicating knowledge progression of science or mathematics concepts in response to intervention engagement. Based on the developed coding schemes (Table 29) codes were manually assigned organizing evidence statements into meaningful groupings that could be combined into emergent themes related to the targeted science and mathematics concepts. Successive rounds of arbitration were conducted between the co-coders until consensus agreement of selection of relevant evidence statements, interpretation, and coding was reached.

Table 29

Semi-Structured Interview Evidence Statements, Codes and Emergent Themes

Evidence Statements	Codes	Emergent Themes
Science Concepts		Concept Knowledge
Evaporation	Pre-No, Pre-Novice, & Pre-Yes	Progression (RQ1)
Sub Concept A	Post-No, Post Novice, & Post-Yes	
Sub Concept B		
Sub Concept C		
Sub Concept D		
Condensation		
Sub Concept A		
Sub Concept B		
Sub Concept C		
Mathematics Concepts	Pre-No, Pre-Novice, & Pre-Yes	Concept Knowledge
Rate of Condensation	Post-No, Post Novice, & Post-Yes	Progression (RQ1)
Sub Concept A		
Sub Concept B		
Area of Irregular Shapes		
Sub Concept A		
Sub Concept B		
Slope/Rate of Change		
Sub Concept A		
Sub Concept B		

Once selection of relevant evidence statements, interpretations, and coding had concluded, the co-coders conducted an analysis of concept knowledge progression for all sub-concepts for each participant. This analysis resulted in the designation of "no progress", "medium progress", or "high progress" for each sub-concept, for each participant. The participant's final concept knowledge progression designation was made based on the highest rated progression scheme designation that the participant provided with their evidence statements for each sub-concept. A summary of the coded utterances concept knowledge progression analysis is shown in Table 30.

Table 30

Coded Utterances Concept Knowledge Progression Analysis

	Evaporation										Condensation									Rate of C						Area						Slope					
Sub	A			B			C			D				A			B			C			A			B			A			B			A			B		
Participant	N	M	H	N	M	H	N	M	H	N	M	H		N	M	H	N	M	H	N	M	H		N	M	H	N	M	H	N	M	H	N	M	H	N	M	H
1			✓			✓			✓	✓						✓			✓	✓				✓			✓			✓			✓			✓			✓
2		✓				✓	✓			✓					✓			✓			✓				✓			✓			✓			✓			✓		
5			✓		✓				✓	✓						✓			✓	✓				✓			✓			✓	✓			✓					✓
7		✓			✓				✓	✓					✓			✓			✓			✓			✓			✓			✓			✓			
9		✓				✓			✓	✓						✓			✓	✓			✓			✓			✓	✓			✓			✓			
11		✓				✓			✓	✓						✓			✓	✓				✓			✓			✓	✓			✓				✓		

Note: red shaded cell indicates participant's Pre/Post Diagnostic Scores showed low gains; green shaded cell indicates participant's Pre/Post Diagnostic Scores showed high gains ✓ **= High Progression;** ✓ **= Moderate Progression;** ✓ **= No Progression**

Conversion of the qualitative progression designations for each sub-concept to quantitative values was done by assigning a "0" for "no progress", "1" for "medium progress", and "2" for "high progress" designations. These quantitative values were summed for each participant giving a coded utterances concept knowledge progression score. If a participant was to demonstrate a "high progress" designation for each of the sub-concepts, they would score a maximum concept knowledge progression score of 26 which is equivalent to having a "high progress" designation score of "2" for each of the 13 sub-concepts. Based on this maximum possible score, a percent concept knowledge progression score was calculated by dividing the participants sum of all sub-concept knowledge progression scores by the maximum possible score of 26 (Table 31).

Table 31

Coded Utterances of Concept Knowledge Progression Score

		Evaporation				Condensation			Rate of Cond		Area		Slope		Σ	%
Part.	Gain	A	B	C	D	A	B	C	A	B	A	B	A	B		
1	LG	1	2	2	0	2	2	0	2	2	2	2	2	2	21	81
2	MG	1	2	0	0	1	1	0	1	0	2	1	1	1	11	42
5	MG	2	1	2	0	2	2	0	1	0	2	0	0	2	14	54
7	MG	1	1	2	0	1	1	0	1	1	1	1	1	0	11	42
9	LG	1	2	2	0	2	2	0	0	1	1	0	0	0	11	42
11	LG	1	2	2	0	2	2	0	2	1	2	0	0	1	15	58
Column Sum		7	10	10	0	10	10	0	7	5	10	4	4	6		

LG = Participant's Pre/Post Diagnostic Scores Indicated Low Gains; MG = Participant's Pre/Post Diagnostic Scores Indicated Most Gains

A Pearson correlation analysis was conducted to determine the strength and direction of the relationship between percent concept knowledge progression score and post Knowledge Total Scores of the six purposefully selected participants. Correlation analysis (Table 32)

indicates a strong positive correlation between the percent concept knowledge progression score and the post Knowledge Total Scores.

Table 32

Correlation: Percent Concept Knowledge Progression and Post Knowledge Score

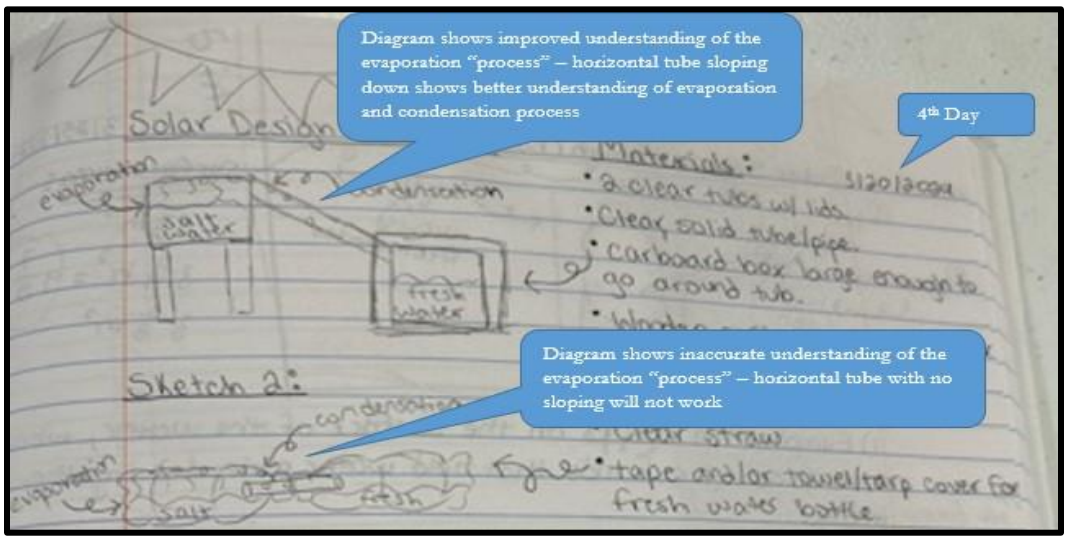
Variables	**n**	***r***	***p***
Percent Progression vs Post Knowledge Total	6	0.896	0.016

Post Intervention Science and Engineering Notebook Analysis

Science and Engineering Interactive Notebooks (SEINs) of all participants were thoroughly reviewed by the co-coders for corroborative evidence of progression toward concept knowledge acquisition previously indicated in the pre/post diagnostics (RQ1). All SEIN entries for each participant were copied. Dates of student SEIN entries as well as the design phase during which the entry was made were identified and labeled. Indications of science and mathematics sub-concept knowledge development were clearly noted and clarifying notes were made so as to provide interpretive detail, between researchers, for targeted design drawings or participant written statements (Figure 5). Indications of sub-concept knowledge attainment labels

Figure 5

Example of SEIN Co-Coder Entries



were then analyzed and summarized by coding them in one of seven possible ways (Table 33).

Table 33

Sub-Concept Knowledge Summary Codes

Sub-Concept Knowledge Summary Code	Summary Code Description
High	Participants provided evidence in their SEINs that indicated sub-concept knowledge changed from low understanding to consistently correct understanding over the course of the intervention.
Moderate	Participants provided evidence in their SEINs that indicated sub-concept knowledge changed from low understanding to some correct understanding over the course of the intervention.
No "A"	Participants provided evidence in their SEINs that indicated sub-concept knowledge did not change and that was always correct over the course of the intervention.
No "B"	Participants provided evidence in their SEINs that indicated sub-concept knowledge did not change and that was only partially correct over the course of the intervention.
No "C"	Participants provided evidence in their SEINs that indicated sub-concept knowledge did not change and that was always incorrect over the course of the intervention.
No "D"	Participants did not provided evidence in their SEINs of sub-concept knowledge change over the course of the intervention.
No "E"	Participants provided evidence in their SEINs that indicated sub-concept knowledge was correct during the research phase of the design but then reverted to just partially correct understanding during the remainder of the intervention.

Using the sub-concept knowledge summary codes presented in Table 35, all 13 SEINs were analyzed to assign codes for each math and science sub-concept observed. Total frequency counts and relative percentages were calculated for every math and science sub-concept coded for (Table 34).

Table 34

SEIN Notebook Concept Progression Analysis

	Frequency Count and Percentage of Progression Codes						
	High	**Moderate**	**No A**	**No B**	**No C**	**No D**	**No E**
Sub-Concepts	*f* (%)	*f* (%)	*f* (%)	*f* (%)	*f* (%)	*f* (%)	*f* (%)
Science							
Evaporation							
Evap-A	7 (54)	2 (15)		2 (15)			2 (15)
Evap- B	10 (77)		3 (23)				
Evap-C	8 (61)		2 (15)	1 (7)			2 (15)
Evap-D						13 (100)	
Condensation							
Cond-A	3 (23)	1 (8)	2 (15)	2 (15)			5 (38)
Cond-B	5 (38)		6 (46)	1 (8)		1 (7)	
Cond-C						11 (85)	2 (15)
Math							
Rate of Condensation							
RateCond-A	3 (23)		7 (54)			3 (23)	
RateCond-B	1 (8)		8 (62)			4 (31)	
Area							
Area- A	1 (8)		5 (38)	2 (15)		5 (38)	
Area-B			1 (8)	2 (15)	1 (8)	9 (69)	
Slope							
Slope-A			9 (69)	1 (8)		3 (23)	
Slope-B			9 (69)	1 (8)		3 (23)	

High = High Progression (low to correct rating); Moderate = Moderate Progression (Incorrect to Some rating); No A = all Correct ratings; No B = all Some ratings; No C = all Incorrect ratings; No D = no ratings; No E = all Some ratings except for Correct rating in the research phase of design; *f* = frequency count; (%) = percent participants out of 13

Participants' SEIN analyses indicated that High concept progression for evaporation sub-concepts A, B, and C occurred as a result of participation in the T/E DBL intervention for 54%, 77% and 61%, respectively, of participants. The participants in the complements of each of the above percentages provided SEIN evidence of ***understanding*** evaporation sub-concepts A, B, and C that was ***always correct*** over the course of the intervention or showed evidence of ***understanding that did not change*** over the course of the intervention and was partially correct. Evidence of participant understanding of condensation sub-concepts A and B indicated that

nearly equal percentages of participants made High and Moderate progression as compared to those who provided evidence of understanding that was ***always correct*** or ***partially correct with no change*** over the course of the intervention. Interestingly, very high percentages of participants, 100% and 85% respectively, ***did not provide SEIN evidence of understanding*** of evaporation sub-concept D or condensation sub-concept C over the course of the intervention. Evidence, provided in SEINs, indicated ***understanding*** of rate of condensation sub-concepts A and B that were either ***High or were correct and did not change*** over the course of the intervention for 77% and 70% of participants, respectively. Evidence from SEINs also indicated that slope sub-concepts A and B that was ***always correct*** and ***did not change*** over the course of the intervention occurred for 69% of participants for each sub-concept. Participants within the compliments of the above percentages did ***not provide evidence of understanding*** of these concepts. Evidence provided in SEINs indicated ***all correct or partially correct understanding*** of area sub-concept A that was ***unchanged*** over the course of the intervention for 38% and 15% of participants, respectively. Approximately 38% of participants ***did not provide evidence*** of area sub-concept A understanding. ***No evidence of understanding*** of area sub-concept B was indicated for 69% of the participants. The remaining 31% of participants provided evidence that indicated ***all correct or partially correct understanding*** of area sub-concept B and that was unchanged over the course of the intervention.

Research Question 2: Impactful T/E DBL Design Experiences

Answering Research Question 2 (RQ2), which involved the investigation of what T/E DBL experiences did participants indicate promoted their acquisition of the targeted complex science and mathematics concepts, required the examination of the Tier-4 (*T4*) post (FTMC)

diagnostic instrument question, post intervention interview responses, and SEIN design phase analysis. A discussion of the findings is provided below.

Post Diagnostic Tier Four Design Experiences Analysis

Post FTMC diagnostic *T4* item responses were organized according to what concept (evaporation, condensation, rate of condensation, area of irregular shapes, and slope and rate of change) they targeted. Qualitative responses for each item were then matched with the corresponding design phase based on intervention daily activity log notes kept by the researcher. For example, Participant 1 responded to Item 1 (evaporation), *T4*, which asked the participant to indicate during which phase of the T/E DBL design process did they perceive their concept knowledge changed, in the following way:

"I feel as if the day we did all of the background, we truly went into detail about all of evaporation and condensation"

This response was crossed referenced with the researcher's intervention daily activity log notes which matched most closely with the Research design phase of the intervention. Another example of this was the response of Participant 2 to Item 3 (area of irregular shape) *T4* which was as follows:

"I really learned more about this when we did the effective condensation area. I used paper towels to measure mine because it was easier to get length and width"

Again, this response matched most closely with the Solution Evaluation 1 design phase of the intervention based on a review of the researcher's intervention daily activity log notes. The indicated "impactful design phases" for each concept were summed across all participants for each concept. A total for each design phase was then summed for each concept. Each table (Tables 35-39) summarizes one concept which were comprised of several sub-concepts.

Table 35

Summary of Impactful Design Phases in Tier 4 Items Related to Evaporation

	Number of Participants Responding						
Design Phases	**Item 1 Evap A**	**Item 7 Evap A**	**Item 19 Evap B**	**Item 14 Evap C**	**Item 21 Evap C**	**Item 13 Evap D**	**Totals**
Problem ID	0	0	0	0	0	0	0
Ideation	0	2*	0	0	0	0	2
Research	3	6	1	1	0	0	11
Potential Solutions	1	0	4	3	0	2	10
Optimization	1	0	0	0	0	1	2
Solution Evaluation 1	5	2	0	0	2	1	10
Alterations	0	0	1	1	0	1	3
Solution Evaluation 2	0	0	2	5	7	0	14
Indeterminate	3	3	5	3	4	8	26

* = two participants indicated that the Ideation design phase was most impactful to their Evaporation A concept understanding

Table 36

Summary of Impactful Design Phases in Tier 4 Items Related to Condensation

	Number of Participants Responding				
Design Phases	**Item 2 Cond A**	**Item 8 Cond B**	**Item 15 Cond B**	**Item 20 Cond C**	**Totals**
Problem ID	0	0	0	0	0
Ideation	0	0	0	0	0
Research	2*	6	2	0	10
Potential Solutions	1	1	3	1	6
Optimization	0	1	0	0	1
Solution Evaluation 1	4	1	4	5	14
Alterations	1	0	0	1	2
Solution Evaluation 2	0	2	0	0	2
Indeterminate	5	2	4	6	17

* = two participants indicated that the Research design phase was most impactful to their Condensation A concept understanding

Table 37

Impactful Design Phases Indicated in Tier 4 Items Related to Rate of Condensation

	Number of Participants Responding			
Design Phases	**Item 22 RateCond A**	**Item 5 RateCond B**	**Item 11 RateCond B**	**Totals**
Problem ID	0	0	0	0
Ideation	0	0	0	0
Research	1*	0	0	1
Potential Solutions	1	0	0	1
Optimization	0	0	0	0
Solution Evaluation 1	5	0	1	6
Alterations	1	0	0	1
Solution Evaluation 2	1	12	10	23
Indeterminate	4	1	2	7

* = one participant indicated that the Research design phase was most impactful to their Rate of Condensation A concept understanding

Table 38

Impactful Design Phases Indicated in Tier 4 Items Related to Area

	Number of Participants Responding								
	Item #/Area								
Design Phases	**#3/A**	**#9/A**	**#10/A**	**#16/A**	**#4/B**	**#17/B**	**#23/B**	**#24/B**	**Totals**
Problem ID	0	0	0	0	0	0	0	0	0
Ideation	0	0	0	0	0	0	0	0	0
Research	0	0	0	0	0	0	0	0	0
Potential Solutions	0	0	0	0	0	0	0	0	0
Optimization	0	0	0	0	0	0	0	0	0
Solution Eval 1	5*	12	11	7	5	11	11	8	70
Alterations	0	0	0	0	0	0	0	0	0
Solution Eval 2	0	0	0	1	0	0	0	1	2
Indeterminate	0	1	2	5	0	2	2	4	16

* = five participants indicated that the Solution Evaluation 1 design phase was most impactful to their Area A concept understanding

Table 39

Impactful Design Phases in Tier 4 Items Related to Slope and Rate of Change

	Number of Participants Responding				
Design Phases	**Item 18 Slope A**	**Item 6 Slope B**	**Item 12 Slope B**	**Item 25 Slope B**	**Totals**
Problem ID	0	0	0	0	0
Ideation	0	0	0	0	0
Research	1*	0	0	0	1
Potential Solutions	0	0	0	0	0
Optimization	0	0	0	0	0
Solution Evaluation 1	2	1	0	4	7
Alterations	0	0	0	0	0
Solution Evaluation 2	7	9	11	5	32
Indeterminate	3	3	2	4	12

* = one participant indicated that the Research design phase was most impactful to their Slope and Rate of Change A concept understanding

A summary of the above results indicates that the four most referenced impactful design phases were Solution Evaluation 1, Solution Evaluation 2, Research, and Potential Solutions. A summary of this finding is presented in Table 40 below.

Table 40

Impactful Design Phase Reference Summary

Science or Mathematics Concept	Impactful Design Phase References
Evaporation	Research – 11 references across 6 items Potential Solutions – 10 references across 6 items Solution Evaluation 1- 10 references across 6 items Solution Evaluation 2 – 14 references across 6 items
Condensation	Research – 10 references across 4 items Potential Solutions – 6 references across 4 items Solution Evaluation 1- 14 references across 4 items
Rate of Condensation	Solution Evaluation 1- 6 references across 3 items Solution Evaluation 2 - 23 references across 3 items
Area	Solution Evaluation 1- 70 references across 8 items
Slope	Solution Evaluation 1- 7 references across 4 items Solution Evaluation 2- 32 references across 4 items

Post Intervention Interview Design Experience Analysis

Transcribed interviews of the six purposefully selected participants were thoroughly reviewed by the researcher and co-researcher for evidence of "impactful design phase" experiences that aided participants in concept knowledge acquisition (RQ2). During the post intervention interviews participants were asked about what experiences during the intervention were most impactful in helping them understand each of the five targeted science and mathematics concepts (evaporation, condensation, rate of condensation, area of irregular shapes, and slope and rate of change). Participant phrases and sentences indicating "impactful design phase" experiences were identified and them matched with a specific design phase based on a review of the researcher's intervention daily activity log notes. Successive rounds of arbitration were conducted between the researchers until consensus agreement of indicated design phases was reached. Design phases were coded with a "1" if a participant indicated that the design phase was impactful in helping them understand a particular concept or a "0" if there was no participant indication that it was helpful in concept knowledge development. Frequency counts of indicated "impactful design phases" were made for each targeted concept. Table 41 summarizes the results of "impactful design phases" indicated by the six purposefully selected participants in post intervention interviews. Results of this analysis indicate that the solution evaluation 1, alteration, and solution evaluation 2 design phases were most impactful on their understanding of the 5 science and mathematics concepts.

Table 41

Summary Interview Evidence of Impactful Design Phases

	Number of Participants Responding							
	Problem Identification	Ideation	Research	Potential Solutions	Optimization	Solution Evaluation 1	Alteration	Learning Outcomes Solution Evaluation 2
Evaporation	0	0	5	1	1	11	5	0
Condensation	0	0	0	4	0	8	10	0
Rate of Condensation	0	0	0	0	0	9	1	8
Area of Irregular Shapes	0	0	0	1	2	8	6	1
Slope and Rate of change	0	0	0	0	1	4	2	9
Σ =	0	0	5	6	4	40	24	18

Note = participants indicating phase of design most impactful on concept understanding.

Science and Engineering Notebook Design Experience Analysis

All participants' SEINs were thoroughly reviewed by the co-coders for evidence such as sketches, notes, labels, calculations, and tabulated data, indicating that they were actively engaged with the targeted concepts/sub-concepts. The co-coders had previously labeled each page of participants' SEINs with the appropriate design phases by matching indicated dates and presented activities with the researcher's intervention daily activity log notes. These labels allowed evidence of progression toward concept knowledge acquisition, which was previously discussed in the above Post Intervention Science and Engineering Notebook Analysis section, to be directly attributed to specific design phases. In order to consider these design phases as being *impactful* to concept knowledge development, only evidence of high, moderate, and No A progression towards concept attainment were examined. As a reminder, No A progression referred to those incidences where individuals provided evidence of correct concept understanding from the very start of the intervention and consistently demonstrated correct

understanding throughout the intervention. Table 42 shows a summary of relative frequencies of impactful design phases from the SEIN analysis. Results indicate that Research, Potential Solution, and Optimization design phases were most impactful on evaporation and condensation concept knowledge development, and that the Solution Evaluation 2 design phase was most impactful on rate of condensation, area, and slope concept knowledge development.

Table 42

SEIN Analysis Impactful Design Phase Evidence

	Phases of Design						
Concepts	**Ideation**	**Research**	**Potential Solution**	**Optimization**	**Solution Eval 1**	**Alterations**	**Solution Eval 2**
Evap A	0%	**23%**	**8%**	**39%**	0%	0%	0%
Evap B	0%	**63%**	**23%**	0%	0%	**8%**	0%
Evap C	0%	**53%**	**8%**	**8%**	0%	**8%**	0%
Evap D	0%	0%	0%	0%	0%	0%	0%
Cond A	**8%**	**23%**	0%	8%	0%	**8%**	**8%**
Cond B	0%	0%	0%	0%	0%	0%	0%
Cond C	0%	0%	0%	0%	0%	0%	0%
RateCond A	0%	0%	0%	0%	**8%**	0%	**77%**
RateCond B	0%	0%	0%	0%	**8%**	0%	**62%**
Area A	0%	0%	0%	0%	0%	0%	**46%**
Area B	0%	0%	0%	0%	0%	0%	**8%**
Slope A	0%	0%	0%	0%	0%	0%	**62%**
Slope B	0%	0%	0%	0%	0%	0%	**8%**

% = Percentage of participants providing evidence of High, Moderate, or "No A" Progression during a given phase of design. "No A" = all evidence of concept knowledge was correct from the start of the intervention.

CHAPTER FIVE: CONCLUSIONS, IMPLICATIONS, AND RECOMMENDATIONS

The purpose of this study was to document concept knowledge progressions of targeted science and mathematics concept among preservice elementary teachers who engaged in a technological/engineering design based learning (T/E DBL) challenge, and to identify those phases of design they perceived most influenced that progression. In this chapter, conclusions based on results of data analysis are discussed and organized by research questions (RQ1 and RQ2 respectively) followed by an overarching conclusion regarding both RQs. Derived from those conclusions are implications, followed by limitations, and recommendations for future study.

Conclusions

Research Question 1 (RQ1): Science and Mathematics Knowledge Progression

When preservice elementary teachers engage in a T/E DBL challenge:

RQ1 – What evidence demonstrates such engagement promotes their knowledge progression towards acquisition of targeted complex science and mathematics concepts compatible with accepted scientific views?

Pre/Post T1 Item Responses

The overall progression towards concept acquisition was measured through analysis of pre/post *T1* Item responses which indicated a statistically significant improvement in *T1 Total Scores* reflecting concept progression. Data presented in Table 14 (p. 91) indicate that participants achieved an average score of 18.68 (out of 25 possible points) on Post *T1Total Scores* as compared to an average score of 14.85 on Pre *T1 Total Scores*. This result was statistically significant at a *t*-value of 4.36 and $p<0.001$. The calculated effect size (Cohen's d) of 1.21 indicates a large effect size which implies practical significance. Given these findings, the

conclusion drawn is that, following engagement in the T/E design challenge, preservice teacher participants progressed in their understanding of the targeted science and mathematics concepts.

Corroborating Evidence of Concept Knowledge Progression

Corroborating evidence of concept knowledge progression included results from the analysis of pre/post *Item Success (IS) scores, Mean Instrument Success (MInst-S) scores, Tier1&2 Alignment Score (T1&2-A), Tier 1&2 Total Score (T1&2-Total), Certainty Scores* (*C*), *Certainty Total Scores (C-total), Knowledge Score (K), and Knowledge Total Score (K-Total).* The following sub-sections provide the conclusions per analysis for each of these variables.

Pre and Post Item Success Scores

As shown in Table 15 (p.92), the majority of test items (19 out of 25, 76%) showed increases in correct responses from pre to post diagnostic testing, related to evaporation, condensation, rate of condensate production per unit area, area of irregular shapes, and slope and rate of change. The conclusion drawn is that participants, following engagement in a T/E design challenge, do improve in their ability to correctly respond to targeted concept item questions.

Six items (24%) showed either no change in correct responses or a decrease in correct responses. Two of the six items showing no change in correct response were items related to the concepts of heat of evaporation and rate of change. Four of the six items showed a decrease in correct responses from pre to post. These items were related to area (2 items), heat of combustion, and rate of condensation per unit area. This result indicates that while the majority of evidence indicates that progression of concept knowledge does occur for preservice elementary teachers who engage in T/E DBL experiences there still can be instructional design weaknesses that can result in calculation errors or allow participants to retain alternate conceptions.

Pre/Post Mean Instrument Success Scores

The *Mean Instrument Success* (*MInst-S*) score was determined by calculating the mean of the *IS* scores. Analysis of pre and post *MInst-S* scores following intervention engagement provided further evidence of participant concept knowledge progression. As shown in Table 18 (p.93), the **Wilcoxon Signed Rank Test revealed a statistically significant difference between pre and post *MInst-S* scores (Post *MInst-S* = 9.72, Pre *MInst-S* = 7.71, z=-3.18, p<0.001). This increase in *MInst-S* is evidence indicative of participant progression towards science and math concept knowledge attainment and both aligns with and supports the** results of the pre/post *T1* Item responses. The conclusion drawn is that participants, following engagement in a T/E design challenge, do improve in their ability to correctly respond to targeted concept item questions.

Tier1&2 Alignment Total Scores

Tier1&2 Alignment scores *(T1&2-A)* for each test item provided a measure of how well a participant knew (a) the concepts addressed by a given item and (b) the reasoning behind them when both *T1* and *T2* were answered correctly. A *Tier 1&2 Total Score* (*T1&2-Total*) was then calculated by summing all of the *T1&2-A* scores for each item per participant. This was done for both pre and post diagnostic assessments and provided a measure of concept knowledge development that was more reliable than simple *T1* and *T1-Total* scores alone, which could be a result of guessing. Analysis of the pre and post *T1&2-Total* Scores matched 2-tailed paired *t*-test (Table 22, p.95) indicates that the difference between the means for the post *T1&2-Total* Score (15.46) and the pre *T1&2-Total* Score (10.54) was statistically significant (t=4.82, p<0.001). Furthermore, the practical strength of the mean differences is substantiated by the large Cohen's d effect size of 1.34. This evidence further substantiates overall participant progression towards

concept knowledge attainment after engagement in T/E DBL, which both aligns with and supports the results of the pre/post *T1* Item responses. The conclusion drawn is that participants, following engagement in a T/E design challenge, do improve in their ability to correctly respond to targeted concept item questions and to correctly indicate the reasoning behind their answers.

Certainty Scores

Instances where participants were sure about their correct understanding of concepts were identified using Tier 3 (*T3*) pre and post responses. This was done through the calculation of *Certainty Scores (C)*, and *Certainty Total Score (C-Total).* Item certainty scores for each item were summed to provide the *C-total* score for each participant which provided a measure of participant confidence in their *T1* and *T2* responses. Results from the pre and post *C-Total* Scores matched paired *t*-test (Table 25, p. 97) indicate that the post *C-Total* Score mean (17.46) was significantly greater than the pre *C-Total* Score mean (8.62) with a t-value =5.43 and $p<0.001$. Furthermore, the practical strength of the mean differences is substantiated by the large Cohen's d effect size of 1.51. This evidence supported the expectation that *C* and *C-Total* Scores would increase in response to engagement in the intervention if T/E DBL supported science and mathematics concept knowledge attainment. It also aligns with and supports the results of the pre/post *T1* Item responses. The conclusion drawn is that participants, following engagement in a T/E design challenge, become more confident in their answers to targeted concept item questions.

Knowledge Scores

When a participant correctly responded to and item's *T1* and *T2*, as well as responding that they were "certain" in *T3*, it produced a *Knowledge Score* (K) that was indicative of a participant that correctly and confidently understands the targeted science or mathematics

concept. The *Knowledge Total Score* (*K-Total*) was then produced by summing the *K* score for all items for each participant. Results from the pre and post *K-Total* Scores matched paired *t*-test (Table 28, p.99) indicated that the difference between the post *K-Total* Score mean (12.39) and the pre *K-Total* Score mean (5.39) was statistically significant ($t=7.39$, $p<0.001$). Furthermore, the practical strength of the mean differences is substantiated by the large Cohen's d effect size of 2.05. These results should be considered as evidence demonstrating progression of accurate and confident acquisition of the assessed science and mathematics concepts due to engagement in T/E DBL and aligns with and supports the results of the pre/post *T1* Item responses. The conclusion drawn is that participants, following engagement in a T/E design challenge, do improve in their ability to correctly respond to targeted concept item questions, correctly indicate the reasoning behind their answers, and become more confident in their answers.

Post Intervention Interview Analysis

Transcribed interviews of the six purposefully selected participants were analyzed by co-coders. Using *a priori* codes, phrases and sentences were analyzed to identify instances of accurate (or inaccurate) concept knowledge of the targeted science and mathematics concepts. These *a priori* codes facilitated organization of evidence statements into meaningful groupings that could be combined into emergent themes related to the targeted science and mathematics concepts.

Once selection of relevant evidence statements, interpretations, and coding had concluded, the co-coders conducted an analysis of concept knowledge progression for all sub-concepts for each participant. As shown in the summary of coded utterances concept knowledge progression analysis (Table 30, p.101), the majority of the six participants interviewed provided evidence of moderate to high progression for sub-concepts; Evap-A, Evap-B, Evap-C, Cond-A,

Cond-B, RateCond-A, RateCond-B, Area-A, and Slope-B. Only three of the six participants interviewed provided evidence of moderate to high knowledge progression for sub-concepts Area-B and Slope-A. The remaining three participants provided no evidence of progression for sub-concepts Area-B and Slope A. Notably, no participants provided evidence of knowledge progression for sub-concepts Evap-D and Cond-C.

The Pearson correlation analysis conducted to determine the strength and direction of the relationship between percent concept knowledge progression score and post Knowledge Total Scores of the six purposefully selected participants indicated a strong positive correlation ($r=0.896$, $p=0.016$) (Table 32, p.103). This serves to corroborate the findings of the TTMC and FTMC diagnostic test analyses as well as serving as another piece of evidence of concept knowledge progression in preservice teachers due to engagement in T/E DBL.

In the case of sub-concepts Evap-D and Cond-C, where the analysis of all participants' responses showed no progression, no interview questions specifically inquired about rate of evaporation per unit area or the rate of condensation per unit area. Hence, there was no available evidence to determine concept knowledge levels for these sub-concepts.

The conclusion drawn from the above results is that the majority of the six participants interviewed, following engagement in a T/E design challenge, provided evidence of moderate to high progression for the majority of sub-concepts. This aligns with and supports the findings of the TTMC and FTMC diagnostic test analyses discussed above indicating that participants, following engagement in a T/E design challenge, do improve in their ability to correctly respond to targeted concept item questions.

