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Creating A Model-Based Chemistry Curriculum Sequence

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CREATING A MODEL-BASED CHEMISTRY CURRICULUM SEQUENCE

by

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CHAPTER ONE

Introduction

There is a discrepancy between the methods that define the scientific process and the style in which science is taught, specifically in regular high school chemistry courses. I contend that the sequence in a typical high school chemistry curriculum shows a focus on explanation and has the negative effect of causing science to become a storyline. I am familiar with this style, as this approach was used in my high school and college classes when I was a student. I used it in my initial teaching years. This approach has benefits; it allows timely progression through a wide range of related concepts and increases a student's ability to explain chemical phenomena. However, recent changes in curriculum at the Advanced Placement (AP) and college level have begun to shed light on an inquiry method that is more germane to science. My exposure to this new inquiry method, through conferences from AP and the National Association for Research in Science Teaching (NARST) has compelled me to compare the two styles. I think the differences between these two styles amounts to nothing less than a paradigm shift in science education. Should we focus on explaining concepts, or do we focus on presenting students with conceptual data?

The biggest change between these styles is not the concepts that are taught, but the way in which they are taught. The importance of each concept is also different for each style, and so the sequencing of concepts is different. One style relies on the similarities in the explanations required for each concept, while the other would rely on the analysis of data and the models which aid data interpretation. However, between these two styles, only one is in large scale use. That traditional style has its concept sequencing mapped out. This can be seen in the chapter structure and sequences of most textbooks. The other style, which I believe to be more worthwhile, has not been mapped out for regular high school chemistry classes. Therefore, I will attempt to map out those concepts, as well as the models, questions and experiments that are required to aid students in interpreting those concepts. The guiding question that helps me to create this curriculum is, *How should core concepts be sequenced in a general high school chemistry course?*

From Science to Storylines and Back again

I have been teaching chemistry for 15 years, and in that time I have changed my approach to the course substantially. The phenomenal hands-on approach to learning that chemistry provides I have always found compelling. No other discipline walks such a fine line with what appears at first to be visual magic. This experimentally-based learning helps to create questions naturally in a student's mind. ("Why did that change color?", "Why does this get so hot?", "How can I make this explode?") These questions can provide the means for creating a very powerful curriculum. However, they can also provide a dependency on the teacher for an explanation. The experiences are controlled by an abstract world far from our senses, and it is easier to rely on outside explanation than to dig into the unseen for answers ourselves. It is as if a parlor trick was shown and the audience was not just there to witness, but they were also offered the trick's revelation. I had been a part of this approach for a long time. As a student, I wanted to be told why, and how, the strange changes I saw happened. As a teacher, I wanted to tell my students the same story I was told. That way, they could explain to someone else just how and why these chemical changes occur. I was a part of this way of passing down knowledge, as was almost everyone else I knew.

Science does not operate on a storyline. The real trick is not revealed by the magician, because then it is not magic, and no one goes home wondering how those changes occurred. Science is the same way. If I tell someone why events happen, I create a storyline, and a little bit of wonder is lost. Science then ceases to be an independent attempt at problem solving and becomes a story. I then become more interested in explaining each part of the story. I become less and less interested in providing students a method for discovering answers on their own. I then make little gimmicks to assist in remembering the explanations. I remember my high school science teacher treating atoms like they were emotional, similar to human beings with wants and desires. It helped to remember why certain actions occurred. These gimmicks place emphasis on the story. The curiosity and wonder, the real magic that exists, ceases to be important. The wonder wears off. We, as teachers, then look for more and more fantastical outcomes to explain, and the erosion of curiosity continues. The natural desire to figure out why something happens is then supplanted with the fear of not understanding the ever-complex storyline.

Historically, chemistry was never run by a storyline until the discovery of electronic structure. In electronic structure there are so many exceptions to the rules that need to be memorized. In many cases, the base concept is created, and then layers of concepts with the exact same focus, but different outcomes, are laid on top. It is so frustrating in understanding the “modern” model of the atom that the Germans literally made up a word for the *collection* of odd rules that governed the electrons as they were being discovered. And we expect students to know those rules early in the course, under the *Aufbau* principle. I remember trying to race students through these concepts, enjoying the fact that I had memorized them. What was really happening though? It is likely that students were accepting a story that I told them, and giving up on the ability to understand how these results were first understood.

Stepping back from these details, looking at the curriculum as a larger picture, helped to ease the problems this storyline created. There were 'big ideas' that connect concepts so well that memorization of the entire story was really not required. For example, electromagnetic attraction explained not just a majority of the Aufbau principle, but inter-molecular forces, intra-molecular forces, atomic structure as well as redox and enthalpy. This was recognized after the introduction of quantum mechanics into the chemistry curriculum shortly after World War 2. In order to capitalize on this new tool, a notable Chemist restructured the concept sequence in order to cover electrons first, and base all the subsequent explanations off the electron's actions (Pauling, 1944). Linus Pauling wrote *General Chemistry* for incoming college freshmen with this new approach. This was significant, not just because he won the Nobel Prize in Chemistry, but because this book made teaching and learning chemistry easier.

The storyline was easier now that a majority of the topics could be explained using the interactions between electrons and the nucleus. Teachers learned chemistry's complex concepts in university and could explain it to their students. I also learned the concepts and explained them in similar fashion. However, they failed to convey the understanding behind these concepts, as had I. I used the anecdotes of electrons having emotions and desires with my students, just as I had been taught. However simple this was to memorize though, it created some real confusion when pondering the fact that electrons have no eyes, heart or brain, and move in such a way as to be nowhere and everywhere simultaneously. I could not help students understand what I myself didn't understand. How did scientists know the nucleus was so small? How do they know the structure of something that is and shall remain invisible? How do they know? In reality I didn't understand how this knowledge was acquired, and I could not explain it. I relayed the story: "they used gold foil and cathode ray tubes." Both pieces of equipment my students will probably never see, and certainly will never use in class.

This approach had brought me so far from the concepts that I could only explain them, I could not understand them. This sounds counterintuitive, but if you can convince someone you understand a topic, you will be credited with the understanding, and this is what happened. Also, if this is the paradigm you have, then it is just as easy to convince yourself you understand something because you memorized someone else's explanation. I started to notice and appreciate this when I started teaching AP.

Using atomic structure first is one of the most common curriculums for teaching chemistry in the world. Most textbooks follow this learning sequence, as well as emphasize the use of electrons to explain a majority of the concepts. However, the current AP curriculum does not use this. I found this out when I was sent to an AP Chemistry conference run by one of the curriculum creators, Dr. Gribbons. Gibbons helped to create the current AP chemistry curriculum. In his lab at Iowa State, he helped to create a set of support materials and labs for general chemistry teachers that focused on inquiry. The entire style of the AP Chemistry Exam changed that year, and the purpose of the exam changed as well. Students were expected to stray off the storyline a bit more, and to be able to analyze novel experimental data.

This emphasis caused me to change my teaching. I had to go back and look at my curriculum, and figure out how I was going to prepare students for a different style of exam. I looked up historical experiments to understand how new concepts were learned and applied. I read Lavoissier's Elements of Chemistry(Lavoissier, 1789), and was struck by how little was known about atomic theory, and yet how accurate they were at relating compositions and energies for which acceptable theories would not appear for centuries. This was the foundation of the discipline, literally, and it was new to me. I looked through the emergence of the laws of thermodynamics, the evolution of the gas laws, mass action and equilibrium, electrochemistry, even the beginnings of photospectroscopy. None of these concepts had been learned with the knowledge of electrons. Not a single one.

Before the turn of the 20th century, university students and scientists worked on chemical concepts at very high levels. For all they knew atoms were either spherical bowling balls or did not really exist, much less that the universe had any electrons. However, that did not affect their abilities to analyze and predict with extreme accuracy. So how was it, I wondered, that the entire history of chemistry lies in between atomic theory and atomic structure, and yet in almost every case atomic structure and theory are taught together? I realized that this probably helped *teachers* to explain the other concepts. In reality, what I thought helped students to understand redox, equilibrium, thermodynamics, etc, was actually over-complicating those concepts. I had been throwing students into the deep end immediately and wondering why they were struggling to stay afloat. So I went back through the curriculum and began looking for data that resembled what had historically led scientists to new conclusions. I found a curriculum which was hopelessly lacking. I felt that showed a core fault in the style I had grown accustomed to.

Inquiry-Based Curriculum

My AP classes started, and I tried to find a way for students to separate themselves from explanation and enhance their ability to analyze and compare. Not surprising, the curriculum sequence I adopted would mirror that of the AP chemistry books that would be created in subsequent years. In this new sequence, atomic structure did not come first. This was, and still is, a very telling sign. The students who take AP chemistry, a more difficult, more rigorous course than regular chemistry, do not start with electrons. They do not explain redox or enthalpy with atomic structure. Why is it that those students needing to work with a greater range and depth of concepts were not using the method that was supposed to make everything easier? Probably because that old method does not make it easier. Probably because inquiry-based AP exams require something more akin to science, and less akin to story-telling.

How do I know that I am sequencing my curriculum well? The fact that I am doing it myself is encouraging, but that does not mean I am going about it the right way. I posed this question to some researchers and professors at the NARST convention a couple years ago. The answer I got back was anything but concrete: there is little research that has been done on science learning sequences in general, much less in chemistry. However, I did learn some important lessons about just how different science is from other disciplines. Science is emergent, and procedural, like nothing else. Therefore, the characteristics that make science curriculum effective, will necessarily be a little different than other disciplines.

I feel that deriving an appropriate method for relating topics is essential. Mapping out concepts and skills historically is as well. For example, understanding how naming chemicals helped to create atomic theory. In addition, I think an appropriate method will also help root out some common misconceptions. Several years back, in fact, I started using some data analysis on AP student scores to see if topics and concepts correlated with each other. My sample sizes were small, and that probably made them inconclusive. However, it did show that certain concepts have higher correlations than others. I also did another study the following year to check student quiz scores with prior year science and math scores. Oddly, there was a low correlation between the actual scores, but a direct correlation with the types of math classes students took. This showed me that high school chemistry scores were not dependent on prior success, but on exposure to an algebra course. Students needed the exposure to skill sets. I believe this is further proof that proper sequencing is not just required in the Chemistry course itself, but is required for laying the foundation of skills and knowledge required before stepping foot into class.

Summary

From an early age I have been entertained by, and in awe of, the dynamic changes that occur in nature. As a student, I was taught the concepts that govern chemistry with an atomic structure first approach. I used this approach when I began teaching as well. This approach focuses on the explanation of chemical concepts based on electron actions. It is an effective and timely approach. After all, it was the seminal work of a Nobel Laureate.

However, this approach fails to shift focus from explanation to understanding. This occurs, I believe, because onus is not placed on students to analyze results. Instead, the focus is on explanations given by the teacher with electrons. Students are told why something occurs instead of being asked why something occurs. This habit of explaining as opposed to analyzing causes a storyline to form. In this way, the use of academic skills related to problem solving are bypassed. This approach also increases the rate at which topics are covered, creating a larger and more complex set of concepts, which reinforces the ease of using a storyline for explanations. At worst, this decreases the dependency on using observation and analysis to the point of reducing student interest.

There is another approach that relies more heavily on student analysis and questioning. This approach, known as inquiry, uses experimental data to induce student questions and interest in new concepts. In order to answer the questions that arise naturally, students must use data analysis skills to discern trends. This approach is more in-line with the practical applications of science research and helps to understand how concepts were discovered originally. However, this approach is newer, and therefore less developed and less widely used.

For the project described in this paper, I have researched the scientific learning process as well as methods for designing science curriculums. Then I have designed an inquiry-based curriculum for chemistry. In order to do this, I have also focused research on the historical context in which concepts were developed. This research is presented in the second chapter of this paper, and some is also outlined in the project's introduction.

In the third chapter of this paper, I outline the current approaches used in chemistry curriculum sequences world wide, as well as past and present methods for designing curriculum. This has provided some of the guidelines for the project, as well as additional rationale. In the project itself, I used the rationale and research from this paper to create a unique curriculum sequence with support material. This material is currently in use in my high school classes, providing opportunities for students to analyze and understand the unique experiences that chemistry provides.

The last chapter of this paper discusses the outcomes and lessons from the project. The experience of creating a curriculum taught me some new methods for sequencing concepts. The experience also taught me the importance of underlying worldviews in the scientific method. Namely, that it is more important to understand that we learn from a collection of mistakes rather than believe that what we hear is and will always be true.

CHAPTER TWO

Literature Review

Introduction

It is probable that a majority of the theories and concepts discussed in this chapter will one day be proven to either be false or ineffective. While this might seem to be pessimistic, it is vitally important to understand and accept if we are to advance and improve our understanding and methods. To accept this is to accept the mindset that we can learn from our mistakes. It is important to believe in ideas which we will one day admit are wrong. These ideas help us in our naive understanding and without them it is highly unlikely that we can progress into more advanced concepts even though they will be disproven. How can we learn from mistakes that we do not admit?

There are many different ways to define learning, improvement upon past experience is just one of them. The definition we give learning impacts how we learn as well as what we learn. If we define learning as a process requiring mistakes, then we will search for mistakes to learn from. If we define learning as passing on knowledge, then we will attempt to emulate prior explanations in order to explain them to someone else. In this way, the debate over what learning is, what it should be, creates the basic differences between the curricular approaches discussed in the first chapter.

Curriculum sequences are a manifestation of learning theories. For example, if we believe that learning is the passing down of knowledge, we would search for methods that help the process of passing on knowledge. In this case, it is likely that students would listen to an expert, in most cases the teacher, and would then require an opportunity to share what they hear. The sequence for the curriculum supported by this theory would need to focus on the most expedient way of helping students explain the concepts covered. This sequence would likely be linear and follow a storyline familiar to the expert, or teacher's. In this example, the principle theory of what learning is helped shape the curriculum sequence and subsequently the student experience in class.

For this project, in order to create a legitimate sequence, it is necessary to define learning as accurately as possible. Therefore, the research described in this chapter will focus on the theoretical basis of how we learn in general and more specifically how we learn science. Once the process of how we learn is presented, the research will focus on how these learning theories frame the strategies that teachers use. Once the learning process and its effect in the classroom are presented, the method for creating a sequence of concepts can begin. However, that method will be described in more detail in chapter three.

The question that this chapter is attempting to answer: *How is an effective high school chemistry curriculum sequence created?* There are two principal theories that help outline what learning is, that of cognitive conflict and social constructivism. Historically, they gave rise to various teaching strategies as well as a range of curriculum sequences. These two theories are therefore the most important to outline and understand first.

Constructivist Theories

How do we know when we have learned something? This is a question that students should be asking themselves. The expectations and beliefs which create curriculum will inevitably dictate the answer. In this way, the theories we have about how we learn form our worldviews (Martusewicz et al., 2015). One of the most influential theories on curriculum, shaping belief and expectation, is constructivism.

Classic Constructivist Theories: Building Meaning from Cognitive Conflict

Jean Piaget described the learning process in a biological sense. Piaget (1952) contended that there is no innate ideology that people are born with. Thoughts and beliefs are not inherited. However, Piaget believed that mental functions are inherited, and universal. Piaget explained that these functions build up concepts, ideas, skills, categories, etc., known as schema. These functions start before birth, and continue in similar fashion until death. Two main functions were detailed, assimilation and accommodation, which accounted for all the possible ways that the mind interacts with its environment and schema.