Post Intervention Science and Engineering Notebook Analysis

Science and Engineering Interactive Notebooks (SEINs) of all participants were thoroughly reviewed by the co-coders for corroborative evidence of progression toward concept knowledge acquisition. Indications of science and mathematics sub-concept knowledge development were clearly noted within targeted design drawings or participant written statements. Indications of sub-concept knowledge attainment labels were then analyzed and summarized by coding them in one of seven possible ways (Table 35). Using those sub-concept knowledge summary codes, all 13 SEINs were analyzed to assign codes for each math and science sub-concept observed. Total frequency counts and relative percentages were calculated for every math and science sub-concept that was coded (Table 36). Analysis of the frequency counts and relative percentages indicated participants' progressions of understanding fell into three main categories; moderate to high progression, all correct with no progression of understanding, or no evidence of concept knowledge progression over the course of the intervention.

The majority of participants made moderated to high concept progression for evaporation (sub-concepts A, B, and C), and condensation (sub-concepts A and B). This was possible because participants encountered these overarching concepts at every stage of the intervention affording participants ample opportunities to record progressive concept related evidence within their SEINs.

The majority of participants provided SEIN evidence for the targeted concept of rate of condensation per unit area that indicated either high progression of understanding or they provided correct rate of condensation per unit area understanding with an initial SEIN entry but provided no further evidence of progression of understanding throughout the remaining SEIN

entries. While participants encountered this concept on multiple occasions, they only performed the related calculations on one day of the intervention. If participants were not diligent in their note taking, SEIN notes related to this concept would only appear once and therefore no *progression* of understanding could be determined.

The majority of participants provided SEIN evidence for the targeted concepts of area, and slope that indicated all entries were correct but did not show progression of understanding. These finding may reflect that participants took notes in their SEINs related to these concepts on one day that involved whole class discussion and volunteer group explanations of their calculation approaches. This occurred on the last day of the of intervention and therefore there were no other opportunities for the participants to provide evidence of concept knowledge progression

Interestingly, evidence reflecting understanding of evaporation sub-concept D (rate dependent on temperature) or condensation sub-concept C (rate within a closed system reaches and equilibrium) over the course of the intervention was lacking in the majority of participant SEIN entries, 100% and 85% respectively. Instances where participants provided no evidence of sub-concept progression within their SEIN entries may be attributed to the SEIN entries being minimally prompted by the instructor. Participants were simply instructed to make notes and sketches of their designs and design thinking throughout the intervention. Lack of evidence of knowledge progression for these sub-concepts may be attributed the free flow of student entries that were not adequately prompted.

Based on findings from SEIN analysis, the conclusion reached is that the majority of participants provided moderate to high progression toward conceptual understanding, or evidenced correct and unchanged understanding over the course of the intervention. This

corroborates TTMC and FTMC test analysis findings and further evidences preservice teachers progress towards concept knowledge attainment following engagement in T/E design based learning.

RQ1 Summary Conclusion

Research Question 1 (RQ1) asks what evidence demonstrates that engagement in T/E DBL challenges promotes knowledge progression towards acquisition of targeted science and mathematics concepts. Analyses of all data sources (pre and post comparison of TTMC and FTMC diagnostic tests, semi-structured interviews, and SEIN analyses) provided evidence of preservice teacher progression toward acquisition of targeted complex science and mathematics concepts compatible with accepted scientific views. The sub conclusions drawn based on analysis of these data sources are:

Pre/Post T1 Item Responses – following engagement in the T/E design challenge, preservice teacher participants progressed in their understanding of the targeted science and mathematics concepts.

Pre/Post Item Success Scores – The conclusion drawn is that participants, following engagement in a T/E design challenge, do improve in their ability to correctly respond to targeted concept item questions.

Pre/Post Mean Instrument Success Scores – The conclusion drawn is that participants, following engagement in a T/E design challenge, do improve in their ability to correctly respond to targeted concept item questions.

Tier 1&2 Alignment Total Scores – The conclusion drawn is that participants, following engagement in a T/E design challenge, do improve in their ability to correctly respond to

targeted concept item questions and to correctly indicate the reasoning behind their answers.

Certainty Scores – The conclusion drawn is that participants, following engagement in a T/E design challenge, become more confident in their answers to targeted concept item questions.

Knowledge Scores – The conclusion drawn is that participants, following engagement in a T/E design challenge, do improve in their ability to correctly respond to targeted concept item questions, correctly indicate the reasoning behind their answers, and become more confident in their answers.

Post Intervention Interview Analysis – The conclusion drawn from the above results is that the majority of the six participants interviewed, following engagement in a T/E design challenge, provided evidence of moderate to high progression for the majority of sub-concepts.

Post Intervention Science and Engineering Notebook Analysis – Based on findings from SEIN analysis, the conclusion reached is that the majority of participants provided evidence of moderate to high progression toward conceptual understanding, or evidenced correct and unchanged understanding over the course of the intervention.

Given the sub conclusions derived from various data analyses, both quantitative and qualitative, the overall conclusion drawn is that engagement of preservice elementary teachers in T/E DBL challenges will promote their knowledge progression towards acquisition of the targeted science and mathematics concepts.

Research Question 2: Impactful T/E DBL Design Experiences

When preservice elementary teachers engaged in a T/E DBL challenge:

RQ2 – What T/E DBL experiences do they indicate promoted their acquisition of the targeted complex science and mathematics concepts?

Answering RQ2 required an examination of Tier-4 (*T4*) post (FTMC) diagnostic instrument question, post intervention interview responses, and SEIN design phase analysis. Conclusions drawn based on findings from each data source are provided in the following sections.

Post Diagnostic Tier Four Design Experiences Analysis

Post FTMC diagnostic *T4* item responses asked the participant to indicate during which phase of the T/E DBL design process did they perceive their concept knowledge changed. Participant responses to *T4* items were organized by concept and were then matched with the corresponding design phase participants engaged in as part of the sequence of instruction throughout the intervention. The indicated "impactful design phases" for each concept were summed across all participants for each concept. A total for each design phase was then summed for each concept.

Based on FTMC *T4* item responses for each concept, from all participants as shown in Tables 37-41 and summarized in Table 42, the most cited *impactful design phases* were Solution Evaluation 1, Solution Evaluation 2, Research, and Potential Solutions.

Analysis of *T4* item responses indicated that participants felt the ***Solution Evaluation 1 and Solution Evaluation 2*** phases of design had the most impact on their development of concept knowledge. During these two design phases participants engaged in evaluations of group results, gallery walks viewing designs from other groups, whole class discussions, and participant discussions of measurements and calculations. As a result, participant experiences included observations of what worked and/or needed to be redesigned, and comparing design

features to more efficient examples or features reflecting newly acquired concept knowledge. As discussed in Chapter 3, design phases, such as ***Solution Evaluation***, can be thought of as a "recourse to an ultimate criterion" which refers to category formation that will be tested in a way that provides evidence that the category was correctly formed or not. It also afforded the participants the opportunity of detecting attributes of exemplars and non-exemplars of the targeted concepts crucial to concept knowledge development (Bruner et al., 1956).

Participants also indicated that the ***Research*** and ***Potential Solutions*** phases of design were impactful in helping them develop concept knowledge. During these phases, participants engage in gathering information about concepts not yet well understood and with reconciling their newly acquired conceptual understandings in the context of applied design challenge realities. These two early phases of design, where concept characterization is initiated, are instrumental in preparing participants for concept validation opportunities presented during the Solution Evaluation phase. This is a good example of theory to practice where learners test their categorization rules immediately after categorization has occurred, and if validation results are clear, then concept attainment is positively affected (Bruner et al., 1956).

From this analysis, one can conclude that there are two early phases of design (***Research*** and ***Potential Solutions***) and two later phases of design (***Solution Evaluation 1 and Solution Evaluation 2***) that have the greatest impact on promoting the abilities of preservice teachers to acquire the targeted complex science and mathematics concepts.

Post Intervention Interview Design Experience Analysis

Transcribed interviews of the six purposefully selected participants were analyzed for evidence of *impactful design phase* experiences aiding their acquisition of targeted concept knowledge (RQ2). Frequency counts of indicated "impactful design phases" were made for each

targeted concept. Table 43 summarizes the results of "impactful design phases" indicated by the six purposefully selected participants in post intervention interviews. Findings from interview analyses (Table 43) indicate that three specific phases of design, ***Solution Evaluation 1***, ***Alteration***, and ***Solution Evaluation 2***, were those having the greatest impact on the ability of participants to understand the targeted science and mathematics concepts. Moreover, these results corroborate findings from the analysis of FTMC *T4* responses. In light of these findings, one can conclude that there are three key phases of design (***Solution Evaluation 1***, ***Alterations,*** and ***Solution Evaluation 2***) during which student experiences will promote their acquisition of the targeted complex science and mathematics concepts. Furthermore, the common theme between FTMC T4 and interview responses is that the ***Solution Evaluation 1 and Solution Evaluation 2*** phases of design provide experiences that most directly promote learner acquisition of targeted complex science and mathematics concepts.

Post Intervention Science and Engineering Notebook Analysis

Content analysis of participant SEINs resulted in coded segments, sketches, calculations, etc. providing multiple sources for evidence of progressions toward concept knowledge acquisition attributable to any given phase of design. Assessment of design phases for evidence of being ***impactful*** with respect to concept knowledge development, was correlated with three categories of progression toward concept attainment: high progression, moderate progression, and No A progression (consistent correct concept understanding). Results (Table 44) indicate there are three key phases of design (***Research, Potential Solution,*** and ***Optimization****)* that most impact student progression toward development of evaporation and condensation concept knowledge, and that one other phase of design (***Solution Evaluation 2****)* found most impactful on rate of condensation, area, and slope concept knowledge development. These findings lead to the

conclusion that the experiences student have throughout all phases of design differ in the extent to which they promote progression toward acquisition of concept knowledge, and the phases of design found most effective in doing so are ***Research, Potential Solutions,*** and ***Solution Evaluation 2***. It is of note that the conclusion reached regarding impactful phases of design based on analysis of student notebooks (SEIN) differs from the conclusion reached based on analysis of participant interviews. Specifically, the content analysis of student notebooks did not find the ***Solution Evaluation 1*** phase of design impactful, which contradicts the participant interview conclusion. This difference in conclusions is likely due to the absence of prompts given during instruction encouraging students to include entries in their notebooks about impactful phases of design.

RQ2 Summary Conclusion

Research Question 2 (RQ2) asks what T/E DBL experiences do the participants indicate promotes their acquisition of the targeted science and mathematics concepts. Analyses of all data sources (FTMC *T4* items, semi-structured interviews, and science and engineering interactive notebooks (SEIN) provided evidence regarding the connection between preservice teacher T/E DBL experiences and the promotion of knowledge acquisition for the targeted complex science and mathematics concepts. The conclusions drawn based on analysis of these data sources are:

Post Diagnostic Tier Four Design Experiences Analysis - there are two early phases of design (*Research* and *Potential Solutions*) and two later phases of design (*Solution Evaluation 1 and Solution Evaluation 2*) that have the greatest impact on promoting the abilities of preservice teachers to acquire the targeted complex science and mathematics concepts.

Post Intervention Interview Design Experience Analysis - there are three key phases of design (*Solution Evaluation 1, Alterations,* and *Solution Evaluation 2*) during which student experiences will promote their acquisition of the targeted complex science and mathematics concepts.

Post Intervention Science and Engineering Notebook Analysis - the experiences student have throughout all phases of design differ in the extent to which they promote progression toward acquisition of concept knowledge, and the phases of design found most effective in doing so are *Research, Potential Solutions,* and *Solution Evaluation 2*.

Based on the collective findings, the conclusion is that *Research, Potential Solutions, Solution Evaluation 1 and Solution Evaluation 2* are the four most impactful phases of design for promotion of conceptual understanding**.**

Implications

The rationale for this study was predicated on the supposition that if preservice teachers were given the opportunity to experience concepts in tangible ways within an I-STEM ED T/E DBL environment (theory to practice), the potential existed for the promotion of science and mathematics concept knowledge. Furthermore, should this pedagogical approach prove to be effective in teaching science and mathematics concept knowledge to preservice teachers, the result would be educators with the capacity to correctly teach the targeted concepts in an integrative way. This rationale was the premise for the research questions driving this study. As such, the implications derived from the research conducted relate specifically to the preparation of pre-service teachers using an Integrative STEM Education Technological and Engineering Design Based Learning (I-STEM ED T/E DBL) pedagogical approach. The following sub-sections describe the implications based on the conclusions drawn.

Implications for Teacher Preparation

As stated previously in Chapter 1, studies have shown that elementary teachers (and hence, pre-service elementary teachers) lack a thorough understanding of science and mathematics concepts and that more experience with the common properties of these theoretical concepts, in various contexts, may help conceptual understanding (C. J. Kruger et al., 1990; Bleicher, 2006; Rollnick & Rutherford, 1990, Koski, 2014, Seaman & Szydlik, 2007). Based on the conclusions to RQ1, it is evident that preservice elementary teachers who engaged in a T/E DBL challenge do progress in their understanding of the targeted science and mathematics concepts. Therefore, T/E DBL pedagogies could help develop stronger science and mathematics concept knowledge within pre-service elementary teachers by affording them opportunities to experience, rather than solely discuss, in a theoretical manner, complex science and mathematics concepts. The results from this study supports the assertions that the presence of authentic problems, the critical need for understanding of targeted concepts, chances to view critical details of exemplars and no-exemplars of practically applied concepts, and immediate validation of concept category assignments all make T/E DBL challenges a rich learning environment (Bruner et al., 1956, Yamauchi & Markman, 2000). One that is likely to strengthen concept knowledge development. Multiple studies have also shown that elementary teachers lack confidence in their understanding of basic facts and scientific ideas such as the properties of matter, differences between chemical and physical changes and the particulate nature of matter (Bulunuz & Jarrett, 2010; Cox & Carpenter, 1989; Kruse et al., 2020; Tuttle et al., 2016). Results from this study support the argument that engagement in T/E DBL increases pre-service elementary teacher's confidence in their understanding of complex science and mathematics concepts.

In addition, since engagement in T/E DBL was found to be effective in teaching science and mathematics concept knowledge to preservice teachers it can be implied that they will have a greater chance of being able to, not only, correctly teach these concepts to their future students but they will also be able to teach the concepts in an integrative way due to their experience and familiarity with the T/E DBL pedagogical approach.

Teaching and Learning Implications

The development and implementation of the TTMC and FTMC diagnostic tests to measure concept knowledge progression during this study was a significant step towards establishing an effective and reliable method for measuring student science and mathematics concept knowledge progression as a result of engagement in T/E DBL. As described in Chapter 3, the tiered multiple choice diagnostics instruments, developed for this research, were modelled after those used in prior studies for assessing the science and mathematics concept knowledge of high school students, undergraduate science students, and preservice teachers (Arslan et al., 2012; Aydeniz et al., 2017; Canpolat, 2006; Chang, 1999; Coştu et al., 2012; Gopal et al., 2004; Kirbulut & Geban, 2014). This provided a measure of construct validity in that the above authors and current researchers agreed that this type of assessment was capable of measuring the theoretical constructs (science and mathematics concepts). In addition, content validity was established through the employment of the expert panel during instrument development. Twenty-five items were created that adequately covered the science and mathematics concepts that were intentionally imbedded within the T/E DBL challenge. Parallel forms of reliability were also established with the comparison of T1 item responses with *Mean Instrument Success (MInst-S) scores, Tier 1&2 Total Score (T1&2-Total), Certainty Total Scores (C-total), and Knowledge Total Score (K-Total)* that found that significant increases in T1 scores were similar to increases

in the comparison variables. Intentional triangulation of data collection methods (TTMC and FTMC diagnostics, Post Treatment Interviews, SEIN evaluations) were implemented. Results indicated that multiple corroborative results were found that supported the findings of TTMC and FTMC findings including a Pearson correlation analysis between percent concept knowledge progression score (from the interviews) and post Knowledge Total Scores (from TTMC and FTMC diagnostics) indicating a strong positive correlation ($r=0.896$, $p=0.016$) (Table 32, p. 103).

The implication is that the TTMC and FTMC diagnostic tests are good candidates for assessing student science and mathematics concepts related to evaporation, condensation, rate of condensation per unit area, area, and slope and rate of change. Sub-concept assessment of heat of evaporation, heat of condensation, Riemann sum area calculations, and slope and rate of change equivalency can also be accomplished using these diagnostic tests.

Technological/Engineering Curricular Development Implications

Based on the conclusions of *RQ2*, it is evident that the design phases of Research, Potential Solution, Solution Evaluation 1, and Solution Evaluation 2 were impactful for the participants in this study. During the Research design phase, students gather information related to concepts that are not thoroughly understood. They explore the topic, investigate prior solutions, and examine the science and mathematics content that is required for a successful engineering solution. This is when concept definition and characterization occur. It includes individual and small group review of informational resources, small group discussion, note taking, and can include whole class review of student findings. The Potential Solutions design phase requires student designers to analyze specific elements of the design, reconcile newly acquired knowledge with design realities, visualize and sketch their solutions, and select the

solution(s) that will be the focus of their prototyping efforts. This includes small group discussions, note taking, and development of design sketches. The Solution Evaluation design phases provide students with the opportunity to evaluate how their designs performed during testing and, equally important, to observe how other groups' designs performed. It allows students to see the characteristics of exemplars and non-exemplars. During this design phase, prototypes are tested, performance data is collected, and interpretations are made regarding attributes of the current design. It includes gallery walks during which group spokespersons describe their design's features and outcomes, group discussion, whole class discussion, calculation examples, and discussions where connections between theory and specific design realities are verified. Validation of correct concept knowledge is rewarded by design success and misconceptions are unambiguously demonstrated by design failures. A T/E DBL challenge necessitates that students research concepts that are unknown, synthesize known and newly acquired concepts into design solution, physically manipulate materials and test design prototypes. This compels them to rely on perceptual categorization processes in more detail than if they were to encounter concept information in a less authentic pedagogical approach.

The implication of these conclusions is that practitioners should encourage student effort during these design phases through questioning, requesting more details in student explanations and reasoning, having them compare and contrast design solutions, and requiring justification of mathematical calculations. Instructional time would be well spent on these phases and the practitioner's efforts in; guiding student research of the intentionally imbedded concepts, requirements of detailed symbolry (design sketches and flow charts) during potential solution development, requirement of prototype operation data collection, in-depth questioning during solution evaluation stages, and guidance during physical and mathematical analysis.

Biases and Limitations

Biases and limitation exist within all studies and must be made evident to the reader so that potential impacts on findings can be assessed. The following section acknowledges the inherent constraints and limitations that existed within this study related to sample size, instrumentation, and treatment implementation.

Sample Size

While this study was meant to be exploratory, the relatively small sample size of 13 participants within this study posed a limitation in that it created a potential for increased variability in responses and makes it difficult to generalize the results to a larger population. Even though the statistical results of the study indicated large t-values and Cohen's d values, the interpretation of results must be tempered due to the sample size.

Instrumentation

The majority of items within the TTMC and FTMC diagnostic tests were developed specifically for this study and had not been implemented prior to the beginning of the study. This fact, combined with the relatively small sample size limits a clear understanding of the reliability of the instrument. Development steps were taken to ensure validity of the instruments but until these instruments are implement again, reliability of the findings will still be in question. In addition, a co-rater was employed to validate the researcher's interpretation of qualitative responses (Tier 4 responses in the FTMC) so as to minimize biases.

Treatment Implementation

In this study the researcher, with intimate knowledge of the diagnostic instrument items and semi-structured interview questions, acted as the instructor throughout the treatment. While questions posed to participants during the treatment were meant to increase participants'

attention to imbedded science and mathematics concepts and to enhance connections between theory and real life applications, there is the possibility that these efforts contributed to the effectiveness of the T/E DBL pedagogical approach. The scale to which this occurred is unknown at this time.

Recommendations

Recommendations for Practitioners

As discussed in the Post Intervention Science and Engineering Notebook Analysis section above, participants were minimally guided when conducting SEIN entries. This led to instances where this data collection device did not provide optimum amounts of evidence related to the research questions. Enhanced SEIN entry guidance in the form of targeted questions would provide greater insight into participant thinking.

This exploratory study focused on short term outcomes of the T/E DBL treatment. Recall that in Chapter 1, one of the guiding rationales for this study was that if this pedagogical approach was found to be effective in teaching science and mathematics concept knowledge to preservice teachers then they will be able to, not only, correctly teach these concepts to their future students but they will also be able to teach the concepts in an integrative way due to their familiarity with the T/E DBL pedagogical approach. A longitudinal study of whether preservice teachers sustain the learning outcomes observed in this study and are capable of using T/E DBL pedagogical approaches in their future classrooms is warranted.

Recommendations for Future Research

Given the sample size for this exploratory study was small (n=13), the findings could not be generalized to a larger population. Replication of this study should be done with larger sample

sizes so that generalizations can be made. Also, repeated implementation of this study with small samples could give insight in to the reliability of the TTMC and FTMC diagnostic instruments.

This study investigated the relationship between engagement in T/E DBL and mathematics concepts. One such concept was Riemann sum. While it was found that overall progression from pre to post diagnostic tests for both science and mathematics did occur, a more detailed look at what was occurring when participants were grappling with the new mathematics concept (Riemann sum) is warranted. There currently is a gap in research knowledge about the effectiveness of teaching new math concepts using T/E DBL. Typically, math concepts that are required in T/E DBL design challenges are those that have been previously taught in siloed mathematics courses. A study that focused on the Riemann sum concept, which is commonly unknown to pre-service elementary teachers, using T/E DBL as the pedagogical approach for developing this knowledge could shed light on this understudied facet of mathematical learning. A specific recommendation to anyone who embarks on this line of research would be to have participants focus on determining a "hyper-accurate" estimate of the area of a targeted irregular shape. This would require participants to make a series of Riemann sum calculations for increasing area estimates that would more closely mimic limit calculations related to numerical integration.

This study also looked into design phases that were deemed "impactful" to participants' conceptual understanding. Fortus et al (2004) informs us that scientific concept knowledge is considered to be constructed knowledge based on past experiences and if the constructed knowledge is sufficient, meaning it explains physical environments and actions, it can be transferred to different contexts. A future study that investigated at what point during the design phase concept knowledge reaches "sufficiency" enabling a participant to correctly transfer a

concept to a different context could provide deeper insights into the student learning within T/E DBL learning.

REFERENCES

AAAS (American Association for the Advancement of Science). (1993). *Benchmarks for science literacy.* Oxford University Press.

AAAS (American Association for the Advancement of Science) & A. (1989). *Science for all Americans.* Oxford University Press.

Anti Kolonial Prodjosantoso, Artanti Mulia Hertina, & Irwanto. (2019). The Misconception Diagnosis on Ionic and Covalent Bonds Concepts with Three Tier Diagnostic Test. *International Journal of Instruction*, *12*(1), 1477–1488. https://doi.org/10.29333/iji.2019.12194a

Appleton, K. (2003). How Do Beginning Primary School Teachers Cope with Science? Toward an Understanding of Science Teaching Practice. *Research in Science Education*, *33*(1), 1–25.

Arslan, H. O., Cigdemoglu, C., & Moseley, C. (2012). A Three-Tier Diagnostic Test to Assess Pre-Service Teachers' Misconceptions about Global Warming, Greenhouse Effect, Ozone Layer Depletion, and Acid Rain. *International Journal of Science Education*, *34*(11), 1667–1686. https://doi.org/10.1080/09500693.2012.680618

Aydeniz, M., Bilican, K., & Kirbulut, Z. D. (2017). Exploring Pre-Service Elementary Science Teachers' Conceptual Understanding of Particulate Nature of Matter through Three-Tier Diagnostic Test. *International Journal of Education in Mathematics, and Technolgy Science*, *5*(2), 221–233.

Banawi, A., Sopandi, W., Kadarohman, A., & Solehuddin, M. (2019). Prospective Primary School Teachers' Conception Change on States of Matter and Their Changes through Predict-Observe-Explain Strategy. *International Journal of Instruction*, *12*(3), 359–374.

Baroody, A. J., Feil, Y., & Johnson, A. R. (2007). An Alternative Reconceptualization of Procedural and Conceptual Knowledge. *Journal for Research in Mathematics Education, 38*(2), 115–131. https://doi.org/10.2307/30034952

Barsalou, L. W. (2003). Abstraction in Perceptual Symbol Systems. *Philosophical Transactions: Biological Sciences, 358*(1435), 1177–1187.

Bartholomew, S. R., Mentzer, N., Jones, M., Sherman, D., & Baniya, S. (2020). Learning by evaluating (LbE) through adaptive comparative judgment. *International Journal of Technology and Design Education*. https://doi.org/10.1007/s10798-020-09639-1

Bourne, L., E., Ekstrand, B., R., & Dominowski, R., L. (1971). *The Psychology of Thinking*. Prentice Hall.

Bransford, J., Brown, A. L., Cocking, R. R., & National Research Council (U.S.). (1999). *How People Learn: Brain, Mind, Experience, and School*. National Academy Press. https://web-p-ebscohost-com.ezproxy.lib.vt.edu/ehost/ebookviewer/ebook?sid=d72abddd-f1d5-4a79-8203-8fcba4901d70%40redis&vid=0&format=EB

Brown, J. S., Collins, A., & Duguid, P. (1989). Situated Cognition and the Culture of Learning. *Educational Researcher, 18*(1), 32–42. https://doi.org/10.2307/1176008

Bruner, J. S. (1960). *The Process of Education*. Harvard University Press.

Bruner, J. S., Austin, G. A., & Goodnow, J. J. (1967). *A study of thinking.* (7th ed.). Wiley.

Bruner, J. S., Goodnow, J. J., & Austin, G. A. (1956). *A study of thinking* (1957-00582-000). John Wiley and Sons. http://ezproxy.ehc.edu:2048/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=psyh&AN=1957-00582-000&site=eds-live

Bulunuz, N., & Jarrett, O. S. (2010). The Effects of Hands-on Learning Stations on Building American Elementary Teachers' Understanding about Earth and Space Science Concepts. *EURASIA Journal of Mathematics, Science and Technology Education*, *6*(2), 85–99.

Bybee, R. W. (2013). *The Case for STEM Education: Challenges and Opportunities*. National Science Teachers Association.

Byrnes, J. P., & Wasik, B. A. (1991). Role of conceptual knowledge in mathematical procedural learning. *Developmental Psychology*, *27*(5), 777–786. https://doi.org/10.1037/0012-1649.27.5.777

C. J. Kruger, M. K. Summers, D. J. Palacio, C. J. Kruger, M. K. Summers, & D. J. Palacio. (1990). An Investigation of Some English Primary School Teachers' Understanding of the Concepts Force and Gravity. *British Educational Research Journal*, *16*(4), 383–397.

Caleon, I., & Subramaniam, R. (2010). Development and Application of a Three-Tier Diagnostic Test to Assess Secondary Students' Understanding of Waves. *International Journal of Science Education*, *32*(7), 939–961. https://doi.org/10.1080/09500690902890130

Canobi, K. H. (2009). Concept-Procedure Interactions in Children's Addition and Subtraction. *Journal of Experimental Child Psychology*, *102*(2), 131–149.

Canpolat, N. (2006). Turkish Undergraduates' Misconceptions of Evaporation, Evaporation Rate, and Vapour Pressure. *International Journal of Science Education*, *28*(15), 1757–1770. https://doi.org/10.1080/09500690600779957

Chang, J.-Y. (1999). Teachers college students' conceptions about evaporation, condensation, and boiling. *Science Education*, *83*(5), 511–526. https://doi.org/10.1002/(SICI)1098-237X(199909)83:5<511::AID-SCE1>3.0.CO;2-E

Chiu, M., Guo, C., & Treagust, D. F. (2007). Assessing Students' Conceptual Understanding in Science: An introduction about a national project in Taiwan. *International Journal of Science Education, 29*(4), 379–390. https://doi.org/10.1080/09500690601072774

Coştu, B., Ayas, A., & Niaz, M. (2012). Investigating the effectiveness of a POE-based teaching activity on students' understanding of condensation. *Instructional Science, 40*(1), 47–67. https://doi.org/10.1007/s11251-011-9169-2

Cotabish, A., Dailey, D., Robinson, A., & Hughes, G. (2013). The Effects of a STEM Intervention on Elementary Students' Science Knowledge and Skills. *School Science & Mathematics, 113*(5), 215–226.

Cox, C. A., & Carpenter, J. R. (1989). Improving Attitudes Toward Teaching Science and Reducing Science Anxiety Through Increasing Confidence in Science Ability in Inservice Elementary School Teachers. *Journal of Elementary Science Education*, *1*(2), 14–34.

Creswell, J. W. (2009). *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches* (Third). SAGE Publications.

Crooks, N. M., & Alibali, M. W. (2014). Defining and measuring conceptual knowledge in mathematics. *Developmental Review, 34*(4), 344–377. https://doi.org/10.1016/j.dr.2014.10.001

Diego-Mantecon, J.-M., Prodromou, T., Lavicza, Z., Blanco, T. F., & Ortiz-Laso, Z. (2021). An attempt to evaluate STEAM project-based instruction from a school mathematics perspective. *ZDM – Mathematics Education*, *53*(5), 1137–1148. https://doi.org/10.1007/s11858-021-01303-9

Douglas, K. A., Gane, B. D., Neumann, K., & Pellegrino, J. W. (2020). Contemporary Methods of Assessing Integrated STEM Competencies. In *Handbook of Research on STEM Education* (pp. 234–254). Routledge/Taylor & Francis Group.

Drake, S. M., & Burns, R. C. (2004). *Meeting Standards Through Integrated Curriculum*. ASCD.

Estrella, S., Zakaryan, D., Olfos, R., & Espinoza, G. (2020). How teachers learn to maintain the cognitive demand of tasks through Lesson Study. *Journal of Mathematics Teacher Education*, *23*(3), 293–310. https://doi.org/10.1007/s10857-018-09423-y

Fan, S.-C., & Yu, K.-C. (2017). How an integrative STEM curriculum can benefit students in engineering design practices. *International Journal of Technology and Design Education*, *27*(1), 107–129. https://doi.org/10.1007/s10798-015-9328-x

Fennema, E., & Franke, M. L. (1992). Teachers' knowledge and its impact. In D. Grouws (Ed.), *Handbook of research on mathematics teaching and learning: A project of the National Council of Teachers of Mathematics* (pp. 147–164). Macmillan Publishing Co, Inc.

Fernandez, C. (2005). Lesson Study: A Means for Elementary Teachers to Develop the Knowledge of Mathematics Needed for Reform-Minded Teaching? *Mathematical Thinking and Learning*, *7*(4), 265–289. https://doi.org/10.1207/s15327833mtl0704_1

Fortus, D., Dershimer, C., Krajcik, J., Marx, R. W., & Mamlok-Naaman, R. (2004). Design-Based Scienceand Student Learning. *Journal of Research in Science Teachingg*, *41*(10), 1081–1110.

Gersten, R., Dimino, J., Jayanthi, M., Kim, J. S., & Santoro, L. E. (2010). Teacher Study Group: Impact of the Professional Development Model on Reading Instruction and Student

Outcomes in First Grade Classrooms. *American Educational Research Journal*, *47*(3), 694–739.

Goldin-Meadow, S., Alibali, M. W., & Church, R. B. (1993). Transitions in concept acquisition: Using the hand to read the mind. *Psychological Review*, *100*(2), 279–297. https://doi.org/10.1037/0033-295X.100.2.279

Gopal, H., Kleinsmidt, J., Case, J., & Musonge, P. (2004). An investigation of tertiary students' understanding of evaporation, condensation and vapour pressure. *International Journal of Science Education*, *26*(13), 1597–1620. https://doi.org/10.1080/09500690410001673829

Gott, R., & Duggan, S. (2002). Problems with the Assessment of Performance in Practical Science: Which way now? *Cambridge Journal of Education*, *32*(2), 183–201. https://doi.org/10.1080/03057640220147540

Großschedl, J., & Harms, U. (2013). Assessing conceptual knowledge using similarity judgments. *Studies in Educational Evaluation*, *39*(2), 71–81. https://doi.org/10.1016/j.stueduc.2012.10.005

Henze, I., & de Vries, M. J. (2021). Henze, I., & de Vries, M. J. (2021). "Chapter 16 Design-Based Concept Learning". In Design-Based Concept Learning in Science and Technology Education. Leiden, The Netherlands: Brill. Doi: Https://doi.org/10.1163/9789004450004_016. In *Design-Based Concept Learning in Science and Technology Education.* Brill.