Assimilation is the organization of a new set of data into an already existing schema. In order to do this, a person must be, “thinking of forms or constructing them internally in order to assimilate to them the contents of experience” (Piaget, 1952, pp. 5-6). The mind must be able to represent an external object, data set, etc, internally, abstractly. This is an integral part of the function of assimilation; the creation of a mental representation for an external existence. The next integral part is the comparison of the newly created representation with the previous schema. Piaget calls this comparison equilibrium when it successfully meets expectations. Successful assimilation occurs when an element from the surrounding environment, that has not been noticed before, is successfully placed into a pre-existing schema (Piaget, 1952). This will cause the schema to expand to include the new element, while the defining characters of the schema itself are unchanged.

Accommodation, on the other hand, occurs when equilibrium can not be reached (Piaget, 1952). During the comparison of the new element with related schema, a conflict occurs as expectations are not met. The existence of the new element implies an incomplete, or an inaccurate schema. In order to solve this problem, Piaget proposed that the mind must change the existing schema in such a way as to include the new element. If that is not possible, the schema itself must be either hybridized into a new schema or restructured all together. This is, as Piaget pointed out, similar to reverse assimilation. Instead of fitting the element into a schema, the schema is manipulated to fit the element. Then the schema and element are compatible, and equilibrium is restored.

In order to properly compare schema and elements to reach equilibrium, the mind uses values. Piaget's identified values include classification, numerical representation, causality and spatial relationships (Piaget, 1952). Another way of thinking about this is that the mind assigns the element with an identity based on its location when it occurred compared to other events, its size and some description about its appearance. These are needed for the comparison with prior elements in the related schema. Piaget also contended that the mind must learn how to assign these values, how to create schema, as well as how to compare schema using these values. If the mind can reach equilibrium through both assimilation and accommodation using a wide range of new experiences requiring the creation of many new schema, then Piaget considers the individual to have reached mental maturity. This ability will become important to support when creating curriculum.

Without prior skills the ability to learn specific schema is absent. The ability to create mental representations of real life elements is needed before comparisons can occur. The ability to classify and assign values is also needed before comparison can occur. In fact, Piaget surmised that problem solving is not really possible before a large set of skills and schema have been accomplished (Piaget, 1952). Without these learners struggle. This theory outlines some hallmarks of good curriculum as well. Three specific curricular requirements that will be used are: activation of prior knowledge, usage of abstract models, and attention to specific variables for comparison.

Additions to the Classic Constructivist Theory

Research to show a correlation between brain research and Piaget's cognitive theories. Crone and Ridderinkhof (2011) outlined prominent studies that observed some physical representations in the brain which might pertain to cognitive growth. Crone and Ridderinkhof showed evidence for stages of cognitive development; as more concepts were gained, more schema formed, the brain grew and changed the type of matter and activity present (Crone & Ridderinkhof, 2011). Crone and Ridderinkhof contended that there was even evidence of certain structural changes in the brain that were required before further cognitive growth could occur. However, the ability to measure the size, composition and overall activity of the brain is far from showing the thought processes held within. If anything, Crone and Ridderinkhof showed the magnitude of complexity that was involved with the progression of cognitive thought.

As the use and analysis of MRI and other brain scans has increased, more specific neurological studies have become available. Most notable is the current attempt to map out how short term memories are formed, recalled, and eventually stored. Short term memories are instrumental in most thought processes (Postle, 2016). For something as complex as learning to be understood, it is important to understand how memories themselves are created and interact.

The physical collection of synaptic and neural changes that occurs when a memory is created is known as an engram. It was assumed that these engrams were retained and stored for long term memory as well. However, as Postle (2016) pointed out, there is a distinction between the physical engram and the mapping in the brain that occurs for working memory. How these two are related is still unknown. However, the prior assumption that these engrams were unchanging has led “to erroneous inferences about neural functioning” (Postle, 2016, p. 151). Subsequent research has shown that memories have the ability to change over time (Chen et al., 2016) and that the pathway for recalling a memory is not the same as the pathway for its creation (Roy et al., 2017). The concept of the physical existence of a memory itself is not set. Like Piaget’s schema, memory itself seems to be re-made, compared, and adapted to an ever-changing existence between what was and what is.

While there are flaws that have been pointed out in Piaget’s theory, like the timing of different stages (Donaldson, 1978) and the growth of plural schema (Solomon, 1983), this theory has been retained and supported over the past 60 years by both cognitive psychology and neuroscience. However, there is still much to be determined.

Do we really have an innate prenatal set of functions that build our learning, and if so, how do they organize the physical structures in the brain? Does perception retain much physical permanence in the brain? How much prior knowledge is required before we can learn something new? It is not easy to uncover the machinations behind the most complex and advanced piece of equipment in the universe. However, what we should take from Piaget is this: learners build up their knowledge independently by analyzing interactions with their environment. There are required skills that must be developed in order for further progress in understanding to be made. These skills include the creation and comparison of internal representations of external realities. Knowledge requires that past experiences be organized in such a way that when provided the appropriate new experience, the new experience can be successfully adapted into the mind.

The Specifics of Cognitive Conflict

What types of experiences help students to develop their understanding? How can students be aided in creating well-adapted schema? One method that appeared to result from Piaget's theory was the use of cognitive conflict. In this method, Limon (2001) explained that students are expected to learn from their own active efforts. The efforts should also include an experience with conflicting elements; and this conflict should set the student on a path in search for equilibrium (Limon, 2001). Ideally, the student would then create some new understanding that can accommodate both the old ideas and the new element. For example, when observing spectral patterns, students might spend a day observing one specific pattern identified with hydrogen. Students on the next day would look at a different spectral pattern, this would be a conflict, but then the student would recognize that it is not the same chemical. Perhaps it is helium. Students would change their understanding of spectral patterns to include a variety of patterns, each associated with a different chemical.

The ability to create a conceptual change using cognitive conflict is a difficult one to master. Some necessary requirements for successful use of cognitive conflict have been outlined. “An individual needs to realise that he/she has to change something and to be willing to do it” (Limon, 2001, p. 359). This creates three important requirements: the required background understanding, the appropriate presentation of anomalous elements, and the motivation to seek a conceptual change. In fact, Chan et al. (1997) called the acknowledgment that problematic elements require a change as knowledge building. In essence, the creation of new knowledge requires the awareness of a uniquely new element and the acceptance and motivation of the change needed for its adaptation.

However, as both Chan (1997) and Limon (2001) outlined, there are significant problems with using cognitive conflict. Perhaps the most significant of these are student reactions towards this type of problem. A prevalent response is to force some sort of assimilation. This might be through ignoring the new element all together, rejecting the inconsistencies it has with prior knowledge, reinterpreting the element as corresponding with prior knowledge or distorting the rationale required so that the element does not appear so problematic (Limon, 2001). Another type of response is to reject or disregard the prior knowledge set in such a way that the new element is seen as completely unique. This creates a new schema and does not attempt to integrate or interact with the other related schema. According to Limon, all of these responses fail to correctly organize and accommodate existing schema. For these students, for one reason or another, the presentation of conflicting elements did not result in knowledge building. Instead, erroneous and inaccurate understandings were made. From Chan and Limon the following requirement will be added to the project: presenting cognitive conflict must be done as explicitly as possible, requiring small, simple cognitive change. Is there an additional aspect to the learning process that might help in accomplishing this?

Social Constructivism

How else can the progression through cognitive conflict be aided? An essential part of the process, according to Vygotsky (1978), is through dialogue. Vygotsky explained that language allows learners a different way to mediate their perception of the world. Their visual, auditory, motor, and sensory experiences are transformed into symbolic representations, including words. Vygotsky contended that words are then used through discussion to discern and rationalize experiences, creating the fundamental process through which learners make meaning.