Henze, I., & Vries, M. J. de. (2021). *Design-Based Concept Learning in Science and Technology Education*. Brill. https://doi.org/10.1163/9789004450004

Hiebert, J., & Grouws, D. A. (2007). Hiebert, J., & Grouws, D. A. (2007). The Effects of Classroom Mathematics Teaching on Students' Learning. In F. Lester (Ed.), Second

Handbook of Research on Mathematics Teaching and Learning (pp. 371-404). Charlotte, NC: Information Age. In F. Lester (Ed.), *Second Handbook of Research on Mathematics Teaching and Learning* (pp. 371–404). Information Age.

Hilbert, T. S., & Renkl, A. (2008). Concept mapping as a follow-up strategy to learning from texts: What characterizes good and poor mappers? *Instructional Science*, *36*(1), 53–73. https://doi.org/10.1007/s11251-007-9022-9

Humphreys, D. (2005). Why Integrative Learning? Why Now? *PeerReview*, 30–31.

Jacobson, E., Bharaj, P., Ahmad, F., & Savich, T. (2019). Prospective Teachers Conceptual Understanding of Linear Functions: Principles or Connections? *Conference Papers -- Psychology of Mathematics & Education of North America*, 1274–1278.

Ke, F. (2014). An implementation of design-based learning through creating educational computer games: A case study on mathematics learning during design and computing. *Computers & Education*, *73*, 26–39. https://doi.org/10.1016/j.compedu.2013.12.010

Kirbulut, Z. D., & Geban, O. (2014). Using Three-Tier Diagnostic Test to Assess Students' Misconceptions of States of Matter. *EURASIA Journal of Mathematics, Science and Technology Education*, *10*(5). https://doi.org/10.12973/eurasia.2014.1128a

Koski, M.-I. (2014). *Connecting knowledge domains: An approach to concept learning in primary science and technology education*.

Kruse, J. W., Wilcox, J., & Menke, L. (2020). Changes in Elementary Teachers' Conceptions About Matter. *Journal of College Science Teaching*, *50*(2), 49–57.

Lasa, A., Abaurrea, J., & Iribas, H. (2020). Mathematical Content on STEM Activities. *Journal on Mathematics Education*, *11*(3), 3. https://doi.org/10.22342/jme.11.3.11327.333-346

Lavi, R., Yehudit, J., Dori, & Dori, D. (2021). Assessing Novelty and Systems Thinking in Conceptual Models of Technology Systems. *IEEE Transactions on Education*, *64*(2), 155–162.

Lenz, K., Dreher, A., Holzäpfel, L., & Wittmann, G. (2020). Are conceptual knowledge and procedural knowledge empirically separable? The case of fractions. *The British Journal of Educational Psychology*, *90*(3), 809–829. https://doi.org/10.1111/bjep.12333

Liu, O. L., Lee, H.-S., & Linn, M. C. (2010). An Investigation of Teacher Impact on Student Inquiry Science Performance Using a Hierarchical Linear Model. *Journal of Research in Science Teaching*, *47*(7), 807–819.

Markman, A. B., & Rein, J. R. (2013). The nature of mental concepts. In D. Reisberg (Ed.), *The Oxford handbook of cognitive psychology.* (2012-26298-021; pp. 321–329). Oxford University Press. https://doi.org/10.1093/oxfordhb/9780195376746.013.0021

Menon, R. (1998). Preservice Teachers' Understanding of Perimeter and Area. *School Science and Mathematics*, *98*(7), 361–367. https://doi.org/10.1111/j.1949-8594.1998.tb17306.x

Montfort, D., Brown, S., & Pollock, D. (2009). An Investigation of Students' Conceptual Understanding in Related Sophomore to Graduate-Level Engineering and Mechanics Courses. *Journal of Engineering Education*, *98*(2), 111–129. https://doi.org/10.1002/j.2168-9830.2009.tb01011.x

National Academy of Engineering. (2002). *Technically speaking: Why do all Americans need to know more about technology.* (In G.Pearson, & A. T. Young (Eds.)). National Academy Press.

National Research Council (U.S.). (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas* (p. 1 online resource (xiv, 385 pages) :). The National Academies Press,.

Niaz, M., & Robinson, W. R. (1992). From 'Algorithmic Mode' to 'Conceptual Gestalt' in Understanding the Behavior of Gases: An epistemological perspective. *Research in Science & Technological Education*, *10*(1), 53–64. https://doi.org/10.1080/0263514920100105

Niemi, D. (1996). Assessing Conceptual Understanding in Mathematics: Representations, Problems, Solutions, Justifications. *Jouranl of Educational Research*, *89*(6), 351–363.

Novak, J. D. (1965). A Model for the Interpretation and Analysis of Concept Formation. *Journal of Research in Science Teaching*, *3*, 72–83.

Nye, B., Konstantopoulos, S., & Hedges, L. V. (2004). How Large Are Teacher Effects? *Educational Evaluation and Policy Analysis*, *26*(3), 237–257.

Organisation for Economic Co-operation and Development, reading and mathematical literacy: a framework for PISA 2006. Retrieved, & (16.4.2013) from http. (2006). *Assessing Scientific, Reading and Mathematical Literacy: A Framework for PISA 2006*. https://eds.a.ebscohost.com/eds/ebookviewer/ebook/bmxlYmtfXzE4NDE3NF9fQU41?sid=ca802cf2-acc0-4dec-a4e4-d5f8459af847@sessionmgr4006&vid=14&format=EB&rid=1

Peşman, H., & Eryılmaz, A. (2010). Development of a Three-Tier Test to Assess Misconceptions About Simple Electric Circuits. *Journal of Educational Research*, *103*(3), 208–222. https://doi.org/10.1080/00220670903383002

Potter, T., Englund, L., Charbonneau, J., MacLean, M. T., Newell, J., & Roll, I. (2017). ComPAIR: A New Online Tool Using Adaptive Comparative Judgement to Support Learning with Peer Feedback. *Teaching and Learning Inquiry: The ISSOTL Journal*, *5*(2), 89–113. https://doi.org/10.20343/teachlearninqu.5.2.8

Reader, W., & Hammond, N. (1994). COMPUTER-BASED TOOLS TO SUPPORT LEARNING FROM HYPERTEXT: CONCEPT MAPPING TOOLS AND BEYOND. *Computers Education*, *22*(1/2), 99–106.

Rittle-Johnson, B., Siegler, R. S., & Alibali, M. W. (2001). Developing conceptual understanding and procedural skill in mathematics: An iterative process. *Journal of Educational Psychology*, *93*(2), 346–362. https://doi.org/10.1037/0022-0663.93.2.346

Robert E. Bleicher & Robert E. Bleicher. (2006). Nurturing Confidence in Preservice Elementary Science Teachers. *Journal of Science Teacher Education*, *17*(2), 165–187.

Robinson, A., Dailey, D., Hughes, G., & Cotabish, A. (2014). The Effects of a Science-Focused STEM Intervention on Gifted Elementary Students' Science Knowledge and Skills. *Journal of Advanced Academics*, *25*(3), 189–213.

Rollnick, M., & Rutherford, M. (1990). African primary school teachers-what ideas do they hold on air and air pressure? *International Journal of Science Education*, *12*(1), 101–113.

Romine, W. L., Schaffer, D. L., & Barrow, L. (2015). Development and Application of a Novel Rasch-based Methodology for Evaluating Multi-Tiered Assessment Instruments: Validation and utilization of an undergraduate diagnostic test of the water cycle. *International Journal of Science Education*, *37*(16), 2740–2768.

Seaman, C., E., & Earles Szydlik, J. (2007). Mathematical sophistication among preservice elementary teachers. *Journal of Math Teacher Education*, *10*, 167–182.

Shulman, L. S. (1987). Knowledge and Teaching Foundations of the New Reform. *Harvard Educational Review*, *57*(1), 1–27.

Shulman, L. S. (2005). Signature pedagogies in the professions. *Daedalus*, *134*(3), 52–59. https://doi.org/10.1162/0011526054622015

Sisman, G. T., & Aksu, M. (2016). A Study on Sixth Grade Students' Misconceptions and Errors in Spatial Measurement: Length, Area, and Volume. *International Journal of Science and Mathematics Education*, *14*, 1293–1319.

Siswaningsih, W., Nahadi, & Widasmara, R. (2019). Development of Three Tier Multiple Choice Diagnostic Test to Assess Students' Misconception of Chemical Equilibrium. *Journal of Physics: Conference Series*, *1280*(3). https://doi.org/10.1088/1742-6596/1280/3/032019

Tapia, M., & Marsh, G. E. (2004). An Instrument to Measure Mathematics Attitudes. *Academic Exchange Quarterly*, *8*(2), 16–21.

Tasman, F., Suherman, & Ahmad, D. (2020). Design Research in Calculus: Students' Journey in Learning Definition of Definite Integral. *Journal of Physics*. https://doi.org/10.1088/1742-6596/1470/1/012046

Teddlie, C., & Tasshakori, A. (2006). A General Typology of Research Designs featuring Mixed Methods. *Research in the Schools*, *13*(1), 12–28.

The MET Project. (2013). *Measures of effective teaching: Study information / https://doi.org/10.3886/ICPSR34771.v1 Publication: [United States?]: [Publisher not identified], Ann Arbor, MI : Inter-university Consortium for Political and Social Research [distributor], 2013 Document: English: Internet Resource Computer File*.

Inter-university Consortium for Political and Social Research [distributor]. https://doi.org/10.3886/ICPSR34771.v1

The Royal Society (Ed.). (1982). Biotechnology and Education. *Journal of Biological Education*, *16*(1), 10–12.

Tuttle, N., Kaderavek, J., Molitor, S., Czerniak, C., Johnson-Whitt, E., Bloomquist, D., Namatovu, W., & Wilson, G. (2016). Investigating the Impact of NGSS-Aligned Professional Development on PreK-3 Teachers' Science Content Knowledge and Pedagogy. *Journal of Science Teacher Education*, *27*(7), 717–745. https://doi.org/10.1007/s10972-016-9484-1

Van Breukelen, D. H. J., De Vries, M. J., & Schure, F. A. (2017). Concept learning by direct current design challenges in secondary education Dave H. J. van Breukelen1 • Marc J. de Vries2 • Frank A. Schure1. *International Journal of Design Education*, *27*, 407–430. https://doi.org/10.1007/s10798-016-9357-0

Vygotsky, L. S. (1991). Genesis of the higher mental functions. In *Learning to think: Child development in social context* (Vol. 2, pp. 32–41). Routledge.

Walma van der Molen, j., Lang, J. de, & Kok, J. (2007). *Elaboration of the Theoretical Framework for the Professionalization of Teachers in the Field of Science and Technology (The Hague) Den Haag: (Program Board VTB-Pro) Programmaraad VTB-Pro.* Program Board VTB-Pro.

Warren, E., & Cooper, T. J. (2009). Developing mathematics understanding and abstraction: The case of equivalence in the elementary years. *Mathematics Education Research Journal*, *21*(2), 76–95. https://doi.org/10.1007/BF03217546

Watson, M. K., Pelkey, J., Noyes, C. R., & Rodgers, M. O. (2016). Assessing Conceptual Knowledge Using Three Concept Map Scoring Methods. *Journal of Engineering Education*, *105*(1), 118–146.

Wells, J., & Ernst, J. (2012). *Integrative STEM Education. Blacksburg, VA: Virginia Tech: Invent the Future, School of Education*. Virginia Tech School of Education.

Wells, J. G. (2016a). Efficacy of the TechnologicalEngineering Design Approach: Imposed Cognitive Demands Within Design-Based Biotechnology Instruction. *Journal of Technology Education*, *27*(2). https://doi.org/10.21061/jte.v27i2.a.1

Wells, J. G. (2016b). I-STEM Ed Exemplar: Implementation of the PIRPOSAL Model. *Technology & Engineering Teacher*, *76*(2), 16–23.

Wells, J. G. (2016c). PIRPOSAL model of Integrative STEM education: Conceptual and Pedagogical Framework for Classroom Implementation. *Technology & Engineering Teacher*, *75*(6), 12–19.

Westbroek, H., Klaassen, K., Bulte, A., & Pilot, A. (2005). Characteristics of meaningful social aspects of genetics. *Research and the Quality of Science Education*, 67–76.

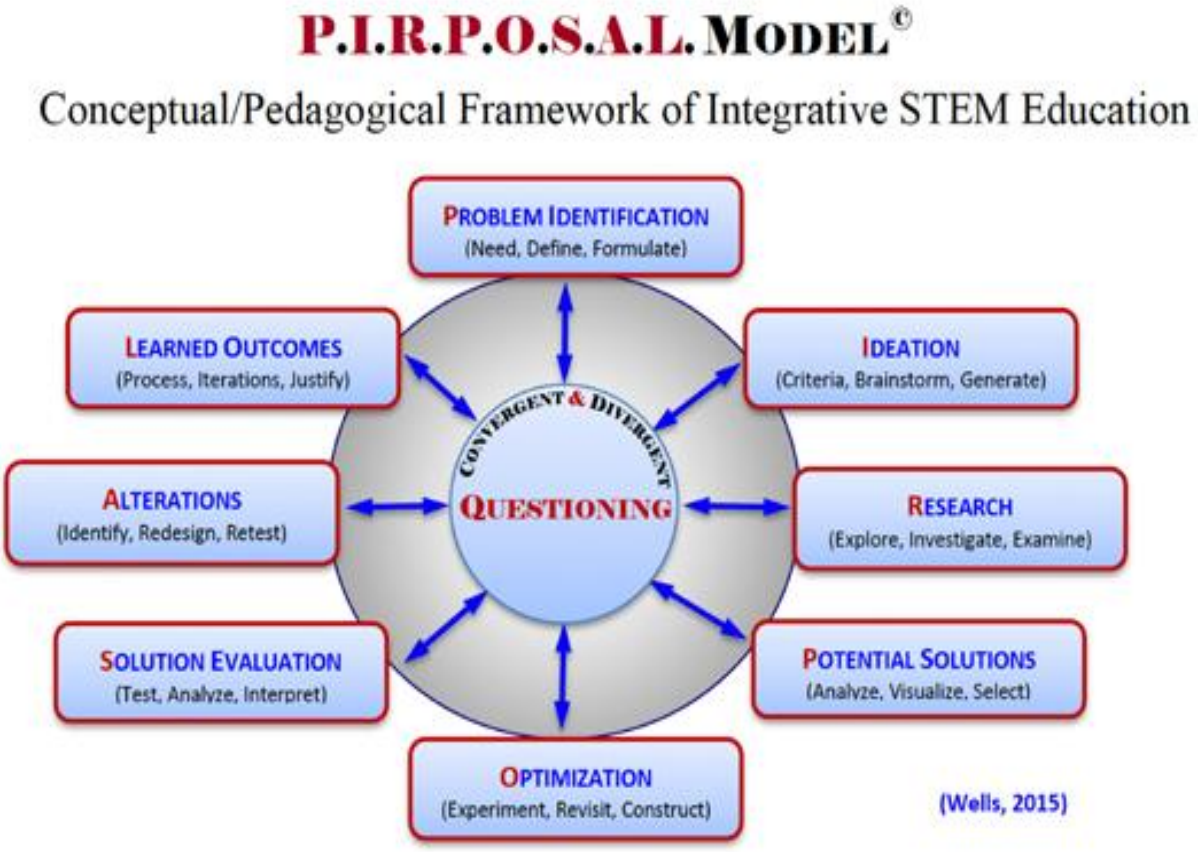
Yamauchi, T., & Markman, A. B. (2000). Inference using categories. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *26*(3), 776–795. https://doi.org/10.1037//0278-7393.26.3.776

Yeh, W., & Barsalou, L. W. (2006). The Situated Nature of Concepts. *The American Journal of Psychology*, *119*(3), 349–384. https://doi.org/10.2307/20445349

APPENDICES

Appendix A

P.I.R.P.O.S.A.L. Model



Appendix B

Institutional Review Board Approval

North End Center, Suite 4120 (MC 0497)
300 Turner Street NW
Blacksburg, Virginia 24061
540/231-3732
irb@vt.edu
http://www.research.vt.edu/sirc/hrpp

MEMORANDUM

DATE: February 21, 2024

TO: John Wells, Mark Allen Hainsworth

FROM: Virginia Tech Institutional Review Board (FWA00000572)

PROTOCOL TITLE: Promoting Preservice Elementary Teacher Acquisition of Science and Mathematics Concept Knowledge: Potential of Technological/Engineering Design Based Learning

IRB NUMBER: **24-035**

Effective February 21, 2024, the Virginia Tech Human Research Protection Program (HRPP) determined that this protocol meets the criteria for exemption from IRB review under 45 CFR 46.104 (d) category(ies) 1.

Ongoing IRB review and approval by this organization is not required. This determination applies only to the activities described in the IRB submission and does not apply should any changes be made. If changes are made and there are questions about whether these activities impact the exempt determination, please submit an amendment to the HRPP for a determination.

This exempt determination does not apply to any collaborating institution(s). The Virginia Tech HRPP and IRB cannot provide an exemption that overrides the jurisdiction of a local IRB or other institutional mechanism for determining exemptions.

All investigators (listed above) are required to comply with the researcher requirements outlined at:

https://secure.research.vt.edu/external/irb/responsibilities.htm

(Please review responsibilities before beginning your research.)

PROTOCOL INFORMATION:

Determined As: **Exempt, under 45 CFR 46.104(d) category(ies) 1**
Protocol Determination Date: **February 21, 2024**

ASSOCIATED FUNDING:

The table on the following page indicates whether grant proposals are related to this protocol, and which of the listed proposals, if any, have been compared to this protocol, if required.

Appendix C

Targeted Propositional Knowledge Statements

Sub-Concepts	Learning Outcome Categories	Targeted Propositional Knowledge Statements
SC-Evap-A	Evaporation	Evaporation is the process by which molecules in the liquid phase are converted to molecules in the gas phase.
SC-Evap-A	Heat of Evaporation	Liquid molecules, located near the surface of a liquid, with sufficient kinetic energy to overcome liquid-phase intermolecular forces, will leave the liquid phase and enter the vapor phase.
SC-Evap-A	Heat of Evaporation	Liquid molecules located near the surface of a liquid can absorb heat energy from their surroundings, gaining enough kinetic energy to overcome liquid-phase intermolecular forces which allows them to leave the liquid phase.
SC-Evap-B	Heat of Evaporation	Liquid molecules with enough kinetic energy to overcome liquid-phase intermolecular forces will leave the liquid–phase and enter the vapor phase. This loss of high-kinetic energy molecules to the gas phase lowers the average kinetic energy of the liquid resulting in cooling of the liquid
SC-Evap-B	Residuals of Evaporation	A solute is a dissolved component of a solution. It is dissolved in a solvent.

SC-Evap-C	Residuals of Evaporation	A solvent that has evaporated and has been re-condensed in a separate container will be free of the solute.
SC-Evap-C	Residuals of Evaporation	Solutes do not evaporate along with the solvent during evaporation. They will remain in the liquid phase unless they are also volatile.
SC-Evap-C	Residuals of Evaporation	As the solvent in a solution evaporates the concentration of the solute within the increases until it reaches saturation at which time crystallization/precipitation of the solute will occur.
SC-Evap-D	Rate of Evaporation	The rate of evaporation is the amount of time required for a given amount of liquid to be changed to a gas through the endothermic process of evaporation.
SC-Evap-D	Rate of Evaporation	The rate of evaporation of a liquid is effected by several factors which include temperature of the liquid, temperature of the air, surface area of the liquid, partial pressure of the vapor, atmospheric pressure, and intermolecular forces of the liquid.
SC-Evap-D	Rate of Evaporation	Evaporation rates within a closed system first increase then decrease to a constant rate as an

		equilibrium is approached between evaporation and condensation rates.
SC-Cond-A	Condensation	Condensation is the process by which molecules in the gaseous phase are converted to molecules in the liquid phase.
SC-Cond-A	Heat of Condensation	Condensation occurs when gaseous molecules lose energy to the immediate environment resulting in slower molecular motion. This slowing in molecular motion allows forces of molecular attraction to combine molecules to form liquids.
SC-Cond-B	Heat of Condensation	The heat energy lost to the surroundings during condensation is known at the heat of condensation and will result in a greater average kinetic energy of the surroundings.
SC-Cond-B	Heat of Condensation	Condensation will occur as the temperature of the gas decreases.
SC-Cond-C	Rate of Condensation	The rate of condensation is the amount of vapor that is changed to a liquid through the exothermic process of condensation in a given amount of time.
SC-Cond-C	Rate of Condensation	The rate of condensation is effected by several factors, including the vapor pressure of the gas above the liquid and the temperature of the liquid or other surfaces that the vapor can contact.

SC-Cond-C	Rate of Condensation	Cooler temperatures of liquids or solid surfaces that the vapor is in contact with can increase the rate of condensation.
SC-Cond-C	Rate of Condensation	In a closed system, the rate of condensation will equal the rate of evaporation after a period of time.
MC-Area-A	Area of Rectangles	The area of a rectangle is the measurement of that region within the perimeter of the rectangle in square units.
MC-Area-A	Area of Rectangles	The area of a rectangle in square units is the product of the measurements of the length and width dimensions of the rectangle.
MC-Area-A	Inscribed-Circumscribed Rectangles	An inscribed rectangle is the largest rectangle that can be drawn within an irregular shape that intersects the edge of the irregular shape but does not go beyond it.
MC-Area-A	Inscribed-Circumscribed Rectangles	A circumscribed rectangle is the smallest rectangle that can be drawn that will completely enclose the irregular shape.
MC-Area-A	Surface Area	The surface area is the measurement in square units of a region that is the outer most layer of an object.
MC-Area-B	Using Riemann Sum	Irregularly shaped areas can be approximated using a series of inscribed or circumscribed rectangles.

MC-Area-B	Using Riemann Sum	Irregularly shaped areas approximated using a series of inscribed rectangles will produce and underestimation of the true area.
MC-Area-B	Using Riemann Sum	Irregularly shaped areas approximated with a series of circumscribed rectangles will produce an over estimation of the true area.
MC-Area-B	Using Riemann Sum	More accurate estimates of the area of an irregularly shaped region can be obtained by minimizing the width of the rectangles used to find the estimate the area.
MC-RateCond-A	Rate of Production per Unit Area	The rate of production is the amount of material produced in a given time.
MC-RateCond-B	Rate of Production per Unit Area	Changing quantities of materials can be averaged over an effective unit area.
MC-RateCond-B	Rate of Production per Unit Area	Production rates of different systems can be compared on a per unit basis.
MC-Slope-A	Rate of Change	The rate of change of a quantity is the ratio of the change of the quantity in relation to the change of another variable.

MC-Slope-B	Slope is the Rate of Change	The slope of a linear function of two variables is equal to the rate of change of those variables.

Appendix D

Propositional Knowledge Statement Editing Review Form

Name of Reviewer:_____

Concept	Sub-concept	Current Propositional Knowledge Statement	Do you wish to make an editorial change?	Revised Propositional Knowledge Statement
Evaporation		Evaporation is the process by which molecules in the liquid phase are converted to molecules in the gas phase.	Yes/No	
	Heat of Evaporation	Liquid molecules, located near the surface of a liquid, with sufficient kinetic energy to overcome liquid-phase intermolecular forces, will leave the liquid phase and enter the vapor phase.	Yes/No	
	Heat of Evaporation	Liquid molecules located near the surface of a liquid can absorb heat energy from their surroundings, gaining enough kinetic energy to overcome liquid-phase intermolecular forces which allows them to leave the liquid phase.	Yes/No	
	Heat of Evaporation	Liquid molecules with enough kinetic energy to overcome liquid-phase intermolecular forces will leave the liquid–phase and enter the vapor phase. This loss of high-kinetic energy molecules to the gas phase lowers the average kinetic energy of the liquid resulting in cooling of the liquid	Yes/No	
Evaporation	Rate of Evaporation	The rate of evaporation is the amount of time required for a given amount of liquid to be changed to a gas through the endothermic process of evaporation.	Yes/No	

	Rate of Evaporation	The rate of evaporation of a liquid is affected by several factors which include temperature of the liquid, temperature of the air, surface area of the liquid, partial pressure of the vapor, atmospheric pressure, and intermolecular forces of the liquid.	Yes/No	
	Rate of Evaporation	Evaporation rates within a closed system first increase then decrease to a constant rate as an equilibrium is approached between evaporation and condensation rates.	Yes/No	
Evaporation	Residuals of Evaporation	A solute is a dissolved component of a solution. It is dissolved in a solvent.	Yes/No	
	Residuals of Evaporation	A solvent that has evaporated and has been re-condensed in a separate container will be free of the solute.	Yes/No	
	Residuals of Evaporation	Solutes do not evaporate along with the solvent during evaporation. They will remain in the liquid phase unless they are also volatile.	Yes/No	
	Residuals of Evaporation	As the solvent in a solution evaporates the concentration of the solute within the increases until it reaches saturation at which time crystallization/precipitation of the solute will occur.	Yes/No	
Condensation		Condensation is the process by which molecules in the gaseous phase are converted to molecules in the liquid phase.	Yes/No	
	Heat of Condensation	Condensation occurs when gaseous molecules lose energy to the immediate environment resulting in slower molecular motion. This slowing in molecular motion allows forces	Yes/No	

		of molecular attraction to combine molecules to form liquids.		
	Heat of Condensation	The heat energy lost to the surroundings during condensation is known at the heat of condensation and will result in a greater average kinetic energy of the surroundings.	Yes/No	
	Heat of Condensation	Condensation will occur as the temperature of the gas decreases.	Yes/No	
Condensation	Rate of Condensation	The rate of condensation is the amount of vapor that is changed to a liquid through the exothermic process of condensation in a given amount of time.	Yes/No	
	Rate of Condensation	The rate of condensation is affected by several factors, including the vapor pressure of the gas above the liquid and the temperature of the liquid or other surfaces that the vapor can contact.	Yes/No	
	Rate of Condensation	Cooler temperatures of liquids or solid surfaces that the vapor is in contact with can increase the rate of condensation.	Yes/No	
	Rate of Condensation	In a closed system, the rate of condensation will equal the rate of evaporation after a period of time.	Yes/No	
Area of 2D Irregular Shapes	Area of Rectangles	The area of a rectangle is the measurement of that region within the perimeter of the rectangle in square units.	Yes/No	
	Area of Rectangles	The area of a rectangle in square units is the product of the measurements of the length and width dimensions of the rectangle.	Yes/No	
	Inscribed-Circumscribed Rectangles	An inscribed rectangle is the largest rectangle that can be drawn within an irregular shape that intersects the edge of the	Yes/No	

		irregular shape but does not go beyond it.		
	Inscribed-Circumscribed Rectangles	A circumscribed rectangle is the smallest rectangle that can be drawn that will completely enclose the irregular shape.	Yes/No	
	Surface Area	The surface area is the measurement in square units of a region that is the outer most layer of an object.	Yes/No	
	Using Riemann Sum	Irregularly shaped areas can be approximated using a series of inscribed or circumscribed rectangles.	Yes/No	
	Using Riemann Sum	Irregularly shaped areas approximated using a series of inscribed rectangles will produce and underestimation of the true area.	Yes/No	
	Using Riemann Sum	Irregularly shaped areas approximated with a series of circumscribed rectangles will produce an over estimation of the true area.	Yes/No	
	Using Riemann Sum	More accurate estimates of the area of an irregularly shaped region can be obtained by minimizing the width of the rectangles used to find the estimate the area.	Yes/No	
Rates of Change	Rate of Production per Unit Area	The rate of production is the amount of material produced in a given time.	Yes/No	
	Rate of Production per Unit Area	Changing quantities of materials can be averaged over an effective unit area.	Yes/No	
	Rate of Production per Unit Area	Production rates of different systems can be compared on a per unit basis.	Yes/No	
	Rate of Change	The rate of change of a quantity is the ratio of the change of the quantity in	Yes/No	

		relation to the change of another variable.		
	Slope is the Rate of Change	The slope of a linear function of two variables is equal to the rate of change of those variables.	Yes/No	

Appendix E

Response Summary Review Rubric

Propositional Knowledge Statement	Proposed Changes	Refined Propositional Knowledge Statement
1) Evaporation is the process by which a liquid molecule is converted to a gaseous molecule (or vapor molecule)	CM-1 Evaporation is the process by which molecules in the liquid phase are converted to molecules in the gas phase. CM-2 No change CM-3 No change CM-4 No change CM-5 No change	Evaporation is the process by which molecules in the liquid phase are converted to molecules in the gas phase.
2) Liquid molecules, located near the surface of a liquid, with sufficient kinetic energy to overcome liquid-phase intermolecular forces, will leave the liquid phase and enter the vapor phase.	CM-1 No change CM-2 No change CM-3 No change CM-4 No change CM-5 No change	Statement Accepted
3) Liquid molecules located near the surface of a liquid can absorb heat energy from their surroundings, gaining enough kinetic energy to overcome liquid-phase intermolecular forces which allows them to leave the liquid phase.	CM-1 No change CM-2 No change CM-3 No change CM-4 No change CM-5 No change	Statement Accepted
4) Liquid molecules with enough kinetic energy to overcome liquid-phase intermolecular forces will leave the liquid–phase and enter the vapor phase. This loss of high-kinetic energy molecules to the gas phase lowers the average kinetic energy of the liquid resulting in cooling of the liquid	CM-1 Liquid molecules with enough kinetic energy to overcome liquid-phase intermolecular forces will leave the liquid–phase and enter the vapor phase. This loss of high-kinetic energy molecules to the gas phase lowers the average kinetic energy of the liquid resulting in cooling of the liquid. CM-2 No change CM-3 No change CM-4 No change	Liquid molecules with enough kinetic energy to overcome liquid-phase intermolecular forces will leave the liquid–phase and enter the vapor phase. This loss of high-kinetic energy molecules to the gas phase lowers the average kinetic energy of the liquid resulting in cooling of the liquid.

		CM-5 No change	
5)	The rate of evaporation is the amount of time required for a given amount of liquid to be changed to a gas through the endothermic process of evaporation.	CM-1 The rate of evaporation is the amount of time required for a given amount of liquid to be changed to a gas through the endothermic process of evaporation. CM-2 No change CM-3 No change CM-4 No change CM-5 No change	The rate of evaporation is the amount of time required for a given amount of liquid to be changed to a gas through the endothermic process of evaporation.
6)	The rate of evaporation of a liquid is affected by several factors which include temperature of the liquid, temperature of the air, surface area of the liquid, partial pressure of the vapor, atmospheric pressure, and intermolecular forces of the liquid.	CM-1 No change CM-2 No change CM-3 The rate of evaporation of a liquid is affected by several factors which include temperature of the liquid, temperature of the air, surface area of the liquid, partial pressure of the vapor, atmospheric pressure, and intermolecular forces of the liquid. CM-4 No change CM-5 No change	The rate of evaporation of a liquid is affected by several factors which include temperature of the liquid, temperature of the air, surface area of the liquid, partial pressure of the vapor, atmospheric pressure, and intermolecular forces of the liquid.
7)	Evaporation rates within a closed system first increase then decrease to a constant rate as an equilibrium is approached between evaporation and condensation rates.	CM-1 No change CM-2 No change CM-3 No change CM-4 No change CM-5 No change	Statement Accepted
8)	A solute is a dissolved component of a solution. It is dissolved in a solvent.	CM-1 No change CM-2 No change CM-3 No change CM-4 No change CM-5 No change	Statement Accepted
9)	A solvent that has evaporated and has been re-condensed in a separate container will be free of the solute.	CM-1 No change CM-2 No change CM-3 No change CM-4 No change CM-5 No change	Statement Accepted
10)	Solutes do not evaporate along with the solvent during evaporation. They will remain in the liquid	CM-1 Solutes do not evaporate along with the solvent during evaporation. They will remain in the	Solutes do not evaporate along with the solvent during evaporation. They will remain in the liquid

	phase unless they are also volatile.	liquid phase unless they are also volatile. CM-2 No change CM-3 No change CM-4 No change CM-5 No change	phase unless they are also volatile.
11)	As the solvent in a solution evaporates the concentration of the solute within the increases until it reaches saturation at which time crystallization/precipitation of the solute will occur.	CM-1 No change CM-2 As the solvent in a solution evaporates the concentration of the solute within the increases until it reaches saturation at which time crystallization/precipitation of the solute will occur. CM-3 No change CM-4 No change CM-5 No change	As the solvent in a solution evaporates the concentration of the solute within the increases until it reaches saturation at which time crystallization/precipitation of the solute will occur.
12)	Condensation is the process by which molecules in the gaseous phase are converted to molecules in the liquid phase.	CM-1 No change CM-2 No change CM-3 No change CM-4 No change CM-5 No change	Statement Accepted
13)	Condensation occurs when gaseous molecules lose energy to the immediate environment resulting in slower molecular motion. This slowing in molecular motion allows forces of molecular attraction to combine molecules to form liquids.	CM-1 No change CM-2 No change CM-3 No change CM-4 No change CM-5 No change	Statement Accepted
14)	The heat energy lost to the surroundings during condensation is known at the heat of condensation and will result in a greater average kinetic energy of the surroundings.	CM-1 No change CM-2 No change CM-3 No change CM-4 No change CM-5 No change	Statement Accepted
15)	Condensation will occur as the temperature of the gas decreases.	CM-1 No change CM-2 No change CM-3 No change CM-4 No change CM-5 No change	Statement Accepted

16) The rate of condensation is the amount of vapor that is changed to a liquid through the exothermic process of condensation in a given amount of time.	CM-1 The rate of condensation is the amount of vapor that is changed to a liquid through the exothermic process of condensation in a given amount of time. CM-2 No change CM-3 No change CM-4 No change CM-5 No change	The rate of condensation is the amount of vapor that is changed to a liquid through the exothermic process of condensation in a given amount of time.
17) The rate of condensation is effected by several factors, including the vapor pressure of the gas above the liquid and the temperature of the liquid or other surfaces that the vapor can contact.	CM-1 No change CM-2 No change CM-3 No change CM-4 No change CM-5 No change	Statement Accepted
18) Cooler temperatures of liquids or solid surfaces that the vapor is in contact with can increase the rate of condensation.	CM-1 No change CM-2 No change CM-3 No change CM-4 No change CM-5 No change	Statement Accepted
19) In a closed system, the rate of condensation will equal the rate of evaporation after a period of time.	CM-1 No change CM-2 No change CM-3 No change CM-4 No change CM-5 No change	Statement Accepted
20) The area of a rectangle is the measurement of that region within the perimeter of the rectangle in square units.	CM-1 No change CM-2 No change CM-3 No change CM-4 No change CM-5 No change	Statement Accepted
21) The area of a rectangle in square units is the product of the measurements of the length and width dimensions of the rectangle.	CM-1 No change CM-2 No change CM-3 No change CM-4 No change CM-5 No change	Statement Accepted
22) An inscribed rectangle is the largest rectangle that can be drawn within an irregular shape that intersects the edge of the irregular shape but does not go beyond it.	CM-1 No change CM-2 No change CM-3 No change CM-4 No change CM-5 No change	Statement Accepted

23) A circumscribed rectangle is the smallest rectangle that can be drawn that will completely enclose the irregular shape.	CM-1 No change CM-2 No change CM-3 No change CM-4 No change CM-5 No change	Statement Accepted
24) The surface area is the measurement in square units of a region that is the outer most layer of an object.	CM-1 No change CM-2 No change CM-3 No change CM-4 No change CM-5 No change	Statement Accepted
25) Irregularly shaped areas can be approximated using a series of inscribed or circumscribed rectangles.	CM-1 No change CM-2 No change CM-3 No change CM-4 No change CM-5 No change	Statement Accepted
26) Irregularly shaped areas approximated using a series of inscribed rectangles will produce and underestimation of the true area.	CM-1 No change CM-2 No change CM-3 No change CM-4 No change CM-5 No change	Statement Accepted
27) Irregularly shaped areas approximated with a series of circumscribed rectangles will produce an over estimation of the true area.	CM-1 No change CM-2 No change CM-3 No change CM-4 No change CM-5 No change	Statement Accepted
28) More accurate estimates of the area of an irregularly shaped region can be obtained by minimizing the width of the rectangles used to find the estimate the area.	CM-1 No change CM-2 No change CM-3 No change CM-4 No change CM-5 No change	Statement Accepted
29) The rate of production is the quantity of material produced in a given time.	CM-1 No change CM-2 No change CM-3 No change CM-4 The rate of production is the amount of material produced in a given time. CM-5 No change	The rate of production is the amount of material produced in a given time.
30) Changing quantities of materials can be averaged over an effective unit area.	CM-1 No change CM-2 No change CM-3 No change	Production rates of different systems can be compared on a per unit basis.

	CM-4 Production rates of different systems can be compared on a per unit basis. CM-5 No change	
31) Production rates of different systems can be compared on a per unit basis.	CM-1 No change CM-2 No change CM-3 No change CM-4 No change CM-5 No change	Statement Accepted
32) The rate of change of a quantity is the ratio of the change of the quantity in relation to the change of another variable.	CM-1 No change CM-2 No change CM-3 No change CM-4 No change CM-5 No change	Statement Accepted
33) The slope of a linear function of two variables is equal to the rate of change of those variables.	CM-1 No change CM-2 No change CM-3 No change CM-4 No change CM-5 No change	Statement Accepted

Appendix F

Successive Rounds of Arbitration

Propositional Knowledge Statement Response Summary Reviews

Stage #2 Final Stage Response Summary

Propositional Knowledge Statement	Proposed Changes	Committee Member Agreement
1)	Evaporation is the process by which molecules in the liquid phase are converted to molecules in the gas phase.	CM-1 Agreed CM-2 Agreed CM-3 Agreed CM-4 Agreed CM-5 Agreed
2)	Statement Accepted in previous arbitration stage	
3)	Statement Accepted in previous arbitration stage	
4)	Liquid molecules with enough kinetic energy to overcome liquid-phase intermolecular forces will leave the liquid–phase and enter the vapor phase. This loss of high-kinetic energy molecules to the gas phase lowers the average kinetic energy of the liquid resulting in cooling of the liquid.	CM-1 Agreed CM-2 Agreed CM-3 Agreed CM-4 Agreed CM-5 Agreed
5)	The rate of evaporation is the amount of time required for a given amount of liquid to be changed to a gas through the endothermic process of evaporation	CM-1 Agreed CM-2 Agreed CM-3 Agreed CM-4 Agreed CM-5 Agreed
6)	The rate of evaporation of a liquid is affected by several factors which include temperature of the liquid, temperature of the air, surface	CM-1 Agreed CM-2 Agreed CM-3 Agreed CM-4 Agreed

	area of the liquid, partial pressure of the vapor, atmospheric pressure, and intermolecular forces of the liquid.	CM-5 Agreed
7)	Statement Accepted in previous arbitration stage	
8)	Statement Accepted in previous arbitration stage	
9)	Statement Accepted in previous arbitration stage	
10)	Solutes do not evaporate along with the solvent during evaporation. They will remain in the liquid phase unless they are also volatile.	CM-1 Agreed CM-2 Agreed CM-3 Agreed CM-4 Agreed CM-5 Agreed
11)	As the solvent in a solution evaporates the concentration of the solute within the increases until it reaches saturation at which time crystallization/precipitation of the solute will occur.	CM-1 Agreed CM-2 Agreed CM-3 Agreed CM-4 Agreed CM-5 Agreed
12)	Statement Accepted in previous arbitration stage	
13)	Statement Accepted in previous arbitration stage	
14)	Statement Accepted in previous arbitration stage	
15)	Statement Accepted in previous arbitration stage	
16)	The rate of condensation is the amount of vapor that is changed to a liquid through the	CM-1 Agreed CM-2 Agreed CM-3 Agreed CM-4 Agreed

	exothermic process of condensation in a given amount of time.	CM-5 Agreed
17)	Statement Accepted in previous arbitration stage	
18)	Statement Accepted in previous arbitration stage	
19)	Statement Accepted in previous arbitration stage	
20)	Statement Accepted in previous arbitration stage	
21)	Statement Accepted in previous arbitration stage	
22)	Statement Accepted in previous arbitration stage	
23)	Statement Accepted in previous arbitration stage	
24)	Statement Accepted in previous arbitration stage	
25)	Statement Accepted in previous arbitration stage	
26)	Statement Accepted in previous arbitration stage	
27)	Statement Accepted in previous arbitration stage	
28)	Statement Accepted in previous arbitration stage	
29)	The rate of production is the amount of material produced in a given time.	CM-1 Agreed CM-2 Agreed CM-3 Agreed CM-4 Agreed CM-5 Agreed

30)	Production rates of different systems can be compared on a per unit basis.	CM-1 Agreed CM-2 Agreed CM-3 Agreed CM-4 Agreed CM-5 Agreed
31)	Statement Accepted in previous arbitration stage	
32)	Statement Accepted in previous arbitration stage	
33)	Statement Accepted in previous arbitration stage	

Appendix G

Review Response Summary

PKS[a]	CM-1[b]	CM-2	CM-3	CM-4	CM-5	% Agreement
1	A[c]	A	A	A	A	100
2	A	A	A	A	A	100
3	A	A	A	A	A	100
4	A	A	A	A	A	100
5	A	A	A	A	A	100
6	A	A	A	A	A	100
7	A	A	A	A	A	100
8	A	A	A	A	A	100
9	A	A	A	A	A	100
10	A	A	A	A	A	100
11	A	A	A	A	A	100
12	A	A	A	A	A	100
13	A	A	A	A	A	100
14	A	A	A	A	A	100
15	A	A	A	A	A	100
16	A	A	A	A	A	100
17	A	A	A	A	A	100
18	A	A	A	A	A	100
19	A	A	A	A	A	100

20	A	A	A	A	A	100
21	A	A	A	A	A	100
22	A	A	A	A	A	100
23	A	A	A	A	A	100
24	A	A	A	A	A	100
25	A	A	A	A	A	100
26	A	A	A	A	A	100
27	A	A	A	A	A	100
28	A	A	A	A	A	100
29	A	A	A	A	A	100
30	A	A	A	A	A	100
31	A	A	A	A	A	100
32	A	A	A	A	A	100
33	A	A	A	A	A	100

[a]PKS = Propositional Knowledge Statement: [b]CM-1 = Expert Panel Committee Member #1
[c] A = Accepted Statement

Appendix H

Final List of Propositional Knowledge Statements

Sub-Concepts	Learning Outcome Categories	Targeted Propositional Knowledge Statements
SC-Evap-A	Evaporation	Evaporation is the process by which molecules in the liquid phase are converted to molecules in the gas phase.
SC-Evap-A	Heat of Evaporation	Liquid molecules, located near the surface of a liquid, with sufficient kinetic energy to overcome liquid-phase intermolecular forces, will leave the liquid phase and enter the vapor phase.
SC-Evap-A	Heat of Evaporation	Liquid molecules located near the surface of a liquid can absorb heat energy from their surroundings, gaining enough kinetic energy to overcome liquid-phase intermolecular forces which allows them to leave the liquid phase.
SC-Evap-B	Heat of Evaporation	Liquid molecules with enough kinetic energy to overcome liquid-phase intermolecular forces will leave the liquid–phase and enter the vapor phase. This loss of high-kinetic energy molecules to the gas phase lowers the average kinetic energy of the liquid resulting in cooling of the liquid
SC-Evap-C	Residuals of Evaporation	A solute is a dissolved component of a solution. It is dissolved in a solvent.
SC-Evap-C	Residuals of Evaporation	A solvent that has evaporated and has been re-condensed in a separate container will be free of the solute.
SC-Evap-C	Residuals of Evaporation	Solutes do not evaporate along with the solvent during evaporation. They will remain in the liquid phase unless they are also volatile.

SC-Evap-C	Residuals of Evaporation	As the solvent in a solution evaporates the concentration of the solute within the increases until it reaches saturation at which time crystallization/precipitation of the solute will occur.
SC-Evap-D	Rate of Evaporation	The rate of evaporation is the amount of time required for a given amount of liquid to be changed to a gas through the endothermic process of evaporation.
SC-Evap-D	Rate of Evaporation	The rate of evaporation of a liquid is effected by several factors which include temperature of the liquid, temperature of the air, surface area of the liquid, partial pressure of the vapor, atmospheric pressure, and intermolecular forces of the liquid.
SC-Evap-D	Rate of Evaporation	Evaporation rates within a closed system first increase then decrease to a constant rate as an equilibrium is approached between evaporation and condensation rates.
SC-Cond-A	Condensation	Condensation is the process by which molecules in the gaseous phase are converted to molecules in the liquid phase.
SC-Cond-A	Heat of Condensation	Condensation occurs when gaseous molecules lose energy to the immediate environment resulting in slower molecular motion. This slowing in molecular motion allows forces of molecular attraction to combine molecules to form liquids.
SC-Cond-B	Heat of Condensation	The heat energy lost to the surroundings during condensation is known at the heat of condensation and will result in a greater average kinetic energy of the surroundings.
SC-Cond-B	Heat of Condensation	Condensation will occur as the temperature of the gas decreases.

SC-Cond-C	Rate of Condensation	The rate of condensation is the amount of vapor that is changed to a liquid through the exothermic process of condensation in a given amount of time.
SC-Cond-C	Rate of Condensation	The rate of condensation is effected by several factors, including the vapor pressure of the gas above the liquid and the temperature of the liquid or other surfaces that the vapor can contact.
SC-Cond-C	Rate of Condensation	Cooler temperatures of liquids or solid surfaces that the vapor is in contact with can increase the rate of condensation.
SC-Cond-C	Rate of Condensation	In a closed system, the rate of condensation will equal the rate of evaporation after a period of time.
MC-Area-A	Area of Rectangles	The area of a rectangle is the measurement of that region within the perimeter of the rectangle in square units.
MC-Area-A	Area of Rectangles	The area of a rectangle in square units is the product of the measurements of the length and width dimensions of the rectangle.
MC-Area-A	Inscribed-Circumscribed Rectangles	An inscribed rectangle is the largest rectangle that can be drawn within an irregular shape that intersects the edge of the irregular shape but does not go beyond it.
MC-Area-A	Inscribed-Circumscribed Rectangles	A circumscribed rectangle is the smallest rectangle that can be drawn that will completely enclose the irregular shape.
MC-Area-A	Surface Area	The surface area is the measurement in square units of a region that is the outer most layer of an object.
MC-Area-B	Using Riemann Sum	Irregularly shaped areas can be approximated using a series of inscribed or circumscribed rectangles.

MC-Area-B	Using Riemann Sum	Irregularly shaped areas approximated using a series of inscribed rectangles will produce and underestimation of the true area.
MC-Area-B	Using Riemann Sum	Irregularly shaped areas approximated with a series of circumscribed rectangles will produce an over estimation of the true area.
MC-Area-B	Using Riemann Sum	More accurate estimates of the area of an irregularly shaped region can be obtained by minimizing the width of the rectangles used to find the estimate the area.
MC-RateCond-A	Rate of Production per Unit Area	The rate of production is the amount of material produced in a given time.
MC-RateCond-B	Rate of Production per Unit Area	Changing quantities of materials can be averaged over an effective unit area.
MC-RateCond-B	Rate of Production per Unit Area	Production rates of different systems can be compared on a per unit basis.
MC-Slope-A	Rate of Change	The rate of change of a quantity is the ratio of the change of the quantity in relation to the change of another variable.
MC-Slope-B	Slope is the Rate of Change	The slope of a linear function of two variables is equal to the rate of change of those variables.

Appendix I

Modification to Prior Study MTMC Test Items

Item Source	Original Item Excerpt	Modified Excerpt
Aydeniz et al., 2017	At room temperature (25^{o}C), there is an open plastic bottle half-filled with water. If this bottle were left for several days in this room, what would happen to the level of water in the bottle? (Note: The humidity in the air should be considered too little).	At room temperature (25^{o}C), there is an open plastic bottle half-filled with water. If this bottle were left for several days in this room, what would happen to the level of water in the bottle? (Note: The humidity in the air should be thought of as not having any effect).
Canpolat, 2006	At a constant temperature, the below open containers A and B contain 100ml of pure water. Compare the evaporation rate of the water in the containers. Explain your answers as best as you can.	At a constant temperature, the below open containers A and B contain 100ml of pure water. Compare the evaporation rate of the water in the containers. d) The water in container A will evaporate faster than container B. e) The water in container A will evaporate slower than container B. f) The water in both containers will evaporate at the same rate.
Canpolat, 2006	There is a closed container in which water is in equilibrium with its vapor. At constant temperature, what could be said about the vapour pressure of water? Explain your answer as carefully as you can.	A clear plastic water bottle is half filled with water that is at room temperature and a cap is tightly screwed onto the bottle. Over time, what will happen to the evaporation rate of the water? a) The evaporation rate will increase. b) The evaporation rate will decrease to zero. c) The evaporation rate will increase then decrease to zero. d) The evaporation rate will increase then remain constant.
Coştu et al., 2012	A watch glass is carefully placed on an electrical heater in which there is a small amount of boiling water. A few minutes later, many tiny water droplets appear on the watch glass surface. Why does this this event occur? Please explain in detail.	A watch glass is placed on a glass container which is sitting on an electrical heater. There is boiling water in the glass container. What will an observer see after a few moments? a) There will be no change in the system. b) Tiny droplets of water will appear on the inside of the watch glass. c) The watch glass will become clear and will start to slowly rotate. Water will collect on the outside of the watch glass.

Coştu et al., 2012	What happens to the hot water and interior surface of each tall plastic cups after a tall plastic cup is placed upside down over each of the wide cups and then a cube of ice is place on one of the upside down cups. Discuss you predictions in your group.	Two same sized wide-mouth cups of hot water are placed on a table and labeled cup A and Cup B. Two identical tall plastic cups are turned upside down and placed over the wide mouth plastic cups with hot water in them. An ice cube is placed on the inverted tall plastic cup that is over cup B. What can you say about the condensation rates in each of the tall plastic cups? a) The condensation rate in the tall plastic cup over cup A will be greater than the condensation rate in the tall plastic cup over cup B. b) The condensation rate in the tall plastic cup over cup B will be greater than the condensation rate in the tall plastic cup over cup A. The condensation rates in the tall plastic cups over cup A and cup B will be the same.
Menon, 1998	Given the area of a rectangle is 24 sq cm, find the perimeter of the figure if the length is 6 cm.	Given the area of a rectangle is 24 sq cm, find the perimeter of the rectangle if the length is 6 cm. a) The perimeter is 30 cm. b) The perimeter is 36 cm. c) The perimeter is 24 cm. d) The perimeter is 20 cm.
Sisman & Aksu, 2016	Students were also asked to calculate the surface area of a rectangular prism in which all dimensions were given (task 6).	(Image Rectangular prism with sides 5in, 3in, and 2 in.) Given the above rectangular prism, determine the surface area of the figure. a) The surface area of the given rectangular prism is 30 sq. in. b) The surface area of the given rectangular prism is 62 sq. in. c) The surface area of the given rectangular prism is 40 sq. in. d) The surface area of the given rectangular prism is 15 sq. in.
Tasman et al., 2020)	Image of a parabolic curve with a series of rectangles inscribed under the curve. Why will the inscribe polygon's area never be larger than area under the curve and the circumscribed polygon never be less than area under the curve"	Image of a parabolic curve with a series of rectangles inscribed under the curve. If the area under the curve in figure A above was to be determined, summing the rectangular areas that are shaded would produce; a) An under-estimation of the area under the curve. b) An over-estimation of the area under the curve.

		c) An exact value of the area under the curve.
Tasman et al., 2020)	Image of a parabolic curve with a series of rectangles inscribed under the curve. Why will the inscribe polygon's area never be larger than area under the curve and the circumscribed polygon never be less than area under the curve"	Image of a parabolic curve with a series of rectangles circumscribed under the curve. If the area under the curve in figure A above was to be determined, summing the rectangular areas that are shaded would produce; a) An under-estimation of the area under the curve. b) An over-estimation of the area under the curve. c) An exact value of the area under the curve.

Appendix J

Diagnostic Item Review Rubric

Item #1 Targeted Propositional Knowledge Statement (PKS) 1a and 1c.
Tier 1: (Source: Aydeniz et al., 2017) At room temperature (25^{o}C), there is an open plastic bottle half-filled with water. If this bottle were left for several days in this room, what would happen to the level of water in the bottle? (Note: The humidity in the air should be thought of as not having any effect). D) The level of water decreases. E) The level of water stays the same. F) The level of water increases
Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐ If yes, please provide revisions below.
Tier 1 Revisions:
Tier 2: Which of the following best describes the reason for your answer for the previous question? b) In order for evaporation to take place, temperature has to be increased. c) Water evaporates with its own energy at every temperature. d) Water evaporates at or above its boiling point which is 100^{o}C. e) In order for evaporation to take place, a liquid has to take heat from its environment. f) Hot air condenses in the bottle.
Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐ If yes, please provide revisions below.
Tier 2 Revisions:

Item #2

(Targeted Propositional Knowledge Statement 1f.)

Tier 1: (Source: Canpolat, 2006)
At a constant temperature, the below open containers A and B contain 100ml of pure water. Compare the evaporation rate of the water in the containers.
Needed Illustration of wide mouth vessel and Erlenmeyer flask here

g) The water in container A will evaporate faster than container B.
h) The water in container A will evaporate slower than container B.
i) The water in both containers will evaporate at the same rate.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 1 Revisions:

Tier 2:
Which of the following best describes the reason for your answer for the previous question?

a) In an open system, the evaporation rates are solely affected by the temperature of the liquid. Since both containers are at the same temperature they will evaporate at the same rate.
b) The water vapor in container A will be funneled up and out of the container leading to faster evaporation.
c) Evaporation in an open system is dependent on surface area. Container B has more surface area so it will evaporate faster.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 2 Revisions:

Item #3

(Targeted Propositional Knowledge Statement 1a and 1b.)

Tier 1: (Source: Hainsworth)

Sandy spills some water on a lab bench and it forms a puddle at room temperature. Which of the following will happen if she leaves the room without cleaning it up?

a) The puddle of water will get smaller.
b) The puddle of water will get bigger.
c) The puddle of water will remain the same size.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 1 Revisions:

Tier 2

Which of the following best describes the reason for your answer for the previous question?

a) Some water molecules at the surface of the liquid have enough kinetic energy to escape from the liquid phase and become vapor
b) Water molecules at the surface of the water are heated which breaks them into hydrogen gas and oxygen gas which then leave the liquid phase.
c) Heat causes water molecules to get lighter in mass. Some molecules become light enough to leave the liquid phase and become water vapor.
d) Natural water vapor in the air is attracted to liquid water and attaches to it.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 2 Revisions:

Item #4

(Targeted Propositional Knowledge Statement 1d.)

Tier 1: (Source: Hainsworth)

Water is sprayed onto the outside of a ceramic jar containing water in the inside. A highly sensitive thermometer is placed into the water contained inside the ceramic jar. The jar, that is now wet on the outside, is placed in a room with a slight breeze. In a short time, with repeated spray applications of water, what will happen to the reading on the thermometer?

a) The reading on the thermometer will be higher than when you started.
b) The reading on the thermometer will be lower than when you started.
c) The reading on the thermometer will be the same as when you started.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 1 Revisions:

Tier 2

Which of the following best describes the reason for your answer for the previous question?

a) The liquid water molecules on the outside of the jar insulate the jar from further loss or gain of heat energy.
b) The water on the outside of the jar adds heat to the jar making the contents warmer.
c) The liquid water molecules on the outside of the jar absorb energy from the jar and become vapor. This loss of energy causes cooling of the jar.
d) The liquid water molecules on the outside of the jar require heat energy to stay in place and therefore heat their surroundings.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 2 Revisions:

Item #5

(Targeted Propositional Knowledge Statement 1i and 1j.)

Tier 1: (Source: Hainsworth)

Samantha collects a muddy water sample from a local creek in a clear water bottle. She puts a cap tightly on the bottle and notices that the sides of the bottle are crystal clear above the muddy water sample. She also notices that the water is staying muddy colored due to its suspended solids. She places the sealed bottle in the sun and leaves. When she returns, what do you think she will see on the inside of the bottle above the muddy water?

a) Small droplets of water that are muddy colored have formed on the inside of the bottle above the muddy water.
b) Small clear droplets of water have formed on the inside of the bottle above the muddy water.
c) A layer of dried mud has formed above the muddy water.
d) There should be no change in what the inside of the bottle looks like.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 1 Revisions:

Tier 2

Which of the following best describes the reason for your answer for the previous question?

a) The mud in the water is a solute and the water is the solvent in this muddy water solution. Solutes evaporate with the solvent when the solution evaporates. When muddy water evaporates within the bottle, it carries with it some mud particles which condenses on the side of the bottle along with the water droplets.
b) The mud in the water is a solute and the water is the solvent in this muddy water solution. Solutes do not evaporate with the solvent when the solution evaporates. When the water evaporates within the bottle, it does not carry any of the mud particles with it and condenses as clear droplets on the side of the water bottle
c) The solids within the muddy water solution volatilize and condense on the sides of the water bottle forming a solid layer. This is due to the ability of wet solids to change phases.
d) The mud particles within the muddy water solution stops evaporation of any kind within the bottle. The liquid water will undergo no change of state.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 2 Revisions:

Item #6

(Targeted Propositional Knowledge Statement 1g.)

Tier 1: (Source Canpolat, 2006)

A clear plastic water bottle is half filled with water that is at room temperature and a cap is tightly screwed onto the bottle. Over time, what will happen to the evaporation rate of the water?

e) The evaporation rate will increase.
f) The evaporation rate will decrease to zero.
g) The evaporation rate will increase then decrease to zero.
h) The evaporation rate will increase then remain constant.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 1 Revisions:

Tier 2
Which of the following best describes the reason for your answer for the previous question?

a) The evaporation rate of water in a closed system will remain constant due to an equilibrium that is established between evaporation and condensation rates.
b) The vapor pressure above the water will increase causing a decrease in evaporation rate.
c) The water above the liquid will become humid which will increase the evaporation rate over time to zero.
d) The evaporation rate will be zero as soon as the cap is tightened and no air is allowed to escape the system.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 2 Revisions:

Item #7

(Targeted Propositional Knowledge Statement 1k.)

Tier 1: (Source: Hainsworth)
Salt water is placed into a jar. The jar has no top on it and it is left out on a counter in a room for several days. What will happen to the concentration of the salt water within the jar over time?

a) The concentration of the salt water within the jar will remain constant.
b) The concentration of salt water within the jar will increase.
c) The concentration of salt water within the jar will decrease.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 1 Revisions:

Tier 2
Which of the following best describes the reason for your answer for the previous question?

a) Since no salt is being removed from the jar there will be no change in the concentration of the salt water.

b) Since salt will evaporate along with the water in the jar there will be no net change in the concentration of salt water in the jar.
c) Since only water evaporates from the jar the concentration of salt water in the jar will increase.
d) Since only water evaporates from the jar the concentration of salt water in the jar will decrease.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 2 Revisions:

Item #8

(Targeted Propositional Knowledge Statement 2a and 2b)

Tier 1: (Source: Coştu et al., 2012) **(Image needed)**
A watch glass is placed on a glass container which is sitting on an electrical heater. There is boiling water in the glass container. What will an observer see after a few moments?
d) There will be no change in the system.
e) Tiny droplets of water will appear on the inside of the watch glass.
f) The watch glass will become clear and will start to slowly rotate.
g) Water will collect on the outside of the watch glass.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 1 Revisions:

Tier 2
Which of the following best describes the reason for your answer for the previous question?
a) Water vapor is lighter than liquid water and rises up to push the watch glass in rotational direction.
b) Heating of the watch glass adds energy to the system which allows humidity in the surroundings to collect on the watch glass.
c) No water is being removed from the overall surroundings so evaporative losses will be insignificant.
d) Gaseous phase water molecules lose energy to the watch glass allowing the gaseous molecules to combine to form liquid water droplets.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 2 Revisions:

Item #9

(Targeted Propositional Knowledge Statement 2a and 2b.)

Tier 1: (Source: Hainsworth)
A cold soda bottle is removed from the refrigerator on a warm and humid day and placed on the counter top. After a few minutes, small water droplets appear on the outside of the bottle. As these droplets form, what will happen to the temperature of the outside of the soda bottle?

a) The temperature of the outside of the soda bottle will decrease.
b) The temperature of the outside of the soda bottle will increase.
c) The temperature of the outside of the soda bottle will stay the same.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 1 Revisions:

Tier 2
Which of the following best describes the reason for your answer for the previous question?

a) Gaseous water molecules lose kinetic energy to the water bottle which causes the water molecules to combine to form liquid water droplets which raises the temperature of the soda bottle.
b) Gaseous water molecules stick to the outside of the soda bottle causing them to form liquid water droplets. This collection of water on the outside surface cools the soda bottle.
c) The soda bottle that has just been taken from the refrigerator has microscopic ice particles on it that slowly melt to form water droplets. This cools the outside of the soda bottle.
d) The outside of the water bottle will not change temperature due to an equilibrium that is established between the cold internal liquid and the warm surrounding air.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 2 Revisions:

Item #10

(Targeted Propositional Knowledge Statement 2f, and 2g.)

Tier 1: (Source: Coştu et al., 2012)
Image required.
Two same sized wide-mouth cups of hot water are placed on a table and labeled cup A and Cup B. Two identical tall plastic cups are turned upside down and placed over the wide mouth plastic cups with hot water in them. An ice cube is placed on the inverted tall plastic cup that is over cup B. What can you say about the condensation rates in each of the tall plastic cups?

c) The condensation rate in the tall plastic cup over cup A will be greater than the condensation rate in the tall plastic cup over cup B.
d) The condensation rate in the tall plastic cup over cup B will be greater than the condensation rate in the tall plastic cup over cup A.
e) The condensation rates in the tall plastic cups over cup A and cup B will be the same.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 1 Revisions:

Tier 2:
Which of the following best describes the reason for your answer for the previous question?

a) Condensation rates are solely dependent on the surface area that condensation occurs on. Since the cups are the same size there will be no difference in the condensation rates.
b) Condensation rates are affected by the temperature of the air above a liquid. Both cups have hot water that is heating the air and therefore will be the same temperature. The condensation rates should be the same.
c) Condensation rates increase with increasing temperature. The hotter the environment is the more water vapor there will be in the air which will lead to greater condensation rates.
d) Condensation rates increase as the temperature of the surface the water vapor is in contact with decreases.
e) Your own write in reason……

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 2 Revisions:

Item #11

(Targeted Propositional Knowledge Statement 2e.)

Tier 1: (Source: Hainsworth)
Jean has a water bottle that is filled with ice water. She is fascinated by the droplets of water that appear on the outside of the water bottle. She has been told that these droplets of water are formed by the process of condensation. She would like to determine the rate of condensation. How could she best determine the rate of condensation?

a) Jean could place a bowl of hot water next to the cold water bottle and measure the amount of water that evaporates from the bowl.
b) Jean could wipe the water droplets into a container and measure the amount of water that she collected in milliliters.
c) Jean could tap the water bottle periodically so that water droplets would fall into a collection device. She would then measure the volume of water collected over a given amount of time.
d) Jean could place a paper towel under the water bottle and let it sit for a while. She would then squeeze out the water into a container and measure the collected volume of water.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 1 Revisions:

Tier 2
Which of the following best describes the reason for your answer for the previous question?

a) Condensation rates can be determined by measuring the volume of condensed liquid.
b) Condensation rates can be determined by measuring the area of condensation that has occurred.
c) Condensation rates can be determined by measuring the given volume of a condensed liquid over a given amount of time.
d) Condensation rates can be determined by understanding that evaporative losses in the near vicinity are equivalent to condensation production.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 2 Revisions:

Item #12

(Targeted Propositional Knowledge Statement 3a and 3b.)