Moving Through a Proximal Zone of Control

Language, unlike a visual picture where everything can be seen at once, is sequential. Vygotsky (1978) added that there is a temporal aspect as well, which aids in the development of concepts that incorporate past, present and future events. This in itself assists learners in memory recall which results in “uniting the elements of past experience with the present” (Vygotsky, 1978, p. 36). This allows the learner to develop intent. However, as recall becomes more difficult, more nuanced, a level of complexity arises that requires the learner to organize the elements requiring recall. Vygotsky considered this organization as the basis for thought: "...to think means to recall, but for the adolescent, to recall means to think" (Vygotsky, 1978, p. 51). It is as if thoughts need to be ordered chronologically, just like sounds must fit chronologically in a word. The ordering requires an internal dialogue. In this way, memory-making becomes the precursor for intentional internal dialogue. For Vygotsky, that dialogue is the mechanism required for the adaptation of, and creation of, new concepts.

How does internal dialogue arise from memory-making? Articulating this process was of central concern to Vygotsky, and his theory of cognitive development hinges on the sequence. Initially, an external experience is internally represented (Vygotsky, 1978). This is the process of memory-making. The elements of this memory must be retained in order for them to be analyzed, compared, etc. Vygotsky believed the retention occurs rarely if left to natural progression, however, artificial cues help the retention. Vygotsky calls these artificial cues signs. Signs can be intentionally left by another person, like a teacher, to purposefully assist the learner in recalling a prior memory *and* a current experience. These cues, when combined with social language and discussion, provide the learner with a basis for comparing the two elements, in some cases with creating a new concept. Vygotsky believed that over time the learner becomes proficient enough in using the external signs that they begin to use and create internal cues to carry out the process. The external discussion then becomes internalized, and the learner is able to conduct internal dialogue which solidifies the creation and understanding of the new concept (Vygotsky, 1978). In this way, the learning process becomes dependent on language and social interaction.

This learning process just described by Vygotsky (1978), is also described as moving a learner through the zone of proximal development. The learner is aided by the use of signs or cues, into an ability or skill area that they would not be able to complete without. Over time, they can accomplish these tasks without artificial assistance. At that point, their ability level widens again through the use of new signs or cues into a new area. The areas that require assistance are known as the zones of proximal development (Vygotsky, 1978).

This theory is similar in fashion to Piaget's theory of cognitive development in certain aspects. The description of memory use by Vygotsky is similar to the process of adaptation described by Piaget. The necessity of background information is vital in both theories, and the preferred outcome of adaptation of a new element into a familiar concept is common as well. Importantly, both theories contend that there are element sets, or concepts, that students can not learn because they do not have the necessary ability levels. However, the use of language in Vygotsky's theory allows the learner to increase their awareness of a problem and to make their intent on solving the problem explicit. The use of signs by Vygotsky in creating internal representations was not articulated by Piaget. Also unique in this theory is that cognitive development is centered around the social and cultural influences. For this project, Vygotsky's theory causes an emphasis to be placed on sign usage with modeling, as well as support through the external and internal dialogue using guided questions.

One problem with this style of learning that Vygotsky pointed out is that, "analysis is essentially description and not explanation as we understand it. Mere description does not reveal the actual causal-dynamic relations that underlie phenomena" (Vygotsky, 1978, p. 62). This is difficult for the observer to notice. A student might understand a specific experience on a very descriptive level, and the explanation they give might convince the observer, the teacher, that they understand the experience on a deeper dynamic level when they do not. It is difficult to access the actual connections that students make, since they are in an internal world in the students mind that teachers have limited access to.

Another problem outlined by Vygotsky (1978) is that the processes themselves have tendencies to become automated. In this style of learning, the cycle depends on a social passing on of information. This process occurs so many times that the initial purpose of the cues themselves can start to become forgotten and lost through the repetition. This occurrence is similar to the third problem outlined, that learners have a tendency to fixate on object importance over process importance. A good curriculum should attempt to address the importance of sign usage and move student focus from objects to processes. This is still relevant since all of these problems manifest themselves in modern-day classrooms (Driver et al., 1994).

Additions to Social Constructivist Theory

How can the social environment, including the teacher, provide appropriate support to help learners move through their zone of proximal development? Ausubel (2000) proposed using advanced organizers to help prepare and identify the required preexisting knowledge base. An advanced organizer is a descriptive document that reviews the past knowledge needed for the current topic. After this, Ausubel suggests using learning materials that are explicit, non-arbitrary, and can therefore be compatible with any related cognitive structures. Bruner (1963) proposed using appropriate scaffolding, along with specific, identified prior knowledge sets. These methods appear to be similar but each deserves a detailed outline if they are to be taken into consideration for use in curriculum building.

Meaningful learning differs from rote memorization in the effect it has on the mind. The mind is required to augment, create or change schema when meaningful learning happens, whereas memorization causes little to no cognitive changes (Ausubel, 2000). Asubel argued that meaningful learning should be the main goal in the classroom. However, various roadblocks, like misconceptions, biases and other personal traits stand in the way of meaningful learning. In order to assist the learner in preparing for meaningful learning, identification of important schema already learned is necessary. Ausubel called these anchoring ideas, as they will serve as anchors for the new schema to connect with. In this way the mental organization required is given a head start.

In order to identify and activate these anchoring ideas, Ausubel (2000) suggested the use of advanced organizers. These can take the form of prose, or possibly be symbolic. However, they are to be more advanced, more in-depth, than the subsequent material that will be presented. In his research, Ausubel typically used single page or less texts that described the highlights of the previous topic. However, as the idea of advanced organizers became more prevalent, most usage was through graphic organizers showing how topics sequentially related to each other. Both organizers are used to ensure that added attention is placed onto the anchoring ideas in order to activate them. After this introductory set, Ausubel suggests the new information should be presented with explicit, non-arbitrary material that is only as complex as required. This helps to reduce the stress on the adaptation process, as well as to inhibit the aforementioned roadblocks.

One of the most significant criticisms of advanced organizers, which was acknowledged by Ausubel (2000), was the wide range of their possible presentations. It remains unclear as to what information is most necessary, and as Ausubel pointed out, the bulk of rationale around the identity of specific anchors remains intuitive. Subsequently, it becomes of great importance to be able to identify the prior cognitive structures that students possess and to organize them into the curriculum at large. This is, in a sense, the clarity that this project is seeking to provide. A method for determining the relationship between anchoring concepts that is not just intuitive has been developed, and the sequence this project helps to organize these.

Another method for approaching the difficulty of learning new information is detailed by Bruner. Instead of expecting learners to make the jump from older schema into a new schema that needs to be created, Bruner (1963) proposed a guided series of smaller steps. These steps require a more in-depth examination of the curriculum than just a determination of where one starts and ends. This also compelled Bruner to believe that if these smaller steps were presented sufficiently, a learner was not held back by specific stages of development but by their prior knowledge. As such, the identification of background knowledge became extremely important to Bruner.

Besides outlining smaller, more focused steps, Bruner (1963) also outlined three distinct areas through which the mind processes and learns information. These three, sensory-motor, iconic and linguistic, have the ability to operate on their own or in tandem. Therefore, Bruner considered the sequence from experience to image-based models, to symbolism in language to encompass the whole of the learning process. This reinforces the rationale for the learning supports used in this project.

Review of Cognitive Learning Theories

Piaget and Vygotsky outlined two distinct theories in how learning occurs. Piaget (1952) laid the groundwork, describing a mental world in which the cognitive structures of schema are built. These require the creation of mental representations that can be linked together. These schemas are then used to compare new representations through either the functions of assimilation or accommodation. Once the representation is successfully placed into an old scheme, assimilated, or successfully placed into a new or augmented scheme, accommodated, a state of equilibrium is reached. The learner accomplishes their task.

Not every attempt at adaptation works. In addition to the presentation of new material, and the access of prior knowledge, other functions are needed in assisting the adaptation of the new material. Vygotsky (1978) described a mental world that seeks supportive structures externally. These cues, or signs, assist in the association of old schema with the new material. To further support this process, language is used to repeat and review the older schema, as well as to solidify the place and importance of the new material. Vygotsky describes the area of mental progress as the zone of proximal control. With support, learners move into this new cognitive ability zone. Through practice, they become proficient in that zone, and the external conversations about the material become internal. This removes the need for support, and pushes the proximal zone of development out further, to where new supports are needed.