Tier 1: (Source: Menon, 1998)
Given the area of a rectangle is 24 sq cm, find the perimeter of the rectangle if the length is 6 cm.

e) The perimeter is 30 cm.
f) The perimeter is 36 cm.
g) The perimeter is 24 cm.
h) The perimeter is 20 cm.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 1 Revisions:

Tier 2
Which of the following best describes the reason for your answer for the previous question?

a) The area of a rectangle in square units is the product of the measurements of the length and width dimensions of the rectangle. The perimeter of a rectangle is the sum of all the sides.
b) The perimeter of a rectangle in square units is the product of the measurements of the length and width dimensions of the rectangle. The area of a rectangle is the sum of all the sides.
c) The sum of the area of a rectangle and a length is equal to the perimeter of a rectangle.
d) The sum of the sides of a rectangle is equal to the perimeter and the area of the rectangle.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 2 Revisions:

Item #13

(Targeted Propositional Knowledge Statement 3a and 3b.)

Tier 1: (Source: Hainsworth) Targeted PKS 3a and 3b

A rectangular rain cover that is 9 ft long and 4 ft wide is hung up over a small deck. What is the area of the rain cover that rain can impact on?

a) 26 sq. ft.
b) 36 sq. ft.
c) 26 ft.
d) 36 ft.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 1 Revisions:

Tier 2

Which of the following best describes the reason for your answer for the previous question?

a) The area of a rectangle in square units is the product of the measurements of the length and width dimensions of the rectangle.
b) The area of a rectangle in linear units is the sum of the measurements of the lengths and widths of the rectangle.
c) The area of a rectangle in linear units is the square of the measurements of the length dimension of the rectangle.
d) The area of the rectangle in square units is the sum of the measurements of the edges of the outside dimensions of the rectangle.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 2 Revisions:

Item #14

(Targeted Propositional Knowledge Statement 3e.)

Tier 1: (Source: (Sisman & Aksu, 2016)

Image needed. (Rectangular prism with sides 5in, 3in, and 2 in.)

Given the above rectangular prism, determine the surface area of the figure.

e) The surface area of the given rectangular prism is 30 sq. in.
f) The surface area of the given rectangular prism is 62 sq. in.
g) The surface area of the given rectangular prism is 40 sq. in.
h) The surface area of the given rectangular prism is 15 sq. in.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 1 Revisions:

Tier 2

Which of the following best describes the reason for your answer for the previous question?

a) The surface area is the measurement in square units of the outermost layer of an object.
b) The surface area of an object is the measurement in square units of the sum of the sides of the object.
c) The surface area of an object is the amount of space in square units that it can hold within it.
d) The surface area of an object is the measurement in square units of the uppermost surface of the object.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 2 Revisions:

Item #15

(Targeted Propositional Knowledge Statement

Tier 1: (Source: Tasman et al., 2020)
Image needed (Image should be of a right triangle with rectangles inscribed, midpoint and circumscribed with the rectangles labeled A,B, and C)

Given the above figure, which rectangle would be described as being inscribed?

a) Rectangle A is an inscribed rectangle.
b) Rectangle B is an inscribed rectangle.
c) Rectangle A is an inscribed rectangle.
d) Rectangles A and B are inscribed rectangles.
e) Rectangles A and C are inscribed rectangles.
f) Rectangles B and C are inscribed rectangles.
g) None of the rectangles are inscribed.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 1 Revisions:

Tier 2:
Which of the following best describes the reason for your answer for the previous question?

a) An inscribed rectangle is a rectangle that has a portion of its area enclosed within another shape.
b) An inscribed rectangle is a rectangle enclosed in an irregular shape which does not intersect the boundary of the irregular shape, except potentially at the corners.
c) An inscribed rectangle encloses another shape.
d) An inscribed rectangle has only one corner that intersects another shape.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 2 Revisions:

Item #16

(Targeted Propositional Knowledge Statement

Tier 1: (Source: Hainsworth)
Image needed: The image will be an irregular closed shape with curved sides. It will be on a separate sheet of paper that students can access. Students will be provided with a ruler and calculator for the calculation.

Given the irregular shape in Figure A, what is the closest approximate area in square inches of the shaded region?

a) 56 in^2 (These need to be adjusted to the actual figure)
b) 56 in^2
c) 56 in^2
d) 56 in^2

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 1 Revisions:

Tier 2:
Which of the following best describes the reason for your answer for the previous question?

a) Finding the area of a single circumscribed rectangle to the irregular shape is the best way to estimate the area of the irregular shape.
b) Finding the area of a single inscribed rectangle to the irregular shape is the best way to estimate the area of the irregular shape.
c) Multiplying a series of rectangular shapes that are similar to the irregular shape and then dividing by the number of rectangles is the best way to estimate the area of the irregular shape.
d) Summing the areas of a series of smaller inscribed (or circumscribed) rectangles associated with the irregular shape will be the best way to estimate the area of the irregular shape.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 2 Revisions:

Item #17

(Targeted Propositional Knowledge Statement

Tier 1: (Source: (Tasman et al., 2020))
Image needed of a parabolic curve with a series of rectangles inscribed under the curve.

If the area under the curve in figure A above was to be determined, summing the rectangular areas that are shaded would produce;

d) An under-estimation of the area under the curve.
e) An over-estimation of the area under the curve.
f) An exact value of the area under the curve.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 1 Revisions:

Tier 2:
Which of the following best describes the reason for your answer for the previous question?

a) The rectangles that are being used for finding the area under the curve do not cover all of the area and therefore would provide an under-estimation.
b) The rectangles that are being used for finding the area under the curve cover more than the targeted area and therefore would provide an over-estimation.

c) The rectangles that are being used for finding the area under the curve cover all of the targeted area and therefore would provide an exact value.

Do you wish to make and editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 2 Revisions:

Item #18

(Targeted Propositional Knowledge Statement

Tier 1: (Source: (Tasman et al., 2020))
Image needed of a parabolic curve with a series of rectangles circumscribed under the curve.

If the area under the curve in figure A above was to be determined, summing the rectangular areas that are shaded would produce;

d) An under-estimation of the area under the curve.
e) An over-estimation of the area under the curve.
f) An exact value of the area under the curve.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 1 Revisions:

Tier 2:
Which of the following best describes the reason for your answer for the previous question?

a) The rectangles that are being used for finding the area under the curve do not cover all of the area and therefore would provide an under-estimation.
b) The rectangles that are being used for finding the area under the curve cover more than the targeted area and therefore would provide an over-estimation.
c) The rectangles that are being used for finding the area under the curve cover all of the targeted area and therefore would provide an exact value.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 2 Revisions:

Item #19

(Targeted Propositional Knowledge Statement

Tier 1: (Source: Hainsworth)
An image is needed of a tear drop shape with fairly large circumscribed rectangles in it.

If the area of the teardrop shape shown above in Figure A was to be estimated using the sum of the rectangles that have been circumscribed, what could you do to create a more accurate estimation?

a) Use inscribed rectangles rather than circumscribed rectangles.
b) Circumscribe more rectangles that are thinner and sum their areas
c) In this case use one circumscribed rectangle to enclose the entire tear drop shape, find its area and multiply by 0.75.
d) Use and inscribed rectangle, find an area and multiply by 1.25.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 1 Revisions:

Tier 2:
Which of the following best describes the reason for your answer for the previous question?

a) Inscribed rectangles will use less space than circumscribed rectangles therefore giving more accurate area estimations.
b) A greater number of thinner circumscribed rectangles will great a smaller amount of over estimation therefore making it more accurate.
c) The area of the teardrop shape is two thirds the area of circumscribed rectangle.
d) The area of an inscribed rectangle within an irregular shape is at least one quarter smaller that the irregular shapes area.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 2 Revisions:

Item #20

(Targeted Propositional Knowledge Statement

Tier 1: (Source: Hainsworth)
A faucet in a sink is steadily dripping water. You place a graduated cylinder under the faucet to capture the drips. After 45 minutes you find that you have captured 75 ml of water in the graduated cylinder. What is the production rate of water that has dripped from the faucet?

a) 45ml of water
b) 75ml of water/min
c) 0.6 ml of water/inch of cylinder
d) 1.67 ml of water/min

Do you wish to make and editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 1 Revisions:

Current Item 20 Tier 2
Which of the following best describes the reason for your answer for the previous question?

a) The rate of production is the amount of material produced in a given time.
b) The rate of production is the amount of material produced.
c) The rate of production of a material is the overall time for the measurement to take place.
d) The rate of production is the amount of material produced per the dimensions of the collection device.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 2 Revisions:

Item #21

(Targeted Propositional Knowledge Statement

Tier 1: (Source: Hainsworth)
Ryleigh and Martina were each designing artificial spider webs to capture flies. Ryleigh's spider web was 100 square centimeters in area and caught 7 flies in 22 minutes. Martina's spider web was 70 square inches and caught 6 flies in 19 minutes. Which spider web design was more efficient? (Assume the amount of available flies in the test location is the same for each student)

a) Ryleigh's spider web design was most efficient
b) Martina's sider web design was most efficient
c) Ryleigh's and Martina's designs were equally efficient

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 1 Revisions:

Tier 2:
Which of the following best describes the reason for your answer for the previous question?

a) Ryleigh caught 7 flies.
b) Martina caught 0.005 flies/minute/square centimeter
c) Ryleigh caught 0.003 flies/minute/square centimeter.
d) Both designs captured approximately the same number of flies per minute.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 2 Revisions:

Item #22

(Targeted Propositional Knowledge Statement

Tier 1: (Source: Hainsworth)
Tyler and Maria are each designing a water mist collection device that will capture excess water from an outdoor restaurant's cooling processes. Tyler's collection device has an area of 12 square feet and collects 500mls/hour. Maria's collection device has an area of 10 square feet collects 450ml/hour. Which device is most efficient?

a) Tyler's device is most efficient.
b) Maria's device is most efficient
c) Tyler's and Maria's collection devices were equally efficient

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 1 Revisions:

Tier 2:
Which of the following best describes the reason for your answer for the previous question?

a) Tyler collected 500mls in one hour.
b) Tyler collected 6000mls of the entire collection device.
c) Maria collected 45ml/hr/ft^2
d) Maria collected 4500 mls

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 2 Revisions:

Item #23

(Targeted Propositional Knowledge Statement

Tier 1: (Source: Hainsworth)
Mark has a rain gauge on his deck. It is a small glass graduated cylinder that allows a person to measure the amount of rain that is captured in it. He notes there are 10ml of water in the rain gauge before a thunderstorm arrives. Ninety minutes later, after the storm passes, he reads that here are 35 ml in the gauge. What is the rate of change of the rainwater in the rain gauge over this time period?

a) The rate of change of rainwater in the rain gauge is 900 ml in one hour.
b) The rate of change of rainwater in the rain gauge 13,500 ml.
c) The rate of change of rainwater in the rain gauge is 0.36 min/ml.
d) The rate of change of rainwater in the rain gauge is 0.28 ml/min

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 1 Revisions:

Tier 2:
Which of the following best describes the reason for your answer for the previous question?

a) The rate of change of a quantity is the initial amount of a quantity times the duration of the event.
b) The rate of change of a quantity is the ratio of the change of the quantity in relation to the change of another quantity.
c) The rate of change of a quantity is the change of a quantity times the change of another quantity.
d) The rate of a change of a quantity is the change in time divided by the change in another quantity.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 2 Revisions:

Item #24

(Targeted Propositional Knowledge Statement

Tier 1: (Source: Hainsworth)
Mathias measured the amount of motor oil dripping out of the engine of a classic car he was restoring. He placed an empty measuring device under the leak and left it overnight. Sixteen hours later he returned and found that he had collected 32 ml of oil. He left the container without emptying it and came back again after 16 hours to find that the total about of oil collected was 64 ml. He plotted his data on an x-y coordinate grid with time on the x-axis and

milliliters collected on the y-axis. He calculated the slope of the straight line that was formed and found it to be 2 ml/hr. What is the rate of change of the motor oil in the collection device?

a) 2 ml of oil/hr
b) ½ ml of oil/hr
c) 64 ml of oil
d) 32 minutes

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 1 Revisions:

Tier 2:

Which of the following best describes the reason for your answer for the previous question?

a) The rate of change of two variables is the total time that has elapsed for the event.
b) The rate of change of two variables is the total amount of one quantity that is being analyzed.
c) The rate of change of a variable is the is the inverse of the slope of the linear function.
d) The slope of a linear function of two variables is equal to the rate of the change of those variables.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 2 Revisions:

Item #25

(Targeted Propositional Knowledge Statement

Tier 1: (Source: Hainsworth)

Maya is an engineer who has designed a mechanical press to remove orange juice from oranges for a small local organic orange grower in Florida. She starts the press and measures how much orange juice is collected over time. She watches the collection container, which has volume marks on the side, and sees that in 15 minutes she has collected 10 gallons of orange juice. At 45 minutes she sees that she has collected 30 gallons of orange juice. What is the rate of change of orange juice in the collection container?

a) 3/2 gallons/min
b) 30 gallons
c) 45 minutes
d) 2/3 gallons/min

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 1 Revisions:

Tier 2:

Which of the following best describes the reason for your answer for the previous question?

a) The slope of the linear function of the two variables is equal to the rate of change of those variables.
b) The rate of change of the two variables is the total amount of time that has elapsed for an event.
c) The rate of change of two variables is the total quantity that is being analyzed.
d) The rate of change of a variable is the inverse of the slope of a linear function.

Do you wish to make an editorial change? Please check your decision: No ☐ Yes ☐

If yes, please provide revisions below.

Tier 2 Revisions:

Appendix K

Diagnostic Item Round 1 Arbitration Results Summary

Item	Tier	Current Diagnostic Item	Proposed Revisions	Refined Diagnostic Item
Item 1	Tier 1	At room temperature (25ºC), there is an open plastic bottle half-filled with water. If this bottle were left for several days in this room, what would happen to the level of water in the bottle? (Note: The humidity in the air should be thought of as not having any effect). D) The level of water decreases. E) The level of water stays the same. F) The level of water increases	PM-1 An open plastic bottle half-filled with water is left on a counter at room temperature for several days. What happens to the level of water in the bottle? (I find the humidity note confusing, and maybe unnecessary. It only has an effect if it is 100%) I'm also getting a bit tripped up on tense. What will happen? What happens? PM-2 There is an open plastic bottle half-filled with water at room temperature (25º C = 77 º F). If this bottle were left for several days in this room, what would happen to the level of water in the bottle? Assume that the humidity in the air has no effect. G) The level of water will decrease.	There is an open plastic bottle half-filled with water at room temperature (70 º F). If this bottle were left for several days in this room, what would happen to the level of water in the bottle? A) The level of water will decrease. B) The level of water will stay the same. C) The level of water will increase

			H) The level of water will stay the same. I) The level of water will increase PM-3 A PM-4 At room temperature (25^oC), there is an open plastic bottle half-filled with water. If this bottle were left for several days in this room (which is not an equilibrium system), what would happen to the level of water in the bottle? (Note: The humidity in the air should be thought of as not having any effect). a) The level of water decreases. b) The level of water stays the same. The level of water increases PM-5 A	
Item 1	Tier 2	Which of the following best describes the reason for your answer for the previous question? f) In order for evaporation to take place, temperature has to be increased.	PM-1 I'm not sure if the best answer is B or D.	Which of the following best describes the reason for your answer for the previous question?

		g) Water evaporates with its own energy at every temperature. h) Water evaporates at or above its boiling point which is 100°C. i) In order for evaporation to take place, a liquid has to take heat from its environment. j) Hot air condenses in the bottle.	PM-2 Which of the following best describes the reason for your answer for the previous question? g) In order for evaporation to take place, temperature has to be increased. h) Water evaporates *with its own energy (???)* at every temperature. i) Water evaporates at or above its boiling point which is 100° C=212 °F. (add space before C) j) In order for evaporation to take place, a liquid has to take heat from its environment. The water will take energy from the environment to escape into a vapor state k) Hot air condenses in the bottle. PM-3 I'd suggest choice "e" be revised to a) Water vapor condenses in the bottle.	a) In order for evaporation to take place, temperature has to be increased. b) Water evaporates with its own energy at every temperature. c) Water evaporates at or above its boiling point which is 212 °F. d) In order for evaporation to take place, a liquid has to take heat from its environment. e) Water vapor condenses in the bottle.

			It is possible to condense air – but it doesn't make sense if the goal is to provide an option for students with the misconception that the "level of water increases" PM-4 A PM-5 A	
Item 2	Tier 1	At a constant temperature, the below open containers A and B contain 100ml of pure water. Compare the evaporation rate of the water in the containers. *Needed Illustration of wide mouth vessel and Erlenmeyer flask here* j) The water in container A will evaporate faster than container B. k) The water in container A will evaporate slower than container B. l) The water in both containers will evaporate at the same rate.	PM-1 The open containers A and B contain 100mL of pure water at constant temperature. Compare the evaporation rate of the water in the containers. PM-2 A PM-3 As represented in the figure, there is about twice as much water in container A when compared to container B. I think it would be better if the volumes looked equivalent. PM-4 At a constant temperature, the below open containers A and B contain 100mL of pure water.	The open containers A and B contain 100mL of pure water at constant temperature. Compare the evaporation rate of the water in the containers. a) The water in container A will evaporate faster than container B. b) The water in container A will evaporate slower than container B. c) The water in both containers will evaporate at the same rate.

			Compare the evaporation rate of the water in the containers. PM-5 Add humidity assumption if necessary	
Item 2	Tier 2	Which of the following best describes the reason for your answer for the previous question? d) In an open system, the evaporation rates are solely affected by the temperature of the liquid. Since both containers are at the same temperature they will evaporate at the same rate. e) The water vapor in container A will be funneled up and out of the container leading to faster evaporation. f) Evaporation in an open system is dependent on surface area. Container B has more surface area so it will evaporate faster.	PM-1 A PM-2 A PM-3 A PM-4 A PM-5 A	No Change Needed. Expert Panel at 100% Agreement.
Item 3	Tier 1	Sandy spills some water on a lab bench and it forms a puddle at room temperature. Which of the following will happen if she leaves the room without cleaning it up? d) The puddle of water will get smaller. e) The puddle of water will get bigger. f) The puddle of water will remain the same size.	PM-1 A PM-2 Sandy spills some water on a lab bench and it forms a puddle at room temperature. Which of the following will happen if she leaves the puddle ~~if she leaves the room~~ without cleaning it up?	Sandy spills some water on a lab bench and it forms a puddle at room temperature. Which of the following will happen if she leaves the room without cleaning it up? a) The puddle of water will get smaller. b) The puddle of water will get bigger. c) The puddle of water will remain the same size.

			a) The puddle of water will get smaller. b) The puddle of water will get bigger. c) The puddle of water will remain the same size. PM-3 A PM-4 A PM-5 A	
Item 3	Tier 2	Which of the following best describes the reason for your answer for the previous question? e) Some water molecules at the surface of the liquid have enough kinetic energy to escape from the liquid phase and become vapor f) Water molecules at the surface of the water are heated which breaks them into hydrogen gas and oxygen gas which then leave the liquid phase. g) Heat causes water molecules to get lighter in mass. Some molecules become light enough to leave the liquid phase and become water vapor. h) Natural water vapor in the air is attracted to liquid water and attaches to it.	PM-1 A PM-2 A PM-3 Consider an additional choice a) The water molecules are at rest and remain in the puddle unless disturbed. PM-4 A PM-5 A	Which of the following best describes the reason for your answer for the previous question? a) Some water molecules at the surface of the liquid have enough kinetic energy to escape from the liquid phase and become vapor b) Water molecules at the surface of the water are heated which breaks them into hydrogen gas and oxygen gas which then leave the liquid phase. c) Heat causes water molecules to get lighter in mass. Some molecules become light enough to leave the liquid phase and become water vapor. d) Natural water vapor in the air is attracted to liquid water and attaches to it.

				e) The water molecules are at rest and remain in the puddle unless disturbed
Item 4	Tier 1	Water is sprayed onto the outside of a ceramic jar containing water in the inside. A highly sensitive thermometer is placed into the water contained inside the ceramic jar. The jar, that is now wet on the outside, is placed in a room with a slight breeze. In a short time, with repeated spray applications of water, what will happen to the reading on the thermometer? d) The reading on the thermometer will be higher than when you started. e) The reading on the thermometer will be lower than when you started. f) The reading on the thermometer will be the same as when you started.	PM-1 Water is sprayed onto the outside of a ceramic jar containing water in the inside. A highly sensitive thermometer is placed into the water contained inside the ceramic jar. The jar, now wet on the outside, is placed in a room with a slight breeze. In a short time, with repeated spray applications of water, what will happen to the temperature inside the jar? a) The temperature of the water in the jar will increase. b) The temperature of the water in the jar will decrease. c) The temperature of the water in the jar will stay the same. PM-2 A ceramic jar containing water has a highly sensitive thermometer placed inside. Water is then sprayed onto the outside of the jar. The jar, which	A ceramic jar containing water has a highly sensitive thermometer placed inside. Water is then sprayed onto the outside of the jar. The jar, which is now wet on the outside, is placed in a room with a slight breeze. After a short time with repeated spray applications of water, what will happen to the reading on the thermometer? a) The temperature of the water in the jar will increase. b) The temperature of the water in the jar will decrease. c) The temperature of the water in the jar will stay the same.

			is now wet on the outside, is placed in a room with a slight breeze. After a short time with repeated spray applications of water, what will happen to the reading on the thermometer? a) The reading on the thermometer will be higher than when you started. b) The reading on the thermometer will be lower than when you started. c) The reading on the thermometer will be the same as when you started. PM-3 A PM-4 A PM-5 A	
Item 4	Tier 2	Which of the following best describes the reason for your answer for the previous question? e) The liquid water molecules on the outside of the jar insulate the jar from further loss or gain of heat energy. f) The water on the outside of the jar adds heat to the jar making the contents warmer. g) The liquid water molecules on the outside of the jar absorb	PM-1 A PM-2 Change answer C to: The liquid water molecules on the outside of the jar absorb energy from the jar and become vapor. This loss of energy causes cooling of the jar, which in turn cools the water inside the jar. PM-3 A	Which of the following best describes the reason for your answer for the previous question? a) The liquid water molecules on the outside of the jar insulate the jar from further loss or gain of heat energy. b) The water on the outside of the jar adds heat to the jar making the contents warmer. c) The liquid water molecules on the outside of the jar absorb

		energy from the jar and become vapor. This loss of energy causes cooling of the jar. h) The liquid water molecules on the outside of the jar require heat energy to stay in place and therefore heat their surroundings.	PM-4 A PM-5 A	energy from the jar and become vapor. This loss of energy causes cooling of the jar, which in turn cools the water inside the jar. d) The liquid water molecules on the outside of the jar require heat energy to stay in place and therefore heat their surroundings.
Item 5	Tier 1	Samantha collects a muddy water sample from a local creek in a clear water bottle. She puts a cap tightly on the bottle and notices that the sides of the bottle are crystal clear above the muddy water sample. She also notices that the water is staying muddy colored due to its suspended solids. She places the sealed bottle in the sun and leaves. When she returns, what do you think she will see on the inside of the bottle above the muddy water? e) Small droplets of water that are muddy colored have formed on the inside of the bottle above the muddy water. f) Small clear droplets of water have formed on the inside of the bottle above the muddy water. g) A layer of dried mud has formed above the muddy water. h) There should be no change in what the inside of the bottle looks like.	PM-1 Samantha collects a muddy water sample from a local creek in a clear water bottle. She puts a cap tightly on the bottle and notices that inside of the bottle is clean and clear above the muddy water sample. She also notices that the water is muddy colored due to its suspended solids. She places the sealed bottle in the sun and leaves. When she returns, what do you think she will see on the inside of the bottle above the muddy water? a) Small muddy-colored droplets of water have formed on the inside of the bottle above the muddy water. b) Small clear, colorless droplets of water have formed on the inside of	Samantha collects a muddy water sample from a local creek in a clear water bottle. She puts a cap tightly on the bottle and notices that inside of the bottle is clean and clear above the muddy water sample. She also notices that the water is muddy colored due to its suspended solids. She places the sealed bottle in the sun and leaves. When she returns, what do you think she will see on the inside of the bottle above the muddy water? a) Small muddy-colored droplets of water have formed on the inside of the bottle above the muddy water. b) Small clear, colorless droplets of water have formed on the inside of the

			the bottle above the muddy water. c) A layer of dried mud has formed above the muddy water. d) There should be no change in what the inside of the bottle looks like. (Maybe this one needs a figure?) PM-2 Samantha collects a muddy water sample from a local creek in a clear water bottle. She puts a cap tightly on the bottle and notices that the sides of the bottle are crystal clear above the muddy water sample (edit?). She also notices that the water is staying muddy colored due to its suspended solids. She places the sealed bottle in the sun and leaves. When she returns, what do you think she will see on the inside of the bottle above the muddy water? a) Small muddy colored droplets of water ~~that are~~ have formed on the inside of the bottle above the muddy water.	bottle above the muddy water. c) A layer of dried mud has formed above the muddy water. d) There should be no change in what the inside of the bottle looks like.

			Small clear droplets of water have formed on the inside of the bottle above the muddy water. A layer of dried mud has formed above the muddy water. There should be no change in what the inside of the bottle looks like. PM-3 A PM-4 A PM-5 A	
Item 5	Tier 2	Which of the following best describes the reason for your answer for the previous question? e) The mud in the water is a solute and the water is the solvent in this muddy water solution. Solutes evaporate with the solvent when the solution evaporates. When muddy water evaporates within the bottle, it carries with it some mud particles which condenses on the side of the bottle along with the water droplets.	PM-1 Which of the following best describes the reason for your answer for the previous question? a) The mud in the water is a solute and the water is the solvent in this muddy water solution. Solutes evaporate with the solvent when the solution evaporates. When muddy water evaporates within the bottle, it carries with it	Which of the following best describes the reason for your answer for the previous question? a) The mud in the water is a solute and the water is the solvent in this muddy water solution. Solutes evaporate with the solvent when the solution evaporates. When muddy water evaporates within the bottle, it carries with it some mud particles

		f) The mud in the water is a solute and the water is the solvent in this muddy water solution. Solutes do not evaporate with the solvent when the solution evaporates. When the water evaporates within the bottle, it does not carry any of the mud particles with it and condenses as clear droplets on the side of the water bottle g) The solids within the muddy water solution volatilize and condense on the sides of the water bottle forming a solid layer. This is due to the ability of wet solids to change phases. h) The mud particles within the muddy water solution stops evaporation of any kind within the bottle. The liquid water will undergo no change of state.	some mud particles which condenses on the side of the bottle along with the water droplets. b) The mud in the water is a solute and the water is the solvent in this muddy water solution. Solutes do not evaporate with the solvent when the solution evaporates. When the water evaporates within the bottle, it does not carry any of the mud particles with it and condenses as clear droplets on the side of the water bottle c) The solids within the muddy water solution volatilize and condense on the sides of the water bottle forming a solid layer. This is due to the ability of wet solids to change phases. d) The mud particles within the muddy water solution stops evaporation of any kind within the bottle. The liquid water will undergo no change of state.	which condenses on the side of the bottle along with the water droplets. b) The mud in the water is a solute and the water is the solvent in this muddy water solution. Solutes do not evaporate with the solvent when the solution evaporates. When the water evaporates within the bottle, it does not carry any of the mud particles with it and condenses as clear droplets on the side of the water bottle c) The solids within the muddy water solution volatilize and condense on the sides of the water bottle forming a solid layer. This is due to the ability of wet solids to change phases. d) The mud particles within the muddy water solution stops evaporation of any kind within the bottle. The liquid water will undergo no change of state. e) There are no changes to what the inside of the bottle looks like because the bottle is capped. Since nothing can

			PM-2 Add item e) to read: There are no changes to what the inside of the bottle looks like because the bottle is capped. Since nothing can escape from the bottle, no evaporation occurs. PM-3 A PM-4 A PM-5 A	escape from the bottle, no evaporation occurs.
Item 6	Tier 1	A clear plastic water bottle is half filled with water that is at room temperature and a cap is tightly screwed onto the bottle. Over time, what will happen to the evaporation rate of the water? i) The evaporation rate will increase. j) The evaporation rate will decrease to zero. k) The evaporation rate will increase then decrease to zero. l) The evaporation rate will increase then remain constant.	PM-1 A clear plastic water bottle is half filled with water that is at room temperature and a cap is tightly screwed onto the bottle. Over time, what will happen to the evaporation rate of the water? a) The evaporation rate will increase. b) The evaporation rate will decrease to zero. c) The evaporation rate will increase at first, then decrease to zero. d) The evaporation rate will increase at first, then remain constant. PM-2 A half full clear plastic water bottle with a lid ~~is half filled with~~ contains room temperature water. ~~that is at room~~	A clear plastic water bottle is half filled with water that is at room temperature and a cap is tightly screwed onto the bottle. Over time, what will happen to the evaporation rate of the water? a) The evaporation rate will increase. b) The evaporation rate will decrease to zero. c) The evaporation rate will increase at first, then decrease to zero. d) The evaporation rate will increase at first, then remain constant. e) No evaporation will occur, so there will be no change in the rate of evaporation.

			~~temperature~~ ~~andA cap is tightly screwed onto the bottle~~. Over time, what will happen to the evaporation rate of the water? a) The evaporation rate will increase. b) The evaporation rate will decrease to zero. c) The evaporation rate will increase then decrease to zero. d) The evaporation rate will increase then remain constant. e) No evaporation will occur, so there will be no change in the rate of evaporation. PM-3 A PM-4 A PM-5 A	
Item 6	Tier 2	Which of the following best describes the reason for your answer for the previous question? e) The evaporation rate of water in a closed system will remain constant due to an equilibrium that is established between evaporation and condensation rates.	PM-1 I think the evaporation rate will remain the same, but the condensation rate will increase until the net evaporation is zero. Not sure which is being asked here.	Which of the following best describes the reason for your answer for the previous question? a) The evaporation rate of water in a closed system will at first increase then will remain constant due to an equilibrium that is established between

		f) The vapor pressure above the water will increase causing a decrease in evaporation rate. g) The water above the liquid will become humid which will increase the evaporation rate over time to zero. h) The evaporation rate will be zero as soon as the cap is tightened and no air is allowed to escape the system.	PM-2 Which of the following best describes the reason for your answer for the previous question? a) (*** make a reference to the fact that it increases before reaching equilibrium) The evaporation rate of water in a closed system will remain constant due to an equilibrium that is established between evaporation and condensation rates. b) The vapor pressure above the water will increase causing a decrease in evaporation rate. c) The water above the liquid will become humid which will increase (decrease??) the evaporation rate over time to zero. d) The evaporation rate will be zero as soon as the cap is tightened and no air is allowed to escape the system. PM-3 A PM-4 A PM-5 A	evaporation and condensation rates. b) The vapor pressure above the water will increase causing a decrease in evaporation rate. c) The water above the liquid will become humid which will increase the evaporation rate over time to zero. d) The evaporation rate will be zero as soon as the cap is tightened and no air is allowed to escape the system.