Recent studies, including brain research, point out a much more complicated world. There appears to be correlations between the physical development and the mental development described by Piaget. There also appears to be physical structures that attempt to build and associate memories in what we now call working memory, in similar fashion to what Vygotsky describes (Crone & Ridderinkhof, 2011). However, the physical processes required for learning are unknown, and these two theories that have stood the test of time still remain just that, theories.

Ausubel (2000) and Bruner (1963) began to outline not just how people learn but how people should teach as well. This is then a sufficient point to stop outlining the general theories on how people learn. For the sake of this paper, an outline of what makes learning science unique is required before going into further theories on how information should be presented. After all, a chemistry curriculum should be grounded in the unique attributes of learning science.

How is Learning Science Unique?

Why is science different from other disciplines? What is it about walking into a laboratory that separates the experience from the stage, the easel, or the debate room? To start with, the subject matter is quite different. The subject matter is tangible, and yet the mind must work with abstractions. A falling apple, an evolving bird species, a moving Earth, are different than relatable human expressions. They come with no language, and the mysteries they bring must be uncovered without any method of communication with the subject matter. However, some people are quite adept at learning science. What makes them proficient in understanding the concepts hidden within that world? What mental processes do they rely on, and what do they pay attention to that others do not?

Collective Causality: The Problem with Emergent Processes

Science is ontologically different from other disciplines. Chi (2005) pointed out that of all the disciplines, there are two based on procedural knowledge: mathematics and science. This accounts for the correlations between proficiencies in the two subjects (Wang, 2005). However, the procedural knowledge that assists a student in mathematics is very different from the type of procedural knowledge required for science. On one hand, mathematics is sequential, with more or less singular causes. On the other hand, Chi pointed out that science is primarily emergent, with multiple causes acting together.

A sequential process follows a linear path. For example, in math you must use an order of operations: complete processes in brackets first, then compute exponents, then multiplication, and finally add. This type of process is very familiar to people, as most of the processes they rely on in their daily lives are sequential as well. Emergent processes, however, are very different. These are not man-made, and the linkage between one function and another is not apparent. This linkage requires an abstract model to understand, and these types of causes are unfamiliar to students (Chi, 2005). For example, Chi used the motion of ducks flying in a V formation. This process emerges from an underlying function that ducks do not talk about, they use the least amount of effort. The reduction of air resistance causes the shape, and the stamina of the un-drafted lead bird determines their change in positions. One might assume that the birds selected a leader and that they have a hierarchy that they fly in, like a squadron of fighter jets might. The difference between the emergent model and the sequential model is so large they can not account for each other even though they describe the same event.

Misconceptions in science learning can occur when an emergent process is mistaken for a sequential one. According to Chi (2005), this is commonplace, as students are simply much more familiar with sequential processes. The misconceptions become very difficult to remove due to the wide disparity in viewpoints and understanding. These misconceptions become engrained, or robust. This happens both in the mind of the learner, in society at large, and in the collective viewpoints of scientists as well (Vosniadou, 2007).

How are these emergent processes learned? Chi (2005) believed that the learning barrier for these would not exist if they were more commonplace. Also, these processes are prevalent throughout scientific concepts, so there must be a method that has been effective. In most cases, it appears that the formation of a mental model is required, one that can be used to relate to the experience from a different perspective (Baddeley, 1992). These models can then be used to describe a hidden function when placed into a new environment. For the purpose of this project, an emphasis will be placed on outlining robust misconceptions, as well as the repetitive use of modeling.

Mental Modeling

Mental models are abstract representations that aid in the analysis of observed relationships. The physical counterparts for these representations may or may not exist. These models are created using specific brain functions, and these must be outlined.

Ideally, this outline will aid in the identification of the memory processes needed for modeling, the supports that aid the attention and activation of these processes, and a possible method for model creation.

Memory Storage. There are two separate systems in place that are used for storing and accessing short term memory. Baddely (1992) calls these specialized temporary memory systems. They include phonologically-based storage, which aids in language and vocabulary, and visuospatial-based storage which aids in imagery. Baddely showed that these systems are separated in a literal sense, meaning that acuity in one system has no correlation to acuity in the other. Also of interest is the fact that these systems are separate from the semantic connections in and between them (Baddely, 1992). In other words, remembering a set of images or a set of vocabulary words does not necessarily improve if they are all schema related. However, the sum of these two systems gives a learner all the basis needed for memory storage.

How these two systems relate to each other is fundamental for science learning. This is due to the requirement for observed spatially related images to be processed using language for schema connection to take place in our working memory. To support these two systems there is a third, mediating system. Baddeley (1992) called this the central executive. This system is responsible for the control and placement of attention between the phonological and the visuospatial stores. This central executive distinguishes working memory from the process of memory storage. Even more interesting is that learning processes are able to take place even when there are deficiencies in memory storage. (Baddeley, 1992) The interaction of attention given to these short term storages and long term storages allows cognitive function to emerge in the central executive. The skill in performing these interactions appears capable of making up for diminished storage.

Visuospatial Working Memory. Creating a mental model to help in representation when learning scientific concepts must have a unique focus in the visuospatial memory storage system. After all, mental models are image-based. Research into this memory system has revealed two distinct subsystems, one that is visual and another that is spatial (Farah et al., 1987). The visual system is concerned with what we consider as imagery. The color, shape, texture, and contrast that are evident when viewing an object are all considered visual. However, relationships like size, location and orientation are all considered spatial. These markers were noted by Piaget (1952) as well when describing how mental representations are made. Farah et al. found that discrepancies between these two were revealed when learners performed better on visual tasks with visual cues, and worse with spatial cues, and vice versa. This showed that learners interact with these two subsystems independently of each other, and proficiency with one memory storage ability has no correlation with ability in storing the other type.

Which subsystem is most useful for science learning? One might expect intuitively that visual storage is helpful in artistic endeavors and spatial storage more so for science. In fact, that is exactly what Kozhevnikov (1999) found. Students using images with more spatial information improved their problem-solving abilities. Students with more visual information were hindered in their abilities. The results showed that images need to be highly structured, but not highly detailed (Kozhevnikov et al., 1999).

In other words, a spatially correct picture of a square labeled car is more useful than a detailed drawing of the car.

How does the learning cycle connect spatial information with model creation or usage? Trafton et al. (2005) showed how this connection is made from heavy input of trial and error with model usage. Trafton believes that a rudimentary representational and spatial model is made in working memory, the internal representation. This closely resembles the actual object the observer sees, the external representation. In order to improve the mind's ability to transform the model, the observer then compares the two models. Trafton et al. noticed this specifically in scientists as they worked on meteorological data. The scientists would refine their internal models through constant rechecks of the external representation. The confidence of the scientist in the internal representation increased with each recheck. At a certain point, the confidence was high enough that the inconsistencies between representations were more likely to encourage rechecks in the external representation. Scientists assumed they had seen the image wrong, because they were certain their internal model was right.

There are two significant aspects in the modeling process in science. The first is that there is an extremely high number of rechecks during the initial modeling stage (Trafton et al., 2005). The second is that static spatial information is more useful, and more preferred than dynamic information when dynamic models are made. This means that when making time dependent moving models, scientists preferred highly detailed pictures instead of detailed videos. The pictures were animated internally by scientists, and the added details during external animation appeared to overload their attempts. This last finding is similar to Kozhevnikovs, in order to create and effectively use mental models, learners can be overloaded by too much information. For the project, an emphasis will be placed on making models simple and spatial, as well as providing repetitive use with these models for rechecks.

Unique Characteristics from the Scientific Learning Process

Learning science appears to be an attention heavy, at times counter-intuitive, multi-system cognitive marathon. A lack of any of the requirements would probably lead to misconceptions. This was explained earlier by Driver et al., Chi, even Vygotsky and Piaget. It is no wonder, therefore, that there appears to be so many common misconceptions in the natural sciences built from both personal experience and society at large. The characteristics of these misconceptions sheds some light into the greater task of moving through a learning cycle fraught with them.

We can understand why misconceptions are created. A lack of attention to the underlying process, a lack of spatial awareness in model use, an inability to select the proper transformations, etc. However, what happens in the mind when these misconceptions are removed? Vosniadou (2007) suggested that the misconceptions are robust and remain in place after identification. Though it might be possible to remove, that process appears to be rare. Instead, most people, even university science professors, must employ an additional system whose purpose appears to be quieting and overriding the original schema. This additional system causes more mental processing, and further adds to the burden of the learning process.

Summary of the Uniqueness of Science

Like other disciplines, science requires a solid foundation of prior knowledge with which to build upon. The use of novel experiences and social interactions are as important to science as they are to other disciplines as well. However, science concepts arise from abstract causes that create unique emergent processes. To understand and adapt to these concepts, mental models are required. These models require a unique system of spatial memory storage to be used and referenced with both phonological and visual systems often. If this is not done, a unique system must then be created to override the misconceptions that arise. The visual experiences that learners see in the classroom not only look fantastical, but the processes required to meaningfully understand them is fantastical as well.

How is Chemistry Taught in the Classroom?

Understanding the processes involved with the mental challenge of learning science provides a sound basis for creating a viable curriculum. However, a review of current teaching practices, and their effectiveness, would also help provide a template for either an original or a modified curriculum. The review that is provided in this paper will show that there is, in fact, a group of common curriculum sequences that are used. Some of these sequences are created with fidelity in the specific cognitive theories mentioned so far. How have these been created, and how do they address the uniqueness of learning science as well as the misconceptions that arise?

The classroom itself presents a much different environment than the university psychology labs used by Piaget, Vygostky, Bruner and others. The attempts for controlling variables, ethics and comparison that must be used in a university research setting are more difficult in a school. A school setting is also not limited to the specific research parameters that a university setting has. A school encompasses a wide range of disciplines, and each classroom encompasses a wide range of students. Not to mention, the class itself incorporates a wide range of concepts throughout the year. This great diversity in expectations and identities brings the experience in a classroom setting closer towards a sense of chaos. Jackson (1968) observed this across classrooms in the United States. In the face of this challenge, teachers employ several non-curricular actions that create unintentional consequences to the curriculum itself. These can be summarized in class rule sets, expectations and flow, all of which remain in place today. How do current classrooms attempt to drive learning in the natural, chaotic classroom?

What Driving Force is Behind Science Learning in Classrooms?

Driver et al. (1994) pointed out that the subject matter for science is not, in fact, the physical phenomenon from nature. Instead, the subject matter of science is actually the human constructs that are shared by the scientific community. This means that science education, besides requiring the learner to build up their knowledge through interaction with nature alone, must include the social introduction into the discourse of science as well. There is a need for the learner to become an apprentice of sorts.

Driver et al. (1994) pointed out both ends of the learning theory spectrum. At one end is the empirical nature of science learning. The processes themselves, the large cognitive concepts learned, are at a point purely theoretical and comprise a best estimate as to the underlying causes and models. On the other end, the complexity required to learn these concepts is well beyond the ability of any single learner to create, much less to create all of them. In other words, science must be learned through interaction with experimentation, however, the full range of concepts is beyond a learner's ability to derive independently. Driver et al. suggested that science education helps learners “to make personal sense of the ways in which knowledge claims are generated and validated, rather than to organize individual sense-making about the natural world” (Driver et al., 1994, p. 6). This appears to be a pragmatic description of the process and an accurate impetus for current curriculum.

How do teachers help students to make personal sense of knowledge claims? One hurdle is the similarity between non-scientific reasoning and theory creation. Students might have their own ‘common’ sense ideas for why certain phenomena occur. These ideas are not grounded in a scientific process, and yet they are confused as being theoretical. A strong identification of scientific method and repetitive use of this method through dialogue is required. Driver et al. (1994) suggested that this repetition often involves the use of symbolic modeling as well as heavy mediating from the teacher. This fuses some of the larger ideas in science learning; students need interaction with experimentation and a familiarity with using and discussing possible models.

How do Teachers Adapt to Science Teaching Strategies? Using the science learning process outlined by Driver et al. as a metric, how close do science classes get in providing the opportunities for exploration and discussion? With the added pressures that Jackson outlined and the prevalence of misconceptions that both Vosniadou and Driver et al. showed, certainly there is some exception. Do teachers typically use more empirical, discovery learning? Do they mediate student discussions around model performance? Do they typically use more of an apprenticeship approach, bringing students into the cultural discourse of science? Piet Lijnse (2010) pointed out that the traditional science curriculum still presented knowledge in a fragmented way, leaving out the overarching connections (Osborne & Dillon, 2008, as cited in Kortland & Klaassen, 2010). Lijnse went on to state that to combat this problem, teachers needed to be presented with a better storyline that connected the concepts and skills in a manner that helped both students and teachers (Lijnse, 2010 as cited in Kortland & Klaassen, 2010). This proves there is a need for the sequence created in this project.

How Chemistry Became a Storyline

The previous examples outline just how much the need to cover science concepts outpaces the abilities to discover those concepts independently. We know from constructivist and even social constructivist theories that science learning requires personal interaction with experimentation. However, we also know that science requires a unique intimacy with spatial modeling and the ability to reference underlying causes for emergent processes. Even with these attributes, normal exposure to society at large still causes arduous overrides of common misconceptions. Science teachers may find the only way out from the chaos and labored process just described is the heavy-handed use of social discussion, at times more teacher than student-centered. At worst, they find the need to stand and tell students what to believe. Both of these last two pragmatic approaches require a good storyline. This might be a need for the student, but much more so for the teacher.

Further complicating the issue is a lack of qualified teachers. Kolbe and Jorgenson (2018) found that almost half of all science teachers have no science-specific degree, and those that do are much more likely to incorporate hands-on, inquiry-based lessons. The relationship they found was that student proficiencies increased with the teacher's background training. Leach and Scott (2000) also found a similar relationship, stating that for science education to improve, a concerted effort should be made to assist more science teachers in creating their own lesson sequences. This supports the notion that the average science teacher is searching for the common 'storyline' of science in the hopes of not just improving student learning, but their own understanding as well.

The Storyline: General Chemistry, by Linus Pauling

The storyline for chemistry can be traced back to a single book, *General Chemistry,* written by the Nobel laureate Linus Pauling (1944). In his preface, Pauling noted that, at the time, most chemistry courses focused on a patch-work curriculum of descriptive chemistry. Descriptive chemistry is in opposition to theoretical chemistry. It does not focus on the explanation as the empirical experiments. Most time in descriptive chemistry is devoted to chemical reactions and the chemical properties of the elements involved in those reactions. Theoretical chemistry focuses on the theory and explanations that cause a variety of phenomena. Pauling's goal was to use his book to unify the concepts covered in a general chemistry course, as well as to provide a strong theoretical framework in order to push curriculum from descriptive to a more theoretical basis (Pauling, 1944). The book used recent discoveries in electron motion as the basis for the bulk of explanation, as well as mechanical statistics. In addition, artistically drawn, spatially-referenced models were prevalent throughout the book, incorporating many novel ways of communicating theory. The book proved to be highly successful and helped shape the methodology and sequencing for how people learn chemistry not just at university, but in high school as well. It is still in print in 2020.