Item 7	Tier 1	Salt water is placed into a jar. The jar has no top on it and it is left out on a counter in a room for several days. What will happen to the concentration of the salt water within the jar over time? d) The concentration of the salt water within the jar will remain constant. e) The concentration of salt water within the jar will increase. f) The concentration of salt water within the jar will decrease.	PM-1 A solution of salt and water is placed into a jar. The jar has no top on it and it is left out on a counter in a room for several days. What will happen to the concentration of the salt water solution over time? a) The concentration of the salt in the solution will remain constant. b) The concentration of salt in the solution will increase. c) The concentration of salt in the solution will decrease. PM-2 Salt water is placed into a jar. The jar has no top on it and it is left out on a counter in a room for several days. What will happen to the concentration of the salt water within the jar over time? a) The concentration of salt water within the jar will increase.	A solution of salt and water is placed into a jar. The jar has no top on it and it is left out on a counter in a room for several days. What will happen to the concentration of the salt water solution over time? a) The concentration of salt in the solution will increase. b) The concentration of salt in the solution will decrease. c) The concentration of the salt in the solution will remain constant.

			b) The concentration of salt water within the jar will decrease. c) The concentration of the salt water within the jar will remain constant.(move to last for consistency) PM-3 A PM-4 A PM-5 A	
Item 7	Tier 2	Which of the following best describes the reason for your answer for the previous question? e) Since no salt is being removed from the jar there will be no change in the concentration of the salt water. f) Since salt will evaporate along with the water in the jar there will be no net change in the concentration of salt water in the jar. g) Since only water evaporates from the jar the concentration of salt water in the jar will increase. h) Since only water evaporates from the jar the concentration of salt water in the jar will decrease.	PM-1 A PM-2 A PM-3 A PM-4 A PM-5 A	No Change Needed. Expert Panel at 100% Agreement.
Item 8	Tier 1	A watch glass is placed on a glass container which is sitting on an electrical heater. There is boiling water in the glass	PM-1 A watch glass is placed on a glass container which is sitting	A glass cover is placed on a glass container which is sitting on an electrical heater. There is boiling water

		container. What will an observer see after a few moments? h) There will be no change in the system. i) Tiny droplets of water will appear on the inside of the watch glass. j) The watch glass will become clear and will start to slowly rotate. k) Water will collect on the outside of the watch glass.	on an electrical heater. There is boiling water in the glass container. What will an observer see after a few moments? a) There will be no change in the system. b) Tiny droplets of water will appear on the underside of the watch glass. c) The watch glass will become clear and will start to slowly rotate. d) Water will collect on the top of the watch glass. Will students know what a watch glass is? Maybe it should just be called a glass cover? PM-2 A glass cover is placed on a glass container which is sitting on an electrical heater. There is boiling water in the glass container. What will an observer see after a few moments? a) There will be no change in the system.	in the glass container. What will an observer see after a few moments? a) There will be no change in the system. b) Tiny droplets of water will appear on the underside of the glass cover. c) The glass cover will become clear and will start to slowly rotate. d) Water will collect on the top of the glass cover.

			b) Tiny droplets of water will appear on the underside inside of the glass cover c) The glass cover will become clear and will start to slowly rotate. d) Water will collect on the outside of the watch glass. e) Water appears on the top of the glass cover **** Image does not make clear that lid is directly on top (i.e. has contact with) the jar PM-3 A PM-4 A PM-5 A	
Item 8	Tier 2	Which of the following best describes the reason for your answer for the previous question? e) Water vapor is lighter than liquid water and rises up to push the watch glass in rotational direction. f) Heating of the watch glass adds energy to the system which allows humidity in the surroundings to collect on the watch glass.	PM-1 change item d) to read: Gaseous water molecules lose energy to the watch glass, allowing the gaseous molecules to condense to form liquid water droplets. PM-2 A PM-3 A PM-4 A	Which of the following best describes the reason for your answer for the previous question? a) Water vapor is lighter than liquid water and rises up to push the glass cover in rotational direction. b) Heating of the heating of the glass cover adds energy to the system which allows humidity in the surroundings to collect on the watch glass.

		g) No water is being removed from the overall surroundings so evaporative losses will be insignificant. h) Gaseous phase water molecules lose energy to the watch glass allowing the gaseous molecules to combine to form liquid water droplets.	PM-5 A	c) No water is being removed from the overall surroundings so evaporative losses will be insignificant. d) Gaseous phase water molecules lose energy to the glass cover allowing the gaseous molecules to condense to form liquid water droplets.
Item 9	Tier 1	A cold soda bottle is removed from the refrigerator on a warm and humid day and placed on the counter top. After a few minutes, small water droplets appear on the outside of the bottle. As these droplets form, what will happen to the temperature of the outside of the soda bottle? d) The temperature of the outside of the soda bottle will decrease. e) The temperature of the outside of the soda bottle will increase. f) The temperature of the outside of the soda bottle will stay the same.	PM-1 A PM-2 A PM-3 A PM-4 A PM-5 A	
Item 9	Tier 2	Which of the following best describes the reason for your answer for the previous question? e) Gaseous water molecules lose kinetic energy to the water bottle which causes the water molecules to combine to form liquid water droplets which raises the temperature of the soda bottle.	PM-1 Change item a) to read: As gaseous water molecules condense on the surface of the soda bottle, they transfer kinetic energy to the bottle which raises the temperature. PM-2 Change item a) to read: Gaseous water molecules in the environment lose kinetic energy	Which of the following best describes the reason for your answer for the previous question? a) As gaseous water molecules in the environment condense on the surface of the soda bottle, they transfer kinetic energy to the soda bottle which raised the temperature of the soda bottle.

		f) Gaseous water molecules stick to the outside of the soda bottle causing them to form liquid water droplets. This collection of water on the outside surface cools the soda bottle. g) The soda bottle that has just been taken from the refrigerator has microscopic ice particles on it that slowly melt to form water droplets. This cools the outside of the soda bottle. h) The outside of the water bottle will not change temperature due to an equilibrium that is established between the cold internal liquid and the warm surrounding air.	to the water bottle which causes the water molecules to combine to form liquid water droplets which raises the temperature of the soda bottle. PM-3 A PM-4 A PM-5 A	b) Gaseous water molecules stick to the outside of the soda bottle causing them to form liquid water droplets. This collection of water on the outside surface cools the soda bottle. c) The soda bottle that has just been taken from the refrigerator has microscopic ice particles on it that slowly melt to form water droplets. This cools the outside of the soda bottle. d) The outside of the water bottle will not change temperature due to an equilibrium that is established between the cold internal liquid and the warm surrounding air.
Item 10	Tier 1	Two same sized wide-mouth cups of hot water are placed on a table and labeled cup A and Cup B. Two identical tall plastic cups are turned upside down and placed over the wide mouth plastic cups with hot water in them. An ice cube is placed on the inverted tall plastic cup that is over cup B. What can you say about the condensation rates in each of the tall plastic cups? f) The condensation rate in the tall plastic cup over cup A will be greater than the condensation rate in the tall plastic cup over cup B.	PM-1 Two identical cups of hot water are placed on a table and labeled Cup A and Cup B. Two identical plastic cups are turned upside down and placed over the cups containing the hot water. An ice cube is placed on the the top cup in B. What can you say about the condensation rates in each of the tall plastic cups? a) The condensation rate in the top cup in A will be greater than the	Two identical cups of hot water are placed on a table as shown in figure A and B above. Two identical plastic cups are turned upside down and placed over the cups containing the hot water. An ice cube is placed on top of the top cup in figure B. What can you say about the condensation rates in each of the top plastic cups? a) The condensation rate in the top cup in figure A will be greater than the

		g) The condensation rate in the tall plastic cup over cup B will be greater than the condensation rate in the tall plastic cup over cup A. h) The condensation rates in the tall plastic cups over cup A and cup B will be the same.	condensation rate in the top cup in B. b) The condensation rate in the top cup in B will be greater than the condensation rate in the top cup in A. c) The condensation rates in the top cups in A and B will be the same. PM-2 Two identical same sized wide-mouth cups of hot water are placed on a table and labeled (figure A vs Cup A) cup A and Cup B. Two identical tall plastic cups are turned upside down and placed over the wide mouth plastic cups with hot water in them. An ice cube is placed on the inverted tall plastic cup that is over cup B. What can you say about the condensation rates in each of the **upside down** ~~tall~~ plastic cups? a) The condensation rate in the tall plastic cup over cup A will be greater than the condensation rate in the tall plastic cup over cup B.	condensation rate in the top cup in figure B. b) The condensation rate in the top cup in figure B will be greater than the condensation rate in the top cup in figure A. c) The condensation rates in the top cups in figure A and figure B will be the same.

			b) The condensation rate in the tall plastic cup over cup B will be greater than the condensation rate in the tall plastic cup over cup A. The condensation rates in the tall plastic cups over cup A and cup B will be the sam PM-3 A PM-4 A PM-5 A	
Item 10	Tier 2	**Tier 2:** Which of the following best describes the reason for your answer for the previous question? f) Condensation rates are solely dependent on the surface area that condensation occurs on. Since the cups are the same size there will be no difference in the condensation rates. g) Condensation rates are affected by the temperature of the air above a liquid. Both cups have hot water that is heating the air and therefore will be the same temperature. The condensation rates should be the same. h) Condensation rates increase with increasing temperature. The hotter the environment is the more water vapor there will be in	PM-1 A PM-2 Condensation rates are affected by the temperature of the air above a liquid. Both cups have hot water that is heating the air and therefore will be the same temperature. The condensation rates should be the same. (I don't think this one makes sense. Rework) PM-3 A PM-4 A PM-5 A	**Tier 2:** Which of the following best describes the reason for your answer for the previous question? a) Condensation rates are solely dependent on the surface area that condensation occurs on. Since the cups are the same size there will be no difference in the condensation rates. b) Condensation rates are affected by the temperature of the air above a liquid. Both cups have hot water that is heating the air and therefore will be the same temperature. The condensation rates should be the same. c) Condensation rates increase with increasing temperature. The hotter the environment is the more water vapor there

		the air which will lead to greater condensation rates. i) Condensation rates increase as the temperature of the surface the water vapor is in contact with decreases.		will be in the air which will lead to greater condensation rates. d) Condensation rates increase as the temperature of the surface the water vapor is in contact with decreases.
Item 11	Tier 1	Jean has a water bottle that is filled with ice water. She is fascinated by the droplets of water that appear on the outside of the water bottle. She has been told that these droplets of water are formed by the process of condensation. She would like to determine the rate of condensation. How could she best determine the rate of condensation? e) Jean could place a bowl of hot water next to the cold water bottle and measure the amount of water that evaporates from the bowl. f) Jean could wipe the water droplets into a container and measure the amount of water that she collected in milliliters. g) Jean could tap the water bottle periodically so that water droplets would fall into a collection device. She would then measure the volume of water collected over a given amount of time. h) Jean could place a paper towel under the water bottle and let it sit for a while. She would then squeeze out the water into a	PM-1 A PM-2 A PM-3 A PM-4 A PM-5 A	No Change Needed. Expert Panel at 100% Agreement.

		container and measure the collected volume of water.		
Item 11	Tier 2	Which of the following best describes the reason for your answer for the previous question? e) Condensation rates can be determined by measuring the volume of condensed liquid. f) Condensation rates can be determined by measuring the area of condensation that has occurred. g) Condensation rates can be determined by measuring the given volume of a condensed liquid over a given amount of time. h) Condensation rates can be determined by understanding that evaporative losses in the near vicinity are equivalent to condensation production.	PM-1 A PM-2 A PM-3 A PM-4 A PM-5 A	No Change Needed. Expert Panel at 100% Agreement.
Item 12	Tier 1	Given the area of a rectangle is 24 sq cm, find the perimeter of the rectangle if the length is 6 cm. i) The perimeter is 30 cm. j) The perimeter is 36 cm. k) The perimeter is 24 cm. l) The perimeter is 20 cm.	PM-1 The area of a rectangle is 24 sq cm. Find the perimeter of the rectangle if the length is 6 cm. a) The perimeter is 30 cm. b) The perimeter is 36 cm. c) The perimeter is 24 cm. d) The perimeter is 20 cm. PM-2 A PM-3 A PM-4 A PM-5 A	The area of a rectangle is 24 sq cm. Find the perimeter of the rectangle if the length is 6 cm. a) The perimeter is 30 cm. b) The perimeter is 36 cm. c) The perimeter is 24 cm. d) The perimeter is 20 cm.

Item 12	Tier 2	Which of the following best describes the reason for your answer for the previous question? e) The area of a rectangle in square units is the product of the measurements of the length and width dimensions of the rectangle. The perimeter of a rectangle is the sum of all the sides. f) The perimeter of a rectangle in square units is the product of the measurements of the length and width dimensions of the rectangle. The area of a rectangle is the sum of all the sides. g) The sum of the area of a rectangle and a length is equal to the perimeter of a rectangle. h) The sum of the sides of a rectangle is equal to the perimeter and the area of the rectangle.	PM-1 Which of the following best describes the reason for your answer for the previous question? a) The area of a rectangle is the product of the measurements of the length and width dimensions of the rectangle. The perimeter of a rectangle is the sum of all the sides. b) The perimeter of a rectangle is the product of the measurements of the length and width dimensions of the rectangle. The area of a rectangle is the sum of all the sides. c) The sum of the area of a rectangle and a length is equal to the perimeter of a rectangle. d) The sum of the sides of a rectangle is equal to the perimeter and the area of the rectangle. PM-2 A PM-3 A PM-4 A	Which of the following best describes the reason for your answer for the previous question? a) The area of a rectangle is the product of the measurements of the length and width dimensions of the rectangle. The perimeter of a rectangle is the sum of all the sides. b) The perimeter of a rectangle is the product of the measurements of the length and width dimensions of the rectangle. The area of a rectangle is the sum of all the sides. c) The sum of the area of a rectangle and a length is equal to the perimeter of a rectangle. d) The sum of the sides of a rectangle is equal to the perimeter and the area of the rectangle.

			PM-5 A	
Item 13	Tier 1	A rectangular rain cover that is 9 ft long and 4 ft wide is hung up over a small deck. What is the area of the rain cover that rain can impact on? e) 26 sq. ft. f) 36 sq. ft. g) 26 ft. h) 36 ft.	PM-1 A rectangular rain cover that is 9 ft long and 4 ft wide is hung up over a small deck. What is the area of the rain cover? a) 26 sq. ft. b) 36 sq. ft. c) 26 ft. d) 36 ft. PM-2 A PM-3 A PM-4 A PM-5 A	No change needed
Item 13	Tier 2	Which of the following best describes the reason for your answer for the previous question? e) The area of a rectangle in square units is the product of the measurements of the length and width dimensions of the rectangle. f) The area of a rectangle in linear units is the sum of the measurements of the lengths and widths of the rectangle. g) The area of a rectangle in linear units is the square of the measurements of the length dimension of the rectangle.	PM-1 Which of the following best describes the reason for your answer for the previous question? a) The area of a rectangle is the product of the measurements of the length and width dimensions of the rectangle. b) The area of a rectangle is the sum of the measurements of the lengths and widths of the rectangle.	Which of the following best describes the reason for your answer for the previous question? a) The area of a rectangle is the product of the measurements of the length and width dimensions of the rectangle. b) The area of a rectangle is the sum of the measurements of the lengths and widths of the rectangle. c) The area of a rectangle is the square of the

		h) The area of the rectangle in square units is the sum of the measurements of the edges of the outside dimensions of the rectangle.	c) The area of a rectangle is the square of the measurements of the length dimension of the rectangle. d) The area of the rectangle is the sum of the measurements of the edges of the outside dimensions of the rectangle. PM-2 A PM-3 A PM-4 A PM-5 A	measurements of the length dimension of the rectangle. d) The area of the rectangle is the sum of the measurements of the edges of the outside dimensions of the rectangle.
Item 14	Tier 1	Image needed. (Rectangular prism with sides 5in, 3in, and 2 in.) Given the above rectangular prism, determine the surface area of the figure. i) The surface area of the given rectangular prism is 30 sq. in. j) The surface area of the given rectangular prism is 62 sq. in. k) The surface area of the given rectangular prism is 40 sq. in. The surface area of the given rectangular prism is 15 sq. in.	PM-1 A PM-2 A PM-3 A PM-4 A PM-5 A	
Item 14	Tier 2	Which of the following best describes the reason for your answer for the previous question? e) The surface area is the measurement in square units of the outermost layer of an object.	PM-1 Which of the following best describes the reason for your answer for the previous question?	Which of the following best describes the reason for your answer for the previous question? a) The surface area is the measurement in square units of

		f) The surface area of an object is the measurement in square units of the sum of the sides of the object. g) The surface area of an object is the amount of space in square units that it can hold within it. h) The surface area of an object is the measurement in square units of the uppermost surface of the object.	a) The surface area is the measurement of the outermost layer of an object. b) The surface area of an object is the measurement of the sum of the sides of the object. c) The surface area of an object is the amount of space that it can hold within it. d) The surface area of an object is the measurement of the uppermost surface of the object. PM-2 Both a) and b) are arguably true for this object. PM-3 A PM-4 A PM-5 A	the outermost layer of an object. b) The surface area of an object is the measurement of the sum of the lengths of each side of the object. c) The surface area of an object is the amount of space in square units that it can hold within it. d) The surface area of an object is the measurement in square units of the uppermost surface of the object.
Item 15	Tier 1	Image needed (Image should be of a right triangle with rectangles inscribed, midpoint and circumscribed with the rectangles labeled A,B, and C) Given the above figure, which rectangle would be described as being inscribed? h) Rectangle A is an inscribed rectangle. i) Rectangle B is an inscribed rectangle.	PM-1 A PM-2 Cannot assess clarity without picture. PM-3 A PM-4 A PM-5 A	Added figure.

		j) Rectangle A is an inscribed rectangle. k) Rectangles A and B are inscribed rectangles. l) Rectangles A and C are inscribed rectangles. m) Rectangles B and C are inscribed rectangles. n) None of the rectangles are inscribed.		
Item 15	Tier 2	Which of the following best describes the reason for your answer for the previous question? e) An inscribed rectangle is a rectangle that has a portion of its area enclosed within another shape. f) An inscribed rectangle is a rectangle enclosed in an irregular shape which does not intersect the boundary of the irregular shape, except potentially at the corners. g) An inscribed rectangle encloses another shape. h) An inscribed rectangle has only one corner that intersects another shape.	PM-1 A PM-2 Item b) An inscribed rectangle is a rectangle enclosed in ~~an irregular~~ shape which does not intersect the boundary of the irregular shape, except potentially at the corners. (I don't think you need this word here, and besides I don't think a right triangle is irregular) PM-3 A PM-4 A PM-5 Item b) An inscribed rectangle is a rectangle enclosed in a geometric shape which does not intersect the boundary of the irregular shape, except potentially at the corners.	Which of the following best describes the reason for your answer for the previous question? a) An inscribed rectangle is a rectangle that has a portion of its area enclosed within another shape. b) An inscribed rectangle is a rectangle enclosed in a geometric shape which does not intersect the boundary of the irregular shape, except potentially at the corners. c) An inscribed rectangle encloses another shape. d) An inscribed rectangle has only one corner that intersects another shape.
Item 16	Tier 1	Image needed: The image will be an irregular closed shape with curved sides.	PM-1 A	Given the irregular shape in Figure A, which value below gives the closest

		It will be on a separate sheet of paper that students can access. Students will be provided with a ruler and calculator for the calculation. Given the irregular shape in Figure A, what is the closest approximate area in square inches of the shaded region? e) 56 in^2 (These need to be adjusted to the actual figure) f) 56 in^2 g) 56 in^2 h) 56 in^2	PM-2 Given the irregular shape in Figure A, ~~what~~ ~~is~~ which value below gives the closest approximate area (in square inches) of the shaded region? PM-3 A PM-4 A PM-5 A	approximate area (in square inches) of the shaded region? a) 56 in^2 (These need to be adjusted to the actual figure) b) 56 in^2 c) 56 in^2 d) 56 in^2
Item 16	Tier 2	Which of the following best describes the reason for your answer for the previous question? e) Finding the area of a single circumscribed rectangle to the irregular shape is the best way to estimate the area of the irregular shape. f) Finding the area of a single inscribed rectangle to the irregular shape is the best way to estimate the area of the irregular shape. g) Multiplying a series of rectangular shapes that are similar to the irregular shape and then dividing by the number of rectangles is the best way to estimate the area of the irregular shape.	PM-1 Summing the areas of a series of smaller inscribed rectangles associated with the irregular shape will be the best way to estimate the area of the irregular shape. PM-2 Which of the following best describes the reason for your answer for the previous question? a) Finding the area of the smallest single circumscribed rectangle to the irregular shape is the best way to estimate the area of the irregular shape. b) Finding the area of the largest inscribed rectangle to the irregular shape is	Which of the following best describes the reason for your answer for the previous question? a) Finding the area of the smallest single circumscribed rectangle to the irregular shape is the best way to estimate the area of the irregular shape. b) Finding the area of the largest inscribed rectangle to the irregular shape is the best way to estimate the area of the irregular shape. c) Multiplying a series of rectangular shapes that are similar to the irregular shape and then dividing by the number of rectangles is

		h) Summing the areas of a series of smaller inscribed (or circumscribed) rectangles associated with the irregular shape will be the best way to estimate the area of the irregular shape.	the best way to estimate the area of the irregular shape. c) Multiplying a series of rectangular shapes that are similar to the irregular shape and then dividing by the number of rectangles is the best way to estimate the area of the irregular shape. d) Summing the areas of multiple ~~a series of~~ smaller inscribed ~~(or circumscribed)~~ rectangles (with potentially different sizes) associated with the irregular shape will be the best way to estimate the area of the irregular shape. PM-3 A PM-4 A PM-5 A	the best way to estimate the area of the irregular shape. d) Summing the areas of multiple smaller inscribed rectangles (with potentially different sizes) associated with the irregular shape will be the best way to estimate the area of the irregular shape.
Item 17	Tier 1	Image needed of a parabolic curve with a series of rectangles inscribed under the curve. If the area under the curve in figure A above was to be determined, summing the rectangular areas that are shaded would produce;	PM-1 If the area under the curve in Figure A above was to be determined, summing the rectangular areas that are shaded would produce; a) An under-estimation of the area under the curve.	If the area under the curve in Figure A above was to be estimated by summing the areas of the shaded rectangles it would produce; a) An under-estimation of the area under the curve.

		g) An under-estimation of the area under the curve. h) An over-estimation of the area under the curve. i) An exact value of the area under the curve.	b) An over-estimation of the area under the curve. c) An exact value of the area under the curve. PM-2 If the area under the curve in Figure A above was to be estimated by summing the areas of the shaded rectangles it would produce; a) An under-estimation of the area under the curve. b) An over-estimation of the area under the curve. c) An exact value of the area under the curve. d) There is not enough information to answer this question PM-3 A PM-4 A PM-5 A	b) An over-estimation of the area under the curve. c) An exact value of the area under the curve. d) There is not enough information to answer this question
Item 17	Tier 2	Which of the following best describes the reason for your answer for the previous question? d) The rectangles that are being used for finding the area under the curve do not cover all of the	PM-1 Which of the following best describes the reason for your answer for the previous question? a) The rectangles do not cover all of the area and	PM-1 Which of the following best describes the reason for your answer for the previous question? a) The rectangles do not cover all of the area and therefore

		area and therefore would provide an under-estimation. e) The rectangles that are being used for finding the area under the curve cover more than the targeted area and therefore would provide an over-estimation. f) The rectangles that are being used for finding the area under the curve cover all of the targeted area and therefore would provide an exact value.	therefore would provide an under-estimation. b) The rectangles cover more than the targeted area and therefore would provide an over-estimation. c) The rectangles cover all of the targeted area and therefore would provide an exact value. PM-2 Which of the following best describes the reason for your answer for the previous question? a) The rectangles that are being used for finding the area under the curve do not cover all of the area and therefore would provide an under-estimation. b) The rectangles that are being used for finding the area under the curve cover more than the targeted area and therefore would provide an over-estimation. c) The rectangles that are being used for finding the area under the curve cover all of the targeted area and	would provide an under-estimation. b) The rectangles cover more than the targeted area and therefore would provide an over-estimation. c) The rectangles cover all of the targeted area and therefore would provide an exact value. d) Since there are no numerical labels in the picture, we don't have enough information to answer

			therefore would provide an exact value. d) Since there are no numerical labels in the picture, we don't have enough information to answer PM-3 PM-4 PM-5 A	
Item 18	Tier 1	Image needed of a parabolic curve with a series of rectangles circumscribed under the curve. If the area under the curve in figure A above was to be determined, summing the rectangular areas that are shaded would produce; g) An under-estimation of the area under the curve. h) An over-estimation of the area under the curve. i) An exact value of the area under the curve.	PM-1 Is this the same as Item 17? PM-2 If the area under the curve in figure A above was to be determined, summing the rectangular areas that are shaded would produce; a) An under-estimation of the area under the curve. b) An over-estimation of the area under the curve. c) An exact value of the area under the curve. d) There is not enough information to answer this question. PM-3 A	If the area under the curve in figure A above was to be determined, summing the rectangular areas that are shaded would produce; a) An under-estimation of the area under the curve. b) An over-estimation of the area under the curve. c) An exact value of the area under the curve. d) There is not enough information to answer this question.

			PM-4 A PM-5 A	
Item 18	Tier 2	Which of the following best describes the reason for your answer for the previous question? d) The rectangles that are being used for finding the area under the curve do not cover all of the area and therefore would provide an under-estimation. e) The rectangles that are being used for finding the area under the curve cover more than the targeted area and therefore would provide an over-estimation. f) The rectangles that are being used for finding the area under the curve cover all of the targeted area and therefore would provide an exact value.	PM-1 A PM-2 Which of the following best describes the reason for your answer for the previous question? a) The rectangles that are being used for finding the area under the curve do not cover all of the area and therefore would provide an under-estimation. b) The rectangles that are being used for finding the area under the curve cover more than the targeted area and therefore would provide an over-estimation. c) The rectangles that are being used for finding the area under the curve cover all of the targeted area and therefore would provide an exact value. d) We would need additional information about the sizes of certain regions to answer this question	PM-2 Which of the following best describes the reason for your answer for the previous question? a) The rectangles that are being used for finding the area under the curve do not cover all of the area and therefore would provide an under-estimation. b) The rectangles that are being used for finding the area under the curve cover more than the targeted area and therefore would provide an over-estimation. c) The rectangles that are being used for finding the area under the curve cover all of the targeted area and therefore would provide an exact value. d) We would need additional information about the sizes of certain regions to answer this question

			PM-3 A PM-4 A PM-5 A	
Item 19	Tier 1	An image is needed of a tear drop shape with fairly large circumscribed rectangles in it. If the area of the teardrop shape shown above in Figure A was to be estimated using the sum of the rectangles that have been circumscribed, what could you do to create a more accurate estimation? e) Use inscribed rectangles rather than circumscribed rectangles. f) Circumscribe more rectangles that are thinner and sum their areas g) In this case use one circumscribed rectangle to enclose the entire tear drop shape, find its area and multiply by 0.75. h) Use and inscribed rectangle, find an area and multiply by 1.25.	PM-1 If the area of the teardrop shape shown above in Figure A was to be estimated using the sum of the rectangles that have been circumscribed, what could you do to create a more accurate estimation? a) Use inscribed rectangles rather than circumscribed rectangles. b) Circumscribe more rectangles that are thinner and sum their areas c) Use one circumscribed rectangle to enclose the entire tear drop shape, find its area, and multiply by 0.75. d) Use an inscribed rectangle, find its area, and multiply by 1.25. PM-2 If the area of the teardrop shape shown above in Figure A was to be estimated using the sum of the rectangles that have been	If the area of the teardrop shape shown above in Figure A was to be estimated using the sum of the rectangles that have been circumscribed, what could you do to create a more accurate estimation? a) Use inscribed rectangles rather than circumscribed rectangles. b) Circumscribe more rectangles that are thinner and sum their areas c) Use one circumscribed rectangle to enclose the entire tear drop shape, find its area, and multiply by 0.75 because the rectangle would miss about a quarter of the area in the teardrop. e) Use an inscribed rectangle, find its area, and multiply by 1.25 because the rectangle would cover more than of the area in the teardrop.

			circumscribed, what could you do to create a more accurate estimation? a) Use inscribed rectangles rather than circumscribed rectangles. b) Circumscribe more rectangles that are thinner and sum their areas c) In this case, use one circumscribed rectangle to enclose the entire tear drop shape, find its area and multiply by 0.75 because the rectangle would miss about a quarter of the area in the teardrop. d) In this case, use and inscribed rectangle, find an area and multiply by 1.25 because the rectangle would cover more than of the area in the teardrop. PM-3 A PM-4 A PM-5 A	

Item 19	Tier 2	Which of the following best describes the reason for your answer for the previous question? e) Inscribed rectangles will use less space than circumscribed rectangles therefore giving more accurate area estimations. f) A greater number of thinner circumscribed rectangles will great a smaller amount of over estimation therefore making it more accurate. g) The area of the teardrop shape is two thirds the area of circumscribed rectangle. h) The area of an inscribed rectangle within an irregular shape is at least one quarter smaller that the irregular shapes area.	PM-1 Which of the following best describes the reason for your answer for the previous question? a) Inscribed rectangles will use less space than circumscribed rectangles therefore giving more accurate area estimations. b) A greater number of thinner circumscribed rectangles will result in a smaller over-estimation therefore making it more accurate. c) The area of the teardrop shape is two thirds the area of circumscribed rectangle. d) The area of an inscribed rectangle within an irregular shape is at least one quarter smaller than the area of the irregular shape. PM-2 Which of the following best describes the reason for your answer for the previous question? a) Inscribed rectangles will use less space than circumscribed rectangles	Which of the following best describes the reason for your answer for the previous question? a) Inscribed rectangles will use less space than circumscribed rectangles therefore giving more accurate area estimations. b) A greater number of thinner circumscribed rectangles will result in a smaller over-estimation therefore making it more accurate. c) The area of the teardrop shape is three fourths the area of circumscribed rectangle. d) The area of an inscribed rectangle within an irregular shape is at least one quarter smaller than the area of the irregular shape.

			therefore giving more accurate area estimations. b) A greater number of thinner circumscribed rectangles will create ~~great~~ a smaller amount of over estimation therefore making it more accurate. c) The area of the teardrop shape is two thirds the area of circumscribed rectangle. (Did you want to make this match the factor given above?) d) The area of an inscribed rectangle within an irregular shape is at least one quarter smaller that the irregular shapes area. PM-3 A PM-4 A PM-5 Change item b) to read: A greater number of thinner circumscribed rectangles will create a smaller amount of over estimation therefore making the estimation more accurate.	
Item 20	Tier 1	A faucet in a sink is steadily dripping water. You place a graduated cylinder under the faucet to capture the drips.	PM-1 A faucet in a sink is steadily dripping water. You	A faucet in a sink is steadily dripping water. You place a