Effects from the Storyline

One of the side effects of this prominent book is the dominant storyline that it built. The shift in focus from descriptive chemistry to theoretical chemistry in no doubt greatly advanced the understanding of complicated chemical concepts. However, universities still struggle with introducing descriptive-based chemistry (Huddle, 1987). For those teachers that have little background, this book most likely frames their understanding. This creates an extra problem, as Huddle points out. “There is a tendency to teach laws and theories *as if they were facts*” (Huddle, p 1, 1981). Here we see the storyline not just emerging but becoming so central as to overshadow the basic tenets of science and the learning cycle.

Summary

Meaningful learning, what Chi (2005) called self-explanation, what Piaget (1952) called adaptation, what Vygotsky (1978) called internalization, is a nuanced and complicated process. We can not actually identify each step of this process with complete confidence. However, we can model it. We can see evidence for it on brain scans; we can identify some of the positive outcomes from it. We can do our best to incorporate personal experiences and come up with a theory for it that allows for the new learning experiences we encounter. The difficulty with understanding how students learn, and subsequently with how we ought to teach, is the same type of difficulty students struggle with when learning science. The actual process is not familiar, and we are left to judge whether one model is sufficient or not, at times discarding previously held beliefs.

The purpose of this project is to create a curriculum sequence that takes into account the theories of learning that I find to be most sufficient. This chapter has outlined those theories and attempted to place them into a sequence that supports the reader in making meaning. This is analogous to what I attempted in the curriculum sequence. A common requirement found among these theories is the recalling of prior knowledge. In order to keep the analogy, it is time to summarize and recall those prior theories.

Constructivist Theories

Piaget's groundbreaking theory described learning as a process of constructing mental concepts. Piaget (1952) contested that people all had an innate set of functions, called assimilation and accommodation, that took place in the construction. People take in outside experiences through a variety of senses and then create mental representations of them. These representations get placed into groups, almost like little algorithms, that Piaget named schema. As new representations are observed, they need to be placed into a schema, a process called adaptation. Usually, new representations find an already formed schema to fit with. That is assimilation. If the representation does not fit into a schema, the prior schema needs to be manipulated in order for the new representation to make sense. That is called accommodation and is accountable for what we would call new learning. The specific function of accommodation appears to require what Limon (2001) calls cognitive conflict, a dissonance between representation and schema.

Vygotsky (1978) included a social aspect when describing the learning process. According to Vygotsky, when new concepts or abilities are learned, the learner moves through a proximal zone of development. This process requires outside assistance, in the forms of signs, which aids the learner in completing the task. These signs are also used with verbal communication which helps to organize the current and former schema. After time, the learner starts to internalize this conversation, as well as the signs, and can complete the entire task in their mind. The learner is then said to have internalized the learning and to have moved through the zone of proximal development.

Ausubel (2000) and Bruner (1963) both added supports based on Vygotsky's theory. Ausubel created advanced organizers to aid in the activation of prior knowledge, creating sites in prior schema to anchor the new experience. Bruner broke the cognitive conflict process into smaller steps, allowing the learner to move through the zone of proximal development by moving through smaller and smaller zones. For Bruner, that required an in-depth understanding of the learning process as well as clarifying prior knowledge.

Uniqueness of Science

The importance of being able to recall past experience causes a unique problem in science. When students recall past experiences, the schema associated with them typically leads to misconceptions. This is because, as Chi (2005) points out, learners are familiar with sequential processes not the emergent ones that science displays. These misconceptions are so prevalent that even scientists have them. As Vosniadou (2007) explained, they require extra cognitive structures to bypass. This environment of unfamiliar emergent processes, paired with misconceptions, creates a lot of extra mental work.

In order to understand unique science processes, learners must use extensive modeling. Baddely, Farah and Trafton show just how unique and repetitious this is. Science concepts heavily use the visuospatial memory storage, (Baddely, 1992) and then interact between this storage and the language-rich phonological stores in the central executive. However, the visuospatial storage is separated into two as well, (Farah et al., 1987) and science relies on the spatial image storage as opposed to the visual. Piaget (1952) described how different markers are used when creating internal representations, and it turned out these markers are very important for learning science. Learners must focus on the spatial markers, and use them to repetitively check the internal representation with the external object (Trafton et al., 2005).

The Storyline

The research shows that science requires a very focused attention to spatial detail and modeling as well as reliable stores of background information. With the right scaffolding of external cues, students can move through their scientific zones of development. However, without them, it is a near-impossible task. In fact, most teachers do not subject their students to it. Perhaps because they weren't subjected to it as students.

Most teachers of science do not have a science background (Kolbe & Jorgenson, 2018), and they look for a familiar storyline to move students through. This storyline is found because of an excellent book by Pauli in 1944 named *General Chemistry*. This book incorporates modeling; it focuses on explanation and meaning-making. It helps students to understand. However, this book's sequence is used so extensively that the learning sequences have become rote. Teachers do not use the experiences for inquiry style lessons but as a repetitive motion that they recall going through. In this sense, chemistry is not taught as a science, as a discovery learning sequence, but as a story, just like any other book.

Chemistry Sequences

It is entirely possible that with the right teacher, the sequences that are in existence can be used to create meaningful learning in chemistry. However, as Jackson (1968) points out, most problems are not to be blamed on the teacher. They are endemic to the process of being in school. Keeping this in mind, as well as the full weight of theory so far discussed, the next chapter will outline the current sequences used in high school chemistry. This will help to answer the question: *How is an effective high school chemistry curriculum sequence created?* The required learning supports have been identified, as well as some important requirements for assessing the sequence. However, the actual process of creating the sequence needs a little more detail. Therefore, also outlined in the next chapter will be the current methods that work, and methods that do not, when creating a sequence of concepts in science.

CHAPTER THREE

Project Description

Introduction

For this project, I have designed a general chemistry curriculum sequence for high school students. The parameters for the design have been set from three different sources. The first parameter was set from the literature review completed in the previous section. The second parameter was set from the current curriculum sequences being used in an attempt to incorporate what works currently. The last parameter was set from two curriculum design models, Understanding by Design and the Taba model. These parameters have been designed to answer the question: *How is an effective high school chemistry curriculum sequence created?*

Learning Theory Parameters

Learning theories provide details about cognitive processes that must be reflected in the curriculum. The first key detail requires that a focus be placed on identifying and activating important prior knowledge for each concept. This was important for the cognitive development theories of Piaget, Vygotsky, Bruner and Ausubel. For this project, the prior knowledge required for the concepts covered in a general chemistry course have been mapped out after reviewing the historical knowledge base that was available and used during each prominent concept discovery. The identification and subsequent mapping of these prior knowledge sets has formed the foundation and rationale for the sequence itself.

The other key points from the literature review are mainly centered on the delivery of information. One key aspect is the type of possible markers associated with the information. Piaget (1952) suggested that the mind creates internal representations using the objects' spatial location, when it occurred compared to other events, its size and some description about its appearance. Of these markers, Baddeley (1992) and Kozhevnikov (1999) show that attention needs to be paid to the spatial references with decreased detail on visual markings. Vygotsky (1978) and Trafton et al. (2005) also described a need for detailed temporal information, so that learners can see the progression of information. Driver et al. (1994) and Trafton et al. also suggested that the usage of these external models is important enough to demand a period of intense comparison. Finally, there are several indications, from several authors, that students need support in focusing attention at specific markers and reducing the clutter of overall information received. All of these will be taken into account in order to identify the most relevant models for each concept, and present them as spatially and temporally accurate as possible while decreasing other markers. In order for modeling to remain prominent, there must be a large amount of attention set aside for it.

The last important aspect from the literature review that has been utilized is the support needed for each student to progress through each concept. Both Vygotsky and Bruner paid particular attention to the importance of this progression. Vygotsky (1978) suggested that social interaction and dialogue is a necessary component. Bruner (1963) further suggested that each progression be broken down into smaller and smaller learning cycles. Both Chi , Driver et al. and Vosniadou (2007) outlined a large handicap with science learning: the prevalence of misconceptions. Chi (2005) suggests providing students with ample opportunities to interact with the unique emergent processes that science concepts possess. Driver et al. (1994) added the importance of explicit use of scientific culture in the classroom. This culture is centered around the creation and analysis of data and observational hypotheses. This culture must be used to counter the common rationale students enter the class with which leads to common misconceptions. Taking all of these into account, the curriculum has attempted to provide experiences for social dialogue, one that aids in the creation of a scientific culture in the classroom. This is done early and often in tandem with the laboratory experiences through guided questions. Prominent misconceptions have been identified as well.

Current Sequence Parameters

There are three prominent chemistry sequences used in today's classrooms worldwide. The most prominent sequence is related to a strategy known as Atoms First. This sequence has evolved from Pauling's *General Chemistry* (1944) and is centered around the usage of atomic structure as a common explanation for all laboratory results. This sequence is therefore considered theoretically based. The next most prominent sequence is for inquiry-based learning. This sequence is also similar in structure to the one outlined by Pauling, however, it has been adapted to a more student-centered and hands-on approach. This sequence is therefore considered to be descriptive and empirically based. The third sequence, which is not prominent in high school in the United States but is somewhat prominent in Europe and worldwide in middle school, is the integrated science sequence. This sequence is centered around cross cutting concepts across disciplines, and has become a blend that is both descriptive and theoretically based.

Atoms First

One of Pauling's (1944) first descriptions about *General Chemistry* was that it focused on theoretical chemistry as opposed to descriptive chemistry. Pauling observed that most chemistry curriculum at the time was not cohesive but independent islands of unrelated descriptive chemistry sequences. What Pauling did was to provide a very cohesive storyline that could be used to explain the results of major concepts covered throughout the course. This required the introduction of atomic structure and electron motion early. Then Pauling used electron modeling and referencing often. Since *General Chemistry* was first written, the use of electron motion as a theoretical tool to drive the curriculum has increased, but problems remained. Years later, a group of text book publishers developed what is now known as the Atoms First approach to combat what they called "fragmented presentation of material found" (Hillesheim, 2016). It was a similar response to a similar problem.

Atoms First relates to the introduction of electron motion and atomic structure before any descriptive chemistry topics, like reactions, are used. This is earlier than Pauling himself placed the topic (Pauling, 1944). This approach was outlined by Hillesheim (2016) with respect to other more traditional styles. Hillesheim identified this approach as being an abstract to concrete approach because of the reliance on the microscopic, abstract concepts of electronic motion. Hillesheim argued that certain topics are quite difficult to understand from a concrete perspective, and that the abstract perspective actually made the understanding more straightforward because the macroscopic concrete observations were very complex. However, the Atoms First approach typically resulted in lower proficiency throughout the chemical curriculum as a whole(Hillesheim, 2016).

There are some positive aspects to using an Atoms First approach. The focus on electron motion allows for a cohesive and repetitive pattern of learning that focuses on theoretical explanation. Pauling (1944) provided excellent spatial models that support this style of learning as well. In addition, there are certain chemistry topics that are supported by this strategy (Hillesheim, 2016), and a majority of teachers prefer this sequence for personal as opposed to theoretical reasons (Sibanda & Hobden, 2016). However, this approach focuses more on the teacher's background knowledge than that of the students (Sirhan, 2006). Also, with a decreased focus on the concrete and descriptive side of chemistry, the Atoms First focus on explanation detracts from an understanding of how concepts were learned.

Inquiry

Inquiry-based curriculum constitutes a loose collection of laboratory-based, descriptive chemistry strategies. Their identification and interest increased during the late 1950's and early 1960's. Shortly after *Sputnik*, the United States passed the National Defense Education Act which increased funding in science education with a small focus on inquiry. That year Schwab (1960) described inquiry as "a process of problem-detecting, formulating, and solving rather than a history and justification of a current theory (p. 178)." This produced what Schwab termed an upward narrative, meaning students first identify a familiar phenomenon and then move slowly toward a climatic phenomenon of cognitive conflict requiring accommodation. Throughout his paper, Schwab placed an emphasis on theories as tentative and changing. Schwab also outlined varying levels of inquiry based on the amount of teacher guidance. The less guidance on the part of a teacher, the more difficult the inquiry style. These are deemed a truer type of inquiry.

The *National Science Education Standards* (NSES) from 1996 include inquiry as the recommended method for delivering science curriculum. (National Research Council, 1996) This document did not define inquiry verbatim, but implied as a definition that inquiry is a way in which students pose questions and investigate phenomena. The NSES also recommended that teachers be given time and opportunity to create an inquiry-driven curriculum. The National Research Council provides teachers with five recurring themes and examples on how to incorporate inquiry into each. First, students are engaged by questions of ‘how’ or ‘why’ in scientific phenomena. Second, students examine empirical evidence about the phenomena. Third, based on the evidence, students create an explanation of the original question. Fourth, explanations are compared and evaluated with others. And lastly, explanations that are robust are communicated (National Research Council, 1996). While these five themes helped to give clarity to what was expected in a specific learning situation, they did not provide the only source of definition for what inquiry learning meant.

There are two prominent pedagogies that use inquiry methods to aid learning. One of them is known as Problem-Based Learning, or PBL. This style traditionally includes students in small groups solving open-ended real-world problems. These can be researched or lab based though the questions are typically student-driven(Markham, 2011). The other is known as Process Oriented Guided Inquiry Learning, or POGIL. This also uses small groups. However, the questions are typically more teacher-driven and the problem more laboratory based or teacher-generated (Trout, 2012). Both of these styles attempt to drive the learning cycle by creating thought-provoking questions whose answers help to spur the next round of thought-provoking questions.

Integrated Science

The integrated approach uses larger cross-cutting ideas to cycle through various disciplines. This curriculum style usually incorporates Chemistry, Physics, Earth Science and Biology together while applying a cross-cutting idea to several disciplines in quick succession (Astrom, 2008). One difficulty with integration is the scope of concepts. Trying to map the cross cutting ideas at the high school level is very complex. Within the first decade of use, the actual integrated curriculums being taught varied so widely that the use of the term integrated to describe them became meaningless (Astrom, 2008). Another suggestion was made that teachers could not have enough background knowledge to effectively present integrated material (Huntley, 1998). However, as technology became more intertwined into education it helped to focus the goal of integrated curriculum.

As Astrom (2008) pointed out, there are four general types of integrated curriculum: concept, context, concepts in context, and Science, Technology and Society, or STS. The initial efforts at integrating curriculum were based on concept mapping to place a concept into multiple disciplines. However, slightly more effective is the focus on science as a process, which is similar to the context type. Concepts in context describes how specific processes are repeatable in each discipline. This is the integrated style that is currently in use across several countries in Europe and has shown some success (Lustig et al., 2009). The last type, STS, is beginning to create a new wave of interest. It has found places in both the US NGSS standards as well as in Europe. This style focuses on cross cutting uses of technology through disciplines and shows the effects of science and technology on society and vice versa. STS makes an attempt at increasing student interest through real world examples as well.

Integrated curriculum has been adapted to several countries in Europe. A three year study there found similar scores between single-subject and integrated curriculum (Lustig et al., 2009). Perhaps an integrated curriculum needs more development. It is possible that this style of curriculum delivery will accomplish its goals and create a more holistic view of science with a unifying approach to learning. However, the lack of interest and confidence in the U.S. has relegated integrated curriculums to lower schools. The most recent NGSS standards have allowed for both inquiry-based curriculum, as well as an integrated style. However, even if I thought an integrated approach was the most beneficial, I do not have the power to change the entire paradigm of science at my school. Integrating curriculum requires an entire change across the entire department. Also, I do not have the same confidence in biological concepts that I have for the physical concepts. Therefore, I will be selecting an inquiry-based curriculum with some influence from Atoms First.

Method Parameters

Taba Model

Inquiry-driven curriculum sequences can trace