		After 45 minutes you find that you have captured 75 ml of water in the graduated cylinder. What is the production rate of water that has dripped from the faucet? e) 45ml of water f) 75ml of water/min g) 0.6 ml of water/inch of cylinder h) 1.67 ml of water/min	place a graduated cylinder under the faucet to capture the drips. After 45 minutes you find that you have captured 75 ml of water in the graduated cylinder. What is the production rate of water from the faucet? a) 45ml of water b) 75ml of water/min c) 0.6 ml of water/inch of cylinder d) 1.67 ml of water/min PM-2 Please consider giving a picture of a graduated cylinder!! PM-3 A PM-4 A faucet in a sink is steadily dripping water. You place a graduated cylinder under the faucet to capture the drips. After 45 minutes you find that you have captured 75 mL of water in the graduated cylinder. What is the production rate of water that has dripped from the faucet? a) 45mL of water	graduated cylinder under the faucet to capture the drips. After 45 minutes you find that you have captured 75 mL of water in the graduated cylinder. What is the production rate of water from the faucet? a) 45mL of water b) 75mL of water/min c) 0.6 mL of water/inch of cylinder d) 1.67 mL of water/min

			b) 75mL of water/min c) 0.6 mL of water/inch of cylinder d) 1.67 mL of water/min PM-5 A	
Item 20	Tier 2	Which of the following best describes the reason for your answer for the previous question? e) The rate of production is the amount of material produced in a given time. f) The rate of production is the amount of material produced. g) The rate of production of a material is the overall time for the measurement to take place. h) The rate of production is the amount of material produced per the dimensions of the collection device.	PM-1 Which of the following best describes the reason for your answer for the previous question? a) The production rate is the amount of material produced in a given time. b) The production rate is the amount of material produced. c) The production rate of a material is the overall time for the measurement to take place. d) The production rate is the amount of material produced divided by the dimensions of the collection device. PM-2 A PM-3 A PM-4 A PM-5 A	Which of the following best describes the reason for your answer for the previous question? a) The production rate is the amount of material produced in a given time. b) The production rate is the amount of material produced. c) The production rate of a material is the overall time for the measurement to take place. d) The production rate is the amount of material produced divided by the dimensions of the collection device.
Item 21	Tier 1	Ryleigh and Martina were each designing artificial spider webs to capture flies. Ryleigh's spider web was 100 square centimeters in area and	PM-1 Ryleigh and Martina were each designing artificial spider webs to capture flies. Ryleigh's	Ryleigh and Martina were each designing artificial spider webs to capture flies. Ryleigh's spider web

		caught 7 flies in 22 minutes. Martina's spider web was 70 square inches and caught 6 flies in 19 minutes. Which spider web design was more efficient? (Assume the amount of available flies in the test location is the same for each student) d) Ryleigh's spider web design was most efficient e) Martina's sider web design was most efficient f) Ryleigh's and Martina's designs were equally efficient	spider web was 100 square centimeters in area and caught 7 flies in 22 minutes. Martina's spider web was 70 square inches and caught 6 flies in 19 minutes. Which spider web design was more efficient? (Assume the number of available flies in the test location is the same for each student) a) Ryleigh's spider web design was most efficient b) Martina's sider web design was most efficient c) Ryleigh's and Martina's designs were equally efficient PM-2 A PM-3 A PM-4 A PM-5 A	was 100 square centimeters in area and caught 7 flies in 22 minutes. Martina's spider web was 70 square inches and caught 6 flies in 19 minutes. Which spider web design was more efficient? (Assume the number of available flies in the test location is the same for each student) a) Ryleigh's spider web design was most efficient b) Martina's sider web design was most efficient c) Ryleigh's and Martina's designs were equally efficient
Item 21	Tier 2	Which of the following best describes the reason for your answer for the previous question? e) Ryleigh caught 7 flies. f) Martina caught 0.005 flies/minute/square centimeter g) Ryleigh caught 0.003 flies/minute/square centimeter.	PM-1 **Answers b and c are both correct (indistinguishable) as originally written.** Which of the following best describes the reason for your answer for the previous question? a) Ryleigh caught 7 flies.	Which of the following best describes the reason for your answer for the previous question? a) Ryleigh caught 7 flies. b) Martina caught more flies/minute/square centimeter

		h) Both designs captured approximately the same number of flies per minute.	b) Martina caught more flies/minute/square centimeter c) Ryleigh caught more flies/minute/square centimeter. d) Both designs captured approximately the same number of flies per minute. PM-2 A PM-3 A PM-4 A PM-5 A	c) Ryleigh caught more flies/minute/square centimeter. d) Both designs captured approximately the same number of flies per minute.
Item 22	Tier 1	Tyler and Maria are each designing a water mist collection device that will capture excess water from an outdoor restaurant's cooling processes. Tyler's collection device has an area of 12 square feet and collects 500mls/hour. Maria's collection device has an area of 10 square feet collects 450ml/hour. Which device is most efficient? d) Tyler's device is most efficient. e) Maria's device is most efficient f) Tyler's and Maria's collection devices were equally efficient	PM-1 These results are too close. Using sig figs, they are essentially the same. Maybe change Maria's to 8 square feet? Tyler and Maria are each designing a water mist collection device that will capture excess water from an outdoor restaurant's cooling processes. Tyler's collection device has an area of 12 square feet and collects 500mls/hour. Maria's collection device has an area of 8 square feet collects 450ml/hour. Which device is most efficient? a) Tyler's device is most efficient.	Tyler and Maria have each built a water mist collection device to capture excess water from an outdoor restaurant's misting cooling processes. Tyler's collection device has an area of 12 square feet and collects 500mL/hr. Maria's collection device has an area of 8 square feet collects 450mL/hr. Which device is most efficient? a) Tyler's device is most efficient. b) Maria's device is most efficient c) Tyler's and Maria's collection devices were equally efficient

			b) Maria's device is most efficient c) Tyler's and Maria's collection devices were equally efficient PM-2 Tyler and Maria ~~are each designing~~ have each built a water mist collection device ~~that will~~ to capture excess water from an outdoor restaurant's cooling processes. Tyler's collection device has an area of 12 square feet and collects 500mls/hour. Maria's collection device has an area of 10 square feet collects 450ml/hour. Which device is most efficient? a) Tyler's device is most efficient. b) Maria's device is most efficient Tyler's and Maria's collection devices were equally efficient **** I don't understand the unit mls (it is just multiple ml? it feels weird	

			PM-3 **“**500mls/hour” should be “500ml/hr” and “450ml/hour” should be “450ml/hr” PM-4 Tyler and Maria are each designing a water mist collection device that will capture excess water from an outdoor restaurant’s cooling processes. Tyler’s collection device has an area of 12 square feet and collects 500mLs/hour. Maria’s collection device has an area of 10 square feet collects 450mL/hour. Which device is most efficient? a) Tyler’s device is most efficient. b) Maria’s device is most efficient c) Tyler’s and Maria’s collection devices were equally efficient PM-5 A	
Item 22	Tier 2	Which of the following best describes the reason for your answer for the previous question? e) Tyler collected 500mls in one hour. f) Tyler collected 6000mls of the entire collection device. g) Maria collected 45ml/hr/ft^2	PM-1 Which of the following best describes the reason for your answer for the previous question? a) Tyler’s device collected more milliliters in one hour than Maria’s device.	Which of the following best describes the reason for your answer for the previous question? a) Tyler’s device collected more milliliters in one hour than Maria’s device.

		h) Maria collected 4500 mls	b) Tyler collected a total of 6000mls. c) Maria's device collected more milliliters per hour per square foot than Tyler's device. d) Maria collected a total of 3600 ml. PM-2 Which of the following best describes the reason for your answer for the previous question? a) Tyler collected 500mls in one hour. b) Tyler collected 6000mls of the entire collection device. (??) c) Maria collected 45ml/hr/ft^2 d) Maria collected 4500 ml PM-3 "mls" should be "ml" PM-4 Which of the following best describes the reason for your answer for the previous question? a) Tyler collected 500mLs in one hour. b) Tyler collected 6000mLs of the entire collection device.	b) Tyler collected a total of 6000mL. c) Maria's device collected more milliliters per hour per square foot than Tyler's device. d) Maria collected a total of 3600 mL.

			c) Maria collected 45mL/hr/ft^2 d) Maria collected 4500 mL PM-5 A	
Item 23	Tier 1	Mark has a rain gauge on his deck. It is a small glass graduated cylinder that allows a person to measure the amount of rain that is captured in it. He notes there are 10ml of water in the rain gauge before a thunderstorm arrives. Ninety minutes later, after the storm passes, he reads that here are 35 ml in the gauge. What is the rate of change of the rainwater in the rain gauge over this time period? e) The rate of change of rainwater in the rain gauge is 900 ml in one hour. f) The rate of change of rainwater in the rain gauge 13,500 ml. g) The rate of change of rainwater in the rain gauge is 0.36 min/ml. h) The rate of change of rainwater in the rain gauge is 0.28 ml/min	PM-1 Mark has a rain gauge on his deck. It is a small glass cylinder with markings that allow a person to measure the amount of rain that is collected. He notes there are 10ml of water in the rain gauge before a thunderstorm arrives. Ninety minutes later, after the storm passes, he reads that here are 35 ml of water in the gauge. What is the rate of change of the rainwater in the rain gauge over this time period? a) The rate of change of rainwater in the rain gauge is 900 ml in one hour. b) The rate of change of rainwater in the rain gauge 13,500 ml. c) The rate of change of rainwater in the rain gauge is 0.36 min/ml. d) The rate of change of rainwater in the rain gauge is 0.28 ml/min	Mark has a rain gauge on his deck. It is a small glass cylinder with markings that allow a person to measure the amount of rain that is collected. He notes there are 10mL of water in the rain gauge before a thunderstorm arrives. Ninety minutes later, after the storm passes, he reads that here are 35 mL of water in the gauge. What is the rate of change of the rainwater in the rain gauge over this time period? a) The rate of change of rainwater in the rain gauge is 900 mL in one hour. b) The rate of change of rainwater in the rain gauge 13,500 mL. c) The rate of change of rainwater in the rain gauge is 0.36 min/mL. d) The rate of change of rainwater in the rain gauge is 0.28 mL/min

			PM-2 add item e) The rate of change is 25 ml/hr. PM-3 It is a small glass graduated cylinder that allows a person to measure the amount of rain that is captured ~~in it~~. PM-4 Mark has a rain gauge on his deck. It is a small glass graduated cylinder that allows a person to measure the amount of rain that is captured in it. He notes there are 10mL of water in the rain gauge before a thunderstorm arrives. Ninety minutes later, after the storm passes, he reads that here are 35 mL in the gauge. What is the rate of change of the rainwater in the rain gauge over this time period? a) The rate of change of rainwater in the rain gauge is 900 mL in one hour. b) The rate of change of rainwater in the rain gauge 13,500 mL. c) The rate of change of rainwater in the rain gauge is 0.36 min/mL. The rate of change of rainwater in the rain gauge is 0.28 mL/min	e) The rate of change is 25 mL/hr.

			PM-5 A	
Item 23	Tier 2	Which of the following best describes the reason for your answer for the previous question? e) The rate of change of a quantity is the initial amount of a quantity times the duration of the event. f) The rate of change of a quantity is the ratio of the change of the quantity in relation to the change of another quantity. g) The rate of change of a quantity is the change of a quantity times the change of another quantity. h) The rate of a change of a quantity is the change in time divided by the change in another quantity.	PM-1 Which of the following best describes the reason for your answer for the previous question? a) The rate of change is the initial amount of a quantity times the duration of the event. b) The rate of change is the ratio of the change of the quantity divided by the change of another quantity. c) The rate of change is the change of a quantity times the change of another quantity. d) The rate of a change is the change in time divided by the change in another quantity. PM-2 A PM-3 A PM-4 A PM-5 A	Which of the following best describes the reason for your answer for the previous question? a) The rate of change is the initial amount of a quantity times the duration of the event. b) The rate of change is the ratio of the change of the quantity divided by the change of another quantity. c) The rate of change is the change of a quantity times the change of another quantity. d) The rate of a change is the change in time divided by the change in another quantity.

Item 24	Tier 1	Mathias measured the amount of motor oil dripping out of the engine of a classic car he was restoring. He placed an empty measuring device under the leak and left it overnight. Sixteen hours later he returned and found that he had collected 32 ml of oil. He left the container without emptying it and came back again after 16 hours to find that the total about of oil collected was 64 ml. He plotted his data on an x-y coordinate grid with time on the x-axis and milliliters collected on the y-axis. He calculated the slope of the straight line that was formed and found it to be 2 ml/hr. What is the rate of change of the motor oil in the collection device? e) 2 ml of oil/hr f) ½ ml of oil/hr g) 64 ml of oil h) 32 minutes	PM-1 I think most students will answer correctly simply because the 2 mL/hr is an obvious value given right at the end of the question. PM-2 A PM-3 "about" should be "amount" PM-4 Mathias measured the amount of motor oil dripping out of the engine of a classic car he was restoring. He placed an empty measuring device under the leak and left it overnight. Sixteen hours later he returned and found that he had collected 32 mL of oil. He left the container without emptying it and came back again after 16 hours to find that the total amount of oil collected was 64 mL. He plotted his data on an x-y coordinate grid with time on the x-axis and milliliters collected on the y-axis. He calculated the slope of the straight line that was formed and found it to be 2 mL/hr. What is	Mathias measured the amount of motor oil dripping out of the engine of a classic car he was restoring. He placed an empty measuring device under the leak and left it overnight. Sixteen hours later he returned and found that he had collected 32 mL of oil. He left the container without emptying it and came back again after 16 hours to find that the total amount of oil collected was 64 mL. He plotted his data on an x-y coordinate grid with time on the x-axis and milliliters collected on the y-axis. He calculated the slope of the straight line that was formed and found it to be 2 mL/hr. What is the rate of change of the motor oil in the collection device? a) 2 mL of oil/hr b) ½ mL of oil/hr c) 64 mL of oil d) 32 minutes

			the rate of change of the motor oil in the collection device? a) 2 mL of oil/hr b) ½ mL of oil/hr c) 64 mL of oil d) 32 minutes PM-5 A	
Item 24	Tier 2	Which of the following best describes the reason for your answer for the previous question? e) The rate of change of two variables is the total time that has elapsed for the event. f) The rate of change of two variables is the total amount of one quantity that is being analyzed. g) The rate of change of a variable is the is the inverse of the slope of the linear function. h) The slope of a linear function of two variables is equal to the rate of the change of those variables.	PM-1 Which of the following best describes the reason for your answer for the previous question? a) The rate of change is the total time that has elapsed for the event. b) The rate of change is the total amount of one quantity that is being analyzed. c) The rate of change can be found by graphing the variables on xy coordinates and finding the inverse of the slope of the line. d) The rate of change can be found by graphing the variables on xy coordinates and finding the slope of the line. PM-2 A	Which of the following best describes the reason for your answer for the previous question? a) The rate of change is the total time that has elapsed for the event. b) The rate of change is the total amount of one quantity that is being analyzed. c) The rate of change can be found by graphing the variables on xy coordinates and finding the inverse of the slope of the line. d) The rate of change can be found by graphing the variables on xy coordinates and finding the slope of the line.

			PM-3 A PM-4 A PM-5 Which of the following best describes the reason for your answer for the previous question? a) The rate of change of one variable with respect to another variable is the total time that has elapsed for the event. b) The rate of change of two variables is the total amount of one quantity that is being analyzed. c) The rate of change of a variable with respect to another variable the is the inverse of the slope of the linear function. d) The slope of a linear function of two variables is equal to the rate of the change of the y variable with respect to the x variable.	
Item 25	Tier 1	Maya is an engineer who has designed a mechanical press to remove orange juice from oranges for a small local organic orange grower in Florida. She starts the press and measures how much orange juice is collected over time. She watches the collection container, which has volume marks on the side, and sees that in 15 minutes she has collected 10 gallons of orange juice. At 45 minutes	PM-1 A PM-2 Add item e) 20 gallons/min PM-3 The correct abbreviation for “gallons” is “gal”; I think “gallons” should be replaced with “gal” PM-4 A	Maya is an engineer who has designed a mechanical press to remove orange juice from oranges for a small local organic orange grower in Florida. She starts the press and measures how much orange juice is collected over time. She watches the collection container, which has volume marks on the side, and sees that in 15 minutes she has collected 10 gallons of orange juice. At 45 minutes she sees that she

		she sees that she has collected 30 gallons of orange juice. e) 3/2 gallons/min f) 30 gallons g) 45 minutes h) 2/3 gallons/min	PM-5 A	has collected 30 gallons of orange juice. a) 3/2 gal/min b) 30 gal c) 45 minutes d) 2/3 gal/min e) 20 gal/min
Item 25	Tier 2	Which of the following best describes the reason for your answer for the previous question? e) The slope of the linear function of the two variables is equal to the rate of change of those variables. f) The rate of change of the two variables is the total amount of time that has elapsed for an event. g) The rate of change of two variables is the total quantity that is being analyzed. h) The rate of change of a variable is the inverse of the slope of a linear function.	PM-1 Which of the following best describes the reason for your answer for the previous question? a) The rate of change is the slope of the line created by graphing the two variables on xy coordinates. b) The rate of change of the two variables is the total amount of time that has elapsed for an event. c) The rate of change of two variables is the total quantity that is being analyzed. d) The rate of change of a variable is the inverse of the slope of the line created by graphing the two variables on xy coordinates. PM-2 Add item e) The rate of change is found by taking the	Which of the following best describes the reason for your answer for the previous question? a) The rate of change is the slope of the line created by graphing the two variables on xy coordinates. b) The rate of change of the two variables is the total amount of time that has elapsed for an event. c) The rate of change of two variables is the total quantity that is being analyzed. d) The rate of change of a variable is the inverse of the slope of the line created by graphing the two variables on xy coordinates. e) The rate of change is found by taking the total difference in quantity and writing units per minute after it

			total difference in quantity and writing units per minute after it PM-3 A PM-4 A PM-5 Which of the following best describes the reason for your answer for the previous question? a) The slope of the linear function of the two variables is equal to the rate of change of the x variable with respect to the y variable. b) The rate of change of the two variables is the total amount of time that has elapsed for an event. c) The rate of change of two variables is the total quantity that is being analyzed. d) The rate of change of a variable is the inverse of the slope of a linear function.	

*PM-1 = Panel Member #1; **A = Current Diagnostic Item Was Accepted

Appendix L

Arbitration Results Summary

Item[a]	Tier	PM-1[b]	PM-2	PM-3	PM-4	PM-5	% Agreement
1	1	A[c]	A	A	A	A	100
1	2	A	D[d]	A	A	A	80
2	1	D	A	A	A	A	80
2	2	A	A	A	A	A	100
3	1	A	D	A	A	A	80
3	2	A	A	D	A	A	80
4	1	A	A	A	A	A	100
4	2	A	A	A	A	A	100
5	1	A	A	A	A	A	100
5	2	A	A	A	A	A	100
6	1	A	A	A	A	A	100
6	2	A	A	A	A	A	100
7	1	A	A	A	A	A	100
7	2	A	A	A	A	A	100
8	1	A	A	A	A	A	100
8	2	D	A	A	A	A	80
9	1	A	A	A	A	A	100
9	2	D	A	A	A	A	80
10	1	A	A	A	A	A	100
10	2	A	A	A	A	A	100

11	1	A	A	A	A	A	100
11	2	A	A	A	A	A	100
12	1	A	A	A	A	A	100
12	2	A	A	A	A	A	100
13	1	D	A	A	A	A	80
13	2	A	A	A	A	A	100
14	1	A	A	A	A	A	100
14	2	A	A	A	A	A	100
15	1	A	A	A	A	A	100
15	2	A	A	A	A	A	100
16	1	A	A	A	A	A	100
16	2	A	A	A	A	A	100
17	1	D	A	A	A	A	80
17	2	A	A	A	A	A	100
18	1	A	A	A	A	A	100
18	2	A	A	A	A	A	100
19	1	A	A	A	A	A	100
19	2	A	A	A	A	A	100
20	1	A	A	A	A	A	100
20	2	A	A	A	A	A	100
21	1	A	A	A	A	A	100
21	2	A	A	A	A	A	100
22	1	A	A	A	A	A	100
22	2	A	A	A	A	A	100
23	1	A	A	A	A	A	100

23	2	A	A	A	A	A	100
24	1	A	A	A	A	A	100
24	2	A	A	A	A	A	100
25	1	A	A	A	A	A	100
25	2	A	A	A	A	A	100

[a]Item = Diagnostic Item; [b]PM-1 = Expert Panel Member #1; [c] A = Accepted the Diagnostic Item as Written; [d]D = Did Not Accept Diagnostic Item as written

Appendix M

Semi-Structured Interview Protocol

Questions developed for the semi-structured interview focused the level of conceptual understanding the interviewee possessed for each of the five targeted math and science concepts: evaporation, condensation, areas of irregular shapes, rates of production, and slopes of production rate data. Particular pre/post TTMC and FTMC responses of interest that were the subject of these questions were incidences where students showed evidence of learning a new concept over the course of the intervention but still retained some misconception about the concept. This was evidenced by participants responding incorrectly to a Tier 1 item on the pre-assessment and then responding correctly to the same Tier 1 item on the post assessment but incorrectly answered the Tier 2 reasoning multiple choice question. In addition, questions requiring participants to elaborate on their perceptions about what phase of the design process or T/E DBL experience most influenced their conceptual learning of the above targeted items were also developed.

Concept responses were used to draft interview questions designed to corroborate participant concept knowledge progression (addressing RQ1). In addition, evidence for what T/E DBL experiences they thought promoted their acquisition of the science and mathematics concepts was corroborated using questions related to participant responses on Tier 4 for each targeted concept (addressing RQ2). Follow up anticipatory questions were asked as a result of interesting or anomalous response phenomena during the interviews in order to clarify participant thinking related to persistent misconceptions. The following lists the science and mathematics concepts which were the subject of the interview questions and provides example questions and probes that could be used.

Science Concept 1: Evaporation. Interview questions on evaporation targeting RQ1 would ask about the degree of concept knowledge progression.

Example Question: Tell me about your understanding of evaporation and how this understanding may have changed over the course of the recent design challenge?

Potential Probes:

1. Tell me about what is happening with the water molecules at surface of the liquid.
2. Where does the energy for evaporation come from?
3. What happens to the salt molecules during evaporation?

Interview questions on evaporation targeting RQ2 ask about the perceived experiential conditions leading to knowledge progression.

Example Question: Was there a particular design experience during the challenge that helped to change your understanding of evaporation?

Potential Probes:

1. What was it about that particular design experience that helped change your understanding of evaporation?

2. Were there any other experiences beyond the challenge itself that helped you better understand the concept of evaporation?

Science Concept 2: Condensation. Interview questions on condensation targeting RQ1 would ask about the degree of concept knowledge progression.

Example Question: Tell me about your understanding of condensation and how this understanding may have changed over the course of the recent design challenge?

Potential Probes:

1. Can you explain more about what was happening to the water molecules in the vapor state when condensation occurs.
2. Tell me a little more about where the energy goes when water molecules in the vapor phase condense to form liquid?

Interview questions on condensation targeting RQ2 would ask about the perceived experiential conditions leading to knowledge progression.

Example Question: Were there any particular design experiences during the challenge that helped change your understanding of condensation?

1. What was it about that particular design experience that helped change your understanding of condensation?
2. Were there any other experiences beyond the challenge itself that helped you better understand the concept of condensation?

Mathematics Concept 1: Areas of Irregular Shapes. Interview questions on areas of irregular shapes targeting RQ1 would ask about the degree of concept knowledge progression.

Example Question: What did you come away with from our design challenge about determining the area of the 2-dimensional irregular shapes?

Potential Probes:

1. How has your approach to finding the area of irregular shapes changed over the course of the challenge?
2. Do you feel you are better at determining the area estimate of a 2-dimensional irregular shape? Can you explain why?

Interview questions on areas of irregular shapes targeting RQ2 would ask about the perceived experiential conditions leading to knowledge progression.

Example Question: Were there any particular design experiences during the challenge that helped change your understanding of how to find the area or irregular shapes?

Potential Probes:

1. What was it about that particular design experience that helped change your understanding of how to determine the area of irregular shapes?
2. Were there any other experiences beyond the challenge itself that helped you better understand the concept of determining the area of irregular shapes?

Mathematics Concept 2: Rates of Condensate Production Per Unit Area. Interview questions on rates of condensate production per unit area targeting RQ1 would ask about the degree of concept knowledge progression.

Example Questions: Tell me about your understanding of how best to estimate the rate of condensation per unit area and how this understanding may have changed over the course of the recent design challenge.

Potential Probes:

1. What is your understanding of how the rate of condensation for different systems can be compared?
2. Can you tell me more about what the production rate per unit area tells you about a given system design? (more efficient, less efficient)

Interview questions on areas of irregular shapes targeting RQ2 would ask about the perceived experiential conditions leading to knowledge progression.

Example Question: Were there any particular design experiences during the challenge that helped change your understanding of how to find the condensation production rate per unit area?

Potential Probes:

1. What was it about that particular design experience that helped change your understanding of how to determine the condensation production rate per unit area?
2. Were there any other experiences beyond the challenge itself that helped you better understand the concept of determining the condensation production rate per unit area?

Mathematics Concept 3: Slopes of Condensate Production Rate Data. Interview questions on slope of production rate data targeting RQ1 would ask about the degree of concept knowledge progression.

Example Question: Tell me about your understanding of the slope of the condensate production data and the rate of change of condensate production.

Potential Probes:

1. How would you explain to another student how you could find the condensate production rate from the slope of your production versus time graph? Can you explain in more detail how you knew these to values were the same?
2. Tell me about what you know about rate of change? Is it related to slope of the production versus time graph somehow? Explain what you mean.

Interview questions on slopes of condensate production rate data targeting RQ2 would ask about the perceived experiential conditions leading to knowledge progression.

Example Question: Were there any particular design experience during the challenge that helped you better understand the rate of change in condensate production?

Potential Probes:

1. What was it about that particular design experience that helped change your understanding of how to determine rates of change?
2. How did this design experience clear up any confusion you might have had about slope and how it relates to the rate of change with the slope of your production data.

The predetermined questions were organized and listed in tabular form (Table M1), which would serve as the protocol to be followed in each individual interview. The entire protocol can be found in Appendix M.

Table M1

Sample: Predetermined Structured Interview Questions and Follow-Up Prompts

Question	Predetermined Structured Interview Questions	Targeted Research Question
1a	Tell me about your understanding of evaporation and how this understanding may have changed over the course of the recent design challenge? Potential Probes: 1. Tell me about what is happening with the water molecules at surface of the liquid. 2. Where does the energy for evaporation come from? 3. What happens to the salt molecules during evaporation?	RQ1

1b	Was there a particular design experience during the challenge that helped to change your understanding of evaporation? Potential Probes: 1. What was it about that particular design experience that helped change your understanding of evaporation? 2. Were there any other experiences beyond the challenge itself that helped you better understand the concept of evaporation?	RQ2
2a	What did you come away with from our design challenge about determining the area of the 2-dimensional irregular shapes? Potential Probes: 1. How has your approach to finding the area of irregular shapes changed over the course of the challenge? 2. Do you feel you are better at determining the area estimate of a 2-dimensional irregular shape? Can you explain why?	RQ1

2b	Were there any particular design experiences during the challenge that helped change your understanding of how to find the area or irregular shapes? Potential Probes: 1. What was it about that particular design experience that helped change your understanding of how to determine the area of irregular shapes? 2. Were there any other experiences beyond the challenge itself that helped you better understand the concept of determining the area of irregular shapes?	RQ2

Appendix N

Design Challenge

Saltwater to Freshwater System Design Challenge

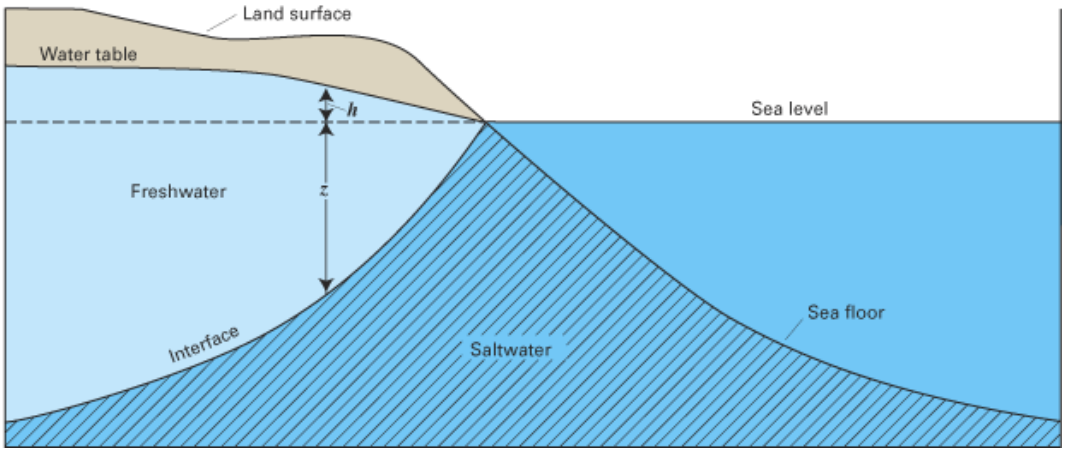
Context:

Many coastal communities, located around the world, have limited access to freshwater. This is due to several factors including: they are located in a desert environment where freshwater is naturally scarce, the population of the community is larger than current freshwater supplies can support, or pollution of local freshwater sources such rivers and streams has occurred. According to a NASA Jet Propulsion Laboratory report, the flow patterns of nearly 300 million rivers worldwide are changing due to climate change and human usage, forcing communities to access freshwater from subsurface aquifers. Coastal communities can be substantially affected by saltwater intrusion into their freshwater aquifers due to over pumping of those aquifers.

Saltwater intrusion occurs when an aquifer containing freshwater is located next to a body of saltwater. The adjoining aquifers are typically kept separate due to water density differences (Figure 1).

Figure 1:

Diagram of adjoining freshwater and saltwater aquifers



Freshwater in aquifers is typically accessed by wells where a pump is lowered into the well and water is pumped out. If many wells are installed in the aquifer and large amounts of freshwater are removed, saltwater will begin to move into the freshwater aquifer and contaminate the freshwater drinking wells. This can lead to water shortages and significant health impacts on local residents.

There may be hope though. Coastal communities, by definition, are located near bodies of saltwater. Couldn't this saltwater be converted to freshwater for human consumption?

Challenge:

You have been asked by the Non-Governmental Organization (NGO) Aqua Matters to design and construct a desktop prototype process that can produce freshwater from saltwater. Keep in mind that many of these coastal communities are poor and lack financial and fuel resources to tackle this problem.

Design Constraints:

1. Your design will be a proof of concept system that can fit in a space no bigger than your desktop.
2. Your prototype must be built from cheap, easily obtained, recycled material.
3. Your prototype must operate on an abundant but very cheap energy source.
4. Your prototype must allow for the easy introduction of saltwater and the equally easy collection of freshwater.
5. You must measure, calculate, and report on various performance variables associated with your prototype to be named later. (Note: The instructor will introduce the need to measure condensate production rate per unit of effective condensation area, rates of change, and conductivity measurements of the freshwater produced)

Objectives:

1. Demonstrate understanding of solar distillation, evaporation, condensation, rate of condensation, area of irregular shapes, and slope and rate of change.
2. Use science, technology, engineering, and mathematics knowledge to construct a working technological solution to this design challenge and report on condensate production rate per unit of effective condensation area, rates of change, and conductivity measurements of the freshwater produced.
3. Demonstrate knowledge of basic tool and materials required for the construction of a working prototype.
4. Develop technical communication skills while working with others in small group and whole class settings.

Materials:

1. Prototyping materials such as recycled plastic bottles and containers, plastic cups, Saran Wrap, aluminum foil, tape, glue, glue guns, fasteners, and paint
2. Materials to make saltwater such as salt, a kitchen scale, a graduated cylinder, and empty milk jugs for saltwater storage.
3. Conductivity meter

Evaluation:

1. Prototype tests including condensation rate and conductivity measurements
2. Area of effective condensation calculations
3. Rate of condensate production per unit of effective condensation area calculations.
4. Slope of the condensate production versus time plot calculations
5. Student written definitions and explanations of evaporation, heat of evaporation, condensation, heat of condensation, solute/solvent interactions.

Appendix O

I-STEM ED T/E DBL Intervention Instructional Plan – Solar Distillation

This plan is a class by class description of interventions/treatments that will be used during the course of the I-STEM ED DBL Solar Distillation Challenge. It includes, materials needed, teacher directed activities, expected student activities, direct questions, reflection activities, and assessments. Due to the unpredictable nature of DBL pedagogical approaches this cannot be a comprehensive list of everything that will happen within the classroom during the challenge but it will be as detailed as possible to give the reader an idea of the pedagogical techniques intended to be used. The intended daily intervention/treatment plans are delineated and correspond to specific design phases as described in the P.I.R.P.O.S.A.L. Model. This model is a conceptual/pedagogical framework for I-STEM ED that includes the following design phases such as; Problem Identification, Ideation, Research, Potential Solutions, Optimization, Solution Evaluation, Alterations, and Learned Outcomes (Wells, 2016a, 2016b, 2016c).

Pre-Challenge Assessments

Assessment #1

- **TTMC Diagnostic Test**

At the start of the semester, approximately eight weeks prior to the beginning of the I-STEM ED T/E DBL Solar Distillation Challenge, participants in this study will take a science and math pre-assessment of the targeted science and math concepts that are the learning objectives of this challenge. The TTMC Diagnostic Science and Math assessment will include 25 multi-tiered multiple choice questions that will assess participant concept knowledge of the targeted science and math concepts which include:

1. Evaporation (molecular change of state, heat of evaporation, solvent-solute transportation mechanism an interactions)
2. Condensation (molecular change of state and heat of condensation)
3. Area of irregular shapes
    a. Inscribed and circumscribed rectangles
    b. Riemann sum calculations
4. Calculation of rate of condensate production by finding the slope of the production versus time plot.
5. Rate of freshwater production per hour per unit area.

Intervention/Treatment Day #1

Challenge Engineering Design Phase(s): Problem Identification – Ideation. The design phases that participants will be immersed in on this first day are the problem identification phase and the ideation phase.

Lesson Topic: Coastal Communities Need for Freshwater. Participants will be introduced to the reality that some coastal communities around the world suffer from the lack of fresh water and they are in need of a technology and engineering solution to this problem.

Lesson Learning Objective(s):

1) Participants will state, in writing, in their SEINs, the reasons coastal communities need freshwater and may have trouble obtaining fresh water for their citizens.
2) Participants will state, in writing, in their SEINs, the effects of current ground and surface water extraction has on coastal community environments.
3) Participants will discuss, in writing in their SEINs, the effects on the human body of lack of fresh drinking water.
4) Participants will state, in writing, in their SEINs, the phase(s) of the engineering design process that they participated in during this class and what typically occurs during these phases.
5) Participants will state, in writing, in their SEINs, ideas applicable and related to the design challenge, that could solve the identified human want or need.

Procedures:

1. Introductory Activities/Hook

On the first day of the challenge, study participants will be introduced to the I-STEM ED DBL Solar Distillation Challenge. They will not be told the title of the challenge so as not to bias the solution ideation process. Participants will view a PowerPoint presentation that introduces them to coastal communities that suffer from a lack of fresh water. The PowerPoint will encourage class research and discussion about the water consumption survival needs of individuals and communities and the repercussions on human health and the environment if these needs are met through destructive abstractive technologies or not

met completely. The PowerPoint will provide participants with insight into environmental damage caused by over extraction of water from surface and groundwater sources.

2. Instructional Activities/Procedures

Participants will be informed that they will be designing a desktop prototype technology that can utilize the abundant salt water resources available to the coastal community to solve the fresh water needs of the previously discussed communities. They will be working in groups of two and will be expected to research, design, build and test this prototype technology. A final report detailing the design challenge, responses to design challenge questions, design sketches, plans for testing, testing results, design modifications, ultimate design performance outcomes, and implications for future designs will be required at the culmination of the design challenge.

The design process will be discussed with the participants at this point in the lesson, specifically the design phases as described in the P.I.R.P.O.S.A.L. Model. This model is a conceptual/pedagogical framework for I-STEM ED that includes the following design phases such as; Problem Identification, Ideation, Research, Potential Solutions, Optimization, Solution Evaluation, Alterations, and Learned Outcomes (Wells, 2016a, 2016b, 2016c). The design phases of the P.I.R.P.O.S.A.L. Model are shown in Figure 1 below.

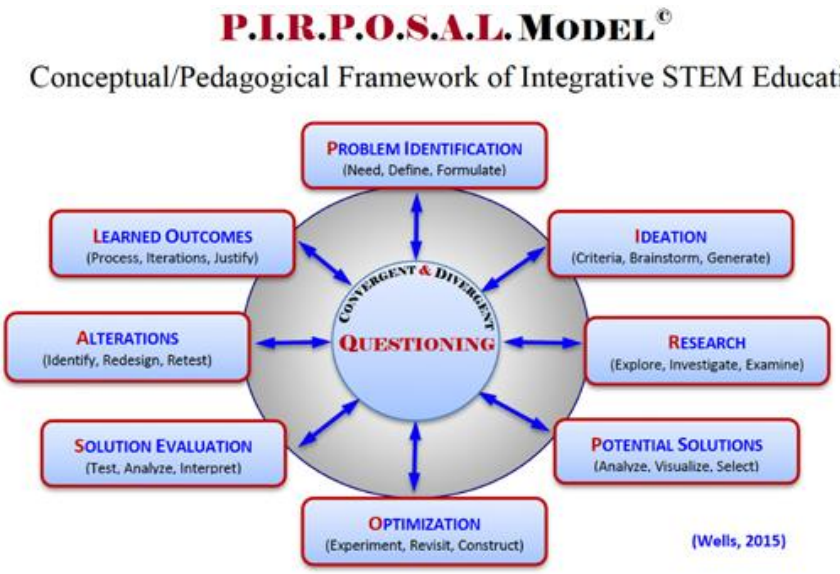


Figure 1. P.I.R.P.O.S.A.L. Model

Participants will be informed that the design phases that are the focus of today's lesson are Problem Identification and Ideation. Participants will be shown a diagram of the P.I.R.P.O.S.A.L. model and the design phases that are to be worked on in this class will be identified. Specific expectations of student learning and participation will be explicitly relayed to the participants and include the following:

1) Participants will state, in writing, in their SEINs, the design challenge.
2) Participants will state, in writing, in their SEINs, the design phases that were encountered in this lesson (Problem Identification and Ideation).
3) Participants will be expected to work with their partners to; develop a description of the design challenge in their own words, formulate group questions about what is unclear about the design challenge to be asked in a whole class discussion, contribute in the processes of researching solutions to the design challenge, be active listeners when their

partners are offering ideas or asking questions, and record discussions, ideas, and answers in the SEINs in and organized and neat manner.

Once participant performance expectations are discussed, a series of design challenge related questions will be presented to the class. The questions are as follows:

1) How much water, on a daily basis, does an individual need to survive?
2) What are the stages of dehydration?
3) How much water does the average person in the U.S. use per day?
4) How much water does the average person around the world use per day?
5) How do coastal communities access fresh water?
6) What are some environmental problems cause by extraction of fresh water by coastal communities?
7) What is an aquafer?
8) What is salt water intrusion?
9) How might you solve the problem of coastal communities needing fresh water?

Participants will be allowed to use information resources provided by the instructor and the internet to answer the above questions. Participants will also be told that they will report their answers to the class in a whole class discussion at the end of the lesson. The instructor will move throughout the classroom answering student questions, monitoring group participation and response note taking, asking clarifying questions, and providing guidance while participants are researching the above question.

3. Closing Activities

A whole class discussion related to student responses to the above questions will be held at the end of class. Groups will be asked to respond and to each question and summary notes will be written on the board. A list of ideas for solving coastal communities' needs for fresh water will be created based on group answers to question nine. Participants will be asked what new information they learned during the lesson and summary statements will also be written on the board.

Supporting Assignments:

Participants will be required to write up their final answers for the following questions in their SEINs and hand in pictures of their responses to the appropriate drop box in Moodle (the current available instructional management system):

1) State in writing the reasons coastal communities need freshwater and may have trouble obtaining fresh water for their citizens.
2) State in writing the effects of current ground and surface water extraction has on coastal community environments.
3) Discuss in writing the effects on the human body of lack of fresh drinking water.
4) State in writing the phase(s) of the engineering design process that you participated in during this class and what occurred during those phases.
5) Participants will be asked to individually begin to develop a design of a system that would solve the design challenge. They are not to use any research technology such as their phones or computers and cannot speak with anyone else about their design. They will be asked to include labelled design sketches and descriptions of how their system will work.

Instructional Materials:

The instructional materials that will be needed for this lesson are as follows:

1) The introductory PowerPoint,
2) P.I.R.P.O.S.A.L. model diagram,
3) Laptop computers for each participant (department Chromebooks can be used if participants do not have personal devices),
4) SEINs for each participant,
5) A Drop Box for final SEIN responses,

Assessing for Learning:

1) Participants will be able to state in writing in their SEINs the reasons coastal communities need freshwater and may have trouble obtaining fresh water for their citizens.
2) Participants will be able to state in writing in their SEINs the effects of current ground and surface water extraction has on coastal community environments.
3) Participants will be able to discuss in writing in their SEINs the effects on the human body of lack of fresh drinking water.
4) Participants will be able to state in writing in their SEINs the phase(s) of the engineering design process that they participated in during this class and what typically occurs during these phases.
5) Participants will discuss and record in their SEINs, ideas, applicable and related to the design challenge, that could solve the identified human want or need.

The instructor will review these assessment tasks prior to the next lesson in order to identify participants with preconceptions about the above learning objectives. Participants with

identified preconceptions will be met with on a one-to-one basis, during the group work phase of the next lesson, in order to re-teach the learning objectives of this lesson.

Intervention/Treatment Day #2

Challenge Engineering Design Phase(s): Ideation – Research. The design phases the participants will be immersed in are the ideation and research phases.

Lesson Topic: Solar distillation of salt water. Participants will be guided towards designing a solar distillation prototype that can be used to produce fresh water from salt water.

Lesson Learning Objective(s):

1) Participants will describe, in writing, in their SEINs, what evaporation is and what changes occur to water molecules during the change from a liquid to gaseous state,
2) Participants will describe, in writing, in their SEINs, what the heat of evaporation is and what its role is in the change of water from a liquid to gaseous state.
3) Participants will describe, in writing, in their SEINs, what condensation is and what changes occur to water molecules during the change from a gaseous to liquid state,
4) Participants will describe in writing, in their SEINs, what the heat of condensation is and what its role is in the change of water from gaseous to liquid state.
5) Participants will describe, in writing, what happens to the solvent(water)-solute(salt) mechanical relationship when salt water evaporates.
6) Participants will state, in writing, in their SEINs, the phase(s) of the engineering design process that they participated in during this class and what typically occurs during these phases.

Procedures:

1) Introductory Activities/Hook

   A short review of what occurred in the last class will be conducted. Participants will be reminded that they participated in the Problem Identification and Ideation phases of design in the last class and will be informed that they will be participating in the Ideation and Research phases of the design during this class. Participants will be shown a diagram of the P.I.R.P.O.S.A.L. model and the design phases that are to be worked on in this class will be identified. Participants will be asked what problems coastal communities face related to water resources. They will be asked what technological solutions they have thought of, or found, that may solve these problems given the abundance of salt water in the locality. A list of possible solutions will be created on the board and participants will be asked to list the pros and cons of each solution strategy. The instructor will guide participants towards a solar distillation technological solution so as to align participant efforts with lesson learning objectives. This will be done by emphasizing the material abundance of salt water, the lower power requirements of this technological approach, the lack of need for high tech materials required in reverse osmosis strategies, and the relatively easier engineering requirements for a prototype design.

2) Instructional Activities/Procedures

   In a whole class discussion setting, the instructor will ask participants what they think they will need to know about solar distillation in order for them to design a functioning solar distillation unit prototype. A list of these aspirational questions will be created and refined by the instructor. The instructor will ensure that the following questions will be researched and addressed by participant groups:

1) What is evaporation?
2) What happens to water molecules when water evaporates and why does this happen?
3) What is the heat of evaporation and what is its role in evaporation?
4) What is condensation?
5) What happens to water molecules when water condenses and why does this happen?
6) What is the heat of condensation and what is its role in condensation?
7) When salt water evaporates what happens to the salt that was in solution? Why?
8) How can knowledge of these ideas be used in a desktop design of a solar distillation unit?
9) What design ideas do you have, provide sketches of your design ideas?
10) Participants will be asked to provide written details in their design sketches where evaporation and condensation will be occurring and why they think this will be occurring at the locations they specified.
11) How will we know, without tasting, if the water that is produced by the solar distillation unit is truly fresh water?

Participants will be asked to work in groups and use the internet and informational resources provided by the instructor to answer these questions in their SEINs. They will be reminded to be as detailed as possible when writing their notes in their SEINS and to include sketches when appropriate to help convey their understanding of the answers. As student groups work, the instructor will move throughout the classroom answering questions and providing clarifying guidance through questioning techniques. In addition, the instructor will be

circulating amongst groups and addressing preconceptions of participants that were identified as a result of the review of the previous lesson's assessment tasks.

Once groups have indicated that they have finished answering the above questions they will be told to begin making a detailed design of a solar distillation unit prototype. They will be told that their design sketches should be created using a straight edge, be as neat as possible, and labeled with details regarding the design. They will also be informed that the class will participate in a gallery walk where groups will display their designs and explain them to the other groups. These deigns sketches will be photographed or scanned and submitted to the instructor via the classroom learning management system. They will be reminded to take into account the information that they just researched in order to help them design their prototypes and to detail where evaporation and condensation will be occurring within the design. They will also be asked to indicate the direction of the heat of evaporation and heat of condensation using arrows on their design sketches and ultimately where the disposition of these heats will be.

3) Closing Activities

With 20 minutes left to go in the period, the class will be called into a whole group discussion where question responses will be reviewed. Summary question response lists will be constructed on the board so participants can add details, to their own SEINs, that they find to be novel question responses. It is anticipated that participants will have found that a conductance reading of the fresh water that is produced will be used to show that the water that is produced is indeed fresh water. A conductance meter will be show to the participants

and its operation will be briefly discussed. Representative conductance values will be researched for seawater and fresh water and recorded in participants' SEINs.

Participants will be instructed that they need to work with their group members after class to prepare their design sketches for the gallery walk that will occur at the beginning of the next class.

Supporting Assignments (ex: homework, projects, papers, etc):

1) Participants will be tasked with working with their group members to create the initial design of their solar distillation unit prototype. They will also be asked to make a materials list of the items they believe they will need to build their prototype. When this design is complete, prior to the next class, participants will be asked to photograph the design sketches and materials list and submit them to the instructor using the classroom learning management system.
2) Participants will be asked to photograph their SEIN notes that they work in this class. These will be clearly labeled and submitted to the instructor using the classroom learning management system.
3) Participants will be asked to answer the questions presented above by working individually and without the use of their SEIN notes. This set of question responses will be photographed and submitted to the instructor using the classroom learning management system.

Instructional Materials:

1) P.I.R.P.O.S.A.L. model diagram,
2) Laptop computers for each participant (department Chromebooks can be used if participants do not have personal devices),
3) SEINs for each participant,
4) A Drop Box for final SEIN responses, design sketches, and question responses.

Assessing for Learning:

1) Participants' SEINs will be reviewed to assess their ability to describe and explain what evaporation is and what changes occur to water molecules during the change from a liquid to gaseous state,
2) Participants' SEINs will be reviewed to assess their ability to describe and explain what the heat of evaporation is and what its role is in the change of water from a liquid to gaseous state.
3) Participants' SEINs will be reviewed to assess their ability to describe and explain what condensation is and what changes occur to water molecules during the change from a gaseous to liquid state,
4) Participants' SEINs will be reviewed to assess their ability to describe and explain what the heat of condensation is and what its role is in the change of water from gaseous to liquid state.
5) Participants' SEINs will be reviewed to assess their ability to describe and explain what happens to the solvent(water)-solute(salt) mechanical relationship when salt water evaporates.

6) Participants' SEINs will be reviewed to assess their ability to describe and explain the phase(s) of the engineering design process that they participated in during this class and what typically occurs during these phases.

Intervention/Treatment Day #3

Challenge Engineering Design Phase(s): Potential Solutions –Optimization. The design phases the participants will be immersed in are the Potential Solutions and Optimization.

Lesson Topic: Solar distillation of salt water. Participants will be guided towards designing a solar distillation prototype that can be used to produce fresh water from salt water.

Lesson Learning Objective(s):

1) Participants will identify where evaporation is occurring in their group's design and where the heat of vaporization will be coming from when questioned by the instructor. They will also be able to indicate this information on their design drawings.
2) Participants will identify where condensation is occurring in their group's design and where the heat of condensation will be given off to when questioned by the instructor. They will also be able to indicate this information on their design drawings.
3) Participants will indicate where fresh water will be collected and where salt concentrations will be increasing in their designs when questioned by their instructor. They will indicate this information on their design drawings.
4) Participants will identify the effective condensation area in their designs when questioned by their instructor. They will describe this area and indicate it by shading the appropriate region on their design drawings.
5) Participants show in writing how an irregular area can be estimated by using the sum of the areas of regular shapes that have been inscribed or circumscribed in the irregular area.

6) Participants will identify, in writing, what design phases they participated in during this class and what typically occurs within these phases.

Procedures:

1) Introductory Activities/Hook

Participants will be asked what design phases were worked on in the previous class period (Ideation and Research) and will be explicitly told that today they will be working within the Potential Solutions and Optimization design phases. The P.I.R.P.O.S.A.L. model diagram will be referenced so as to provide a graphic model of the design phases. Participant groups will then be asked to place their design sketches and material lists on the front board. Each group will be given time to explain their designs, how they will work, and what materials they plan to use for the construction of their prototype. Groups will be given time to conduct a gallery walk and ask detailed questions of their classmates. The instructor will question individual groups about their design, pointing out possible weakness by asking critical questions of the participants. This will be done in an effort to clarify student thinking about their design and ideas about construction techniques.

A whole group discussion will be conducted regarding the design challenge requirement that participants determine the production rate for fresh water per effective condensation unit area. The reason for this requirement will be discussed and explained that it would allow future designers to scale up the prototype to meet water production needs in a future design scenario. The effective condensation area will be described as the surface area (in square inches) of the prototype's region where condensation droplets will be effectively conveyed into the fresh water capture container. Condensation can occur in many areas within the prototype but only condensation droplets that form in the effective condensation area will be conveyed to the fresh

water collection container. This region in the prototype will be irregular and will require a specialized technique to estimate its area (Riemann Sum). Participants will be asked to consider how they will try to calculate this area and be ready to explain their ideas to the class at a later time.

2) Instructional Activities/Procedures

Participants will be provided with materials and tools to begin construction of their prototype. The instructor will be circulating the classroom asking participants questions about where they believe evaporation and condensation will be occurring in their prototype. They will also be asked where they believe the heat of evaporation will be coming from and where the heat of condensation will be going to. If a group has considered recapturing the heat of condensation for use in a multistage distillation unit, this design will be brought to the attention of the entire class and the group members will be encouraged to explain their thinking that led to the design. If no group has thought of the recapturing the heat of condensation for increased efficiency in a multistage condensation unit then the instructor will ask questions to the entire class such as the following:

a) Where does the heat of condensation go?

b) Can the heat of condensation be used in some way so as to encourage more evaporation?

Participants will be encouraged to make progress on their prototypes and will be assisted by the instructor when they have questions. They will be encouraged to make detailed notes in their SEINs about what is occurring during the construction phase, what ideas were considered and what design decisions were made. They will be asked to also record any new learning that has occurred during their work.

4) Closing Activities

With 20 minutes left in the class period a whole group discussion will be held with groups reporting on their progress and revisiting the previously expressed problem of measuring the effective condensation area. Participants will be asked to describe the general shape of what they consider their effective condensation area and will be asked to sketch a general likeness of it on the board and in their SEINs. Participant ideas about how to calculate the area of an irregular area will be discussed and ideas will be summarized on the board. If participants offer the idea that the irregular area can be broken up into inscribed of circumscribed regular areas these ideas will be explored more closely and clarified for the rest of the class. If these ideas are not offered, the instructor will begin by asking the class how they could find the area of a rectangle, then the area of a composite shape made of two rectangles, then the area of a composite shape made of a rectangle and a triangle. The intent of this sequential questioning approach will be to lead the participants towards the conception that irregular areas can be broken into regular areas and that the sum of those regular areas will be an estimate of the area of the irregular area. Participants will be asked why the sum of the regular areas is an "estimate" of the irregular area and not an exact value of the area. They will be guided towards the conception that regular rectangles inscribed or circumscribed in an irregular area leaves tiny spaces that either over estimate or underestimate (depending on the method used) the area for the irregular area. These over/under estimations will be shown in detailed on the board by the instructor. Participants will be asked to roughly sketch their effective condensation areas divided up into regular rectangular areas by consistently inscribing them or circumscribing them. They will then be asked to write in their SEINs a description of how they would be able to calculate an estimate of the area of their

irregular effective condensation area. They will be asked to indicate if they think it will be an over or under estimation.

Supporting Assignments (ex: homework, projects, papers, etc):

1) Participants will be asked to photograph their SEIN notes and design drawings and submit them to the instructor using the classroom learning management system.
2) Participants will be given a worksheet with an image of an irregular area. Students will be instructed to inscribe rectangles with widths of 1cm onto the figure and then estimate the area of the irregular area. The worksheet will ask the participants if their estimate is an over or under estimation of the irregular shape and what they would do to improve the accuracy of the estimate. This worksheet will be photocopied and submitted to the instructor using the classroom learning management system.
3) Students will be asked to identify in their SEINs the design phases that they were engaged in during this class (Potential Solutions and Optimization) and what activities and actions are typical for designer during these phases. This SEIN description will be photocopied and submitted to the instructor using the classroom learning management system.

Instructional Materials:

1) P.I.R.P.O.S.A.L. model diagram,
2) Laptop computers for each participant (department Chromebooks can be used if participants do not have personal devices),
3) SEINs for each participant,
4) An Irregular Figure Area Calculation Worksheet

5) A Drop Box for final SEIN responses, design sketches, and the Irregular Figure Area Calculation Worksheets.

Assessing for Learning:

1) Participants' will be questioned to assess if they can identify where evaporation is occurring in their group's design and where the heat of vaporization will be coming. A record of the results of these questions will be kept by the instructor. Their design drawings will also be reviewed to determine if they can correctly determine where evaporation is occurring and where the heat of evaporation is coming from.
2) Participants' will be questioned to assess if they can identify where condensation is occurring in their group's design and where the heat of condensation will be dissipated to. A record of the results of these questions will be kept by the instructor. Their design drawings will also be reviewed to determine if they can correctly determine where condensation is occurring and where the heat of condensation is dissipating to.
3) Participants will be questioned to assess if they are able to indicate where fresh water will be collected and where salt concentrations will be increasing in their designs. A record of these question results will be kept by the instructor. Their design drawings will be reviewed to assess if they are able to indicate this information on their design drawings.
4) Participants will be questioned to assess their ability to identify the effective condensation area in their designs. A record or these question results will be kept by the instructor. Their design drawings will be reviewed to assess their ability to describe this area.
5) Each participant's Irregular Figure Area Calculation Worksheet and SEIN notes related to irregular area calculations will be reviewed to assess their knowledge of how an

irregular area can be estimated by using the sum of the areas of regular shapes that have been inscribed or circumscribed in the irregular area.

6) Participants' SEINs will be reviewed to assess their able to identify in writing what design phases were worked on in this class and what typically occurs during these phases.

Intervention/Treatment Day # 4

Challenge Engineering Design Phase(s): Optimization – Solution Evaluation. The design phases the participants will be immersed in are the Optimization and Solution Evaluation

Lesson Topics: Solar distillation of salt water. Participants will be guided towards finishing the construction of their group's solar distillation prototype, calculating an estimate of the area of the effective condensation area, and deciding how they will evaluate their prototype's performance at producing fresh water from salt water.

Lesson Learning Objective(s):

1) Participants will calculate an estimate of an area for an irregular two dimensional shape through the use of the Riemann Sum concept.
2) Participants will state in writing how they will collect data on the production of fresh water over time, graph it, and use the slope of the fresh water production line to calculate the rate of fresh water production.
3) Participants will make a salt water solution that will approximate seawater with the same percent of salt by weight.
4) Participants will identify, in writing, what design phases they participated in during this class and what typically occurs within these phases

Procedures:

1) Introductory Activities/Hook

The class will begin with a discussion about what stage of the design process the class working within and what the class expectations will be. The design phases the participants will be immersed in are the Optimization and Solution Evaluation phases. Participants will be told that they are expected to finish building their prototypes, calculate an estimate of the effective condensation area, create a salt water solution that has the same percent salt by weight as seawater, and collect fresh water production data so as to test the efficiency of their prototype.

2) Instructional Activities/Procedures

Participants will work on their prototype in an effort to finish the design. As they are working, the instructor will circulate throughout the classroom and inquire about how they plan to calculate the effective condensation area of their finished prototype. It is anticipated that students will trace the outline of the effective condensation area by inverting their prototype and marking the edges of the designated region. There may be other methods that provide a suitable two dimensional irregular figure. They will then calculate the area estimate through the use of Riemann Sum concepts. The instructor will remind the groups that all calculations and notes should be recorded in their SEINs.

The instructor will also inquire how the groups will collect fresh water production data. It is anticipated that groups will monitor and measure the amount of fresh water produced over time and record this data in a table.

Once the groups have completed their prototypes a whole group discussion will be held to discuss the data that groups anticipate they will collect. The instructor will ask participants how that data could be plotted on a graph. The relevance and appropriateness of a time versus fresh water production graph will be arrived at through directed questioning by the instructor. Participants will be asked to predict what the shape of the graph will look like, which will most likely be a fairly linear graph, and what the slope of this line represents. The units of the slope of the line (ml/hr) will be discussed and connected to the reporting requirements of the challenge.

3) Closing Activities

Participants will be instructed to charge their prototypes with seawater and place the prototypes in prepared area that is in the sun. They will be instructed to coordinate with their group members to schedule times where the prototype can be visited and fresh water production can be measured. Data collection will begin immediately.

Participants will also be instructed on the use of conductance meter and will be asked to measure the conductance of the water that is produced. These conductance reading of the fresh water produced will be recorded each time production data is recorded.

Supporting Assignments (ex: homework, projects, papers, etc):

1) Participants will be required to visit their prototypes periodically over the next three days to record fresh water production data. This data will be recorded in their SEINS and submitted to the instructor through the classroom learning management system.
2) Participants will be required to plot their data on a graph with time, in hours, as the independent variable and cumulative fresh water production amounts, in ml, as the dependent variable. The slope of the best fit line will be calculated and the production rate in ml/hour will be reported. These fresh water production data plots and slope calculations will be submitted to the instructor using the classroom learning management system.
3) Participants will be required to measure the conductance of the water that is produced each time water production amounts are measured. This data will be recorded in their SEINS and submitted to the instructor through the classroom learning management system.
4) Participants will be required to photograph their prototypes and submit these photographs to the instructor through the classroom management system.

Instructional Materials:

1) Conductance meter
2) Designated solar exposure area suitable for locating all of the prototypes

3) Graduated cylinders 10 ml and 50 ml
4) Minitab Statistical Software

Assessing for Learning:

1) Participants' SEINS will be reviewed to assess their ability to calculate an estimate of an area for an irregular two dimensional shape through the use of the Riemann Sum concept.
2) Participants' SEINS will be reviewed to assess their ability to collect data on the production of fresh water over time, graph it, and use the slope of the fresh water production line to calculate the rate of fresh water production.
3) Participants' SEINS will be reviewed to assess their ability to produce a salt water solution with the same percent of salt by weight. Conductivity readings will be compared to published conductivity values for salt water.
4) Participants will identify, in writing, what design phases they participated in during this class and what typically occurs within these phases.

Intervention/Treatment Day #5

Challenge Engineering Design Phase(s): Solution Evaluation – Alterations. The design phases the participants will be immersed in are the Solution Evaluation and Alterations

Lesson Topics: Solar distillation of salt water. Participants will be evaluating their prototype's performance at producing fresh water from salt water. They will be assessing the design to determine what alterations could be made to increase production. Participants will be collecting fresh water production data and conductivity readings from their prototypes. Participants will be

plotting this data and analyzing the slope of the freshwater production versus time plot to determine an overall hourly production rate.

Lesson Objective(s):

1) Participants will state in writing how they collected data on the production of fresh water over time, graph it, and use the slope of the fresh water production line to calculate the rate of fresh water production.
2) Participants will calculate, in their SEINs, the fresh water production rate per hour per effective condensation unit area
3) Participants will correctly identify where evaporation and condensation is occurring in their prototypes and the dispositions of the heats of evaporation and condensation when verbally questioned by the instructor.
4) Participants will identify possible design weaknesses in their prototype and offer scientific reasons related to evaporation and condensation in writing, in their SEINs, and verbally to the instructor.
5) Participants will state, in writing, in their SEINs, the phase(s) of the engineering design process that they participated in during this class and what typically occurs during these phases.

<u>Procedures:</u>

1) Introductory Activities/Hook

Participants will be informed that we will be working within the Solution Evaluation and Alteration design phases. They will be shown the design phases on the P.I.R.P.O.S.A.L model graphic and the class will discuss the typical design activities that occur during these phases which include data collection, calculation, graph construction, alteration identification, and actual alteration design and building activities.

2) Instructional Activities/Procedures

Participants will be instructed to examine their prototypes. They will be specifically told to collect their most recent fresh water production data and add it to their SEIN data collection tables. They will then be instructed to graph the data that they have collected over the time between the last class and this class and plot the data by hand in their SEINs (Fresh water production in ml versus time in hours). Students will be asked to determine the fresh water production rate per hour by calculating the slope of the line. They will then be asked to calculate the fresh water production rate per hour per unit effective condensation area.

While this is occurring the instructor will circulate through the classroom and ask students to identify where evaporation and condensation are occurring within the prototype. They will also be asked about the disposition of the heat of evaporation and the heat of condensation within the prototype. The instructor will record student responses by using a check list and comment sheet.

Participants will be instructed to identify design weaknesses within their prototype and to suggest a reason for them. Participants will be asked to propose a solution to the design weaknesses, sketch the solutions in the SEINs, and be ready to explain them in a whole class discussion.

A whole class discussion will be held and participant groups will be asked to explain the data they collected, how it was graphed and how they calculated the fresh water production rate per hour per unit effective condensation area. Fresh water conductance readings will be shared with the class. They will also be asked to discuss what design weaknesses they have identified and what solutions they have envisioned. The instructor will revisit the concept of heat of condensation and ask the class if this heat could be used to enhance the evaporation. Participant ideas will be discussed.

Time will be given for participant groups to work on design alterations, recharge them with saltwater and place them in the prepared area in the sun.

3) Closing Activities

Closing activities will include photo documenting prototype alterations, correcting production rate calculations if needed, and developing new data collection tables. Participants will be asked to update their SEINs with the latest information and descriptions regarding any alterations that they have done on their prototypes.

Supporting Assignments (ex: homework, projects, papers, etc):

1) Participants will be required to monitor, measure, and record their fresh water production until the next class. Participants will also be required to measure conductance of the water that is produced.
2) Participants will be required to plot their fresh water production amounts on a graph and calculate the production rate per hour based on the graph.
3) Participants will be required to calculate the fresh water production rate per hour per unit effective condensation area. They will then compare the pre alterations production rate and post alterations production rate per unit effective condensation rate and determine if the alterations that were advantageous to the design.

Instructional Materials:

1) Conductance meter
2) Designated solar exposure area suitable for locating all of the prototypes
3) Graduated cylinders 10 ml and 50 ml
4) Minitab Statistical Software

Assessing for Learning:

1) Participants' SEINs will be examined to assess their ability to state in writing how they collected data on the production of fresh water over time, graph it, and use the slope of the fresh water production line to calculate the rate of fresh water production.

2) Participants' SEINS will be examined to assess their ability to calculate the fresh water production rate per hour per effective condensation unit area.
3) Participants will be verbally asked by the instructor to identify where evaporation and condensation is occurring in their prototypes and the dispositions of the heats of evaporation and condensation.
4) Participants' SEINs will be examined to assess their ability to identify possible design weaknesses in their prototype and offer scientific reasons related to evaporation and condensation in writing.
5) Participants' SEINs will be examined to assess their ability to state, in writing, the phase(s) of the engineering design process that they participated in during this class and what typically occurs during these phases.

Post-Challenge Assessments

Assessment #1

- **Post-Challenge FTMC Diagnostic Test**

In the next class period after the conclusion of the I-STEM ED T/E DBL Solar Distillation Challenge, participants in this study will take the science and math pre-assessment of the targeted science and math concepts that were the learning objectives of this challenge. The Post-Challenge Science and Math assessment will include 25 (number) multi-tiered multiple choice questions that will assess participant concept knowledge of the targeted science and math concepts which include:

1) Evaporation (molecular change of state, heat of evaporation, solvent-solute transportation mechanism an interactions)

2) Condensation (molecular change of state and heat of condensation)
3) Area of irregular shapes
    a. Inscribed and circumscribed rectangles
    b. Riemann sum calculations
4) Rate of freshwater production per hour per unit area.
5) Calculation of rate of condensate production by finding the slope of the production versus time plot and equating that to the Rate of Change.

Assessment #2

- **Semi-structured interviews**

Semi-structured interviews of selected individuals representing various levels of science and mathematics abilities. The interviews will ask corroborating and clarifying questions related to learning objectives related to evaporation, condensation, the use of Riemann sum procedures to determine the area of irregular shapes, determine the rate of condensate production per unit area, and use of the slope of the fresh water production versus time graph to determine production rate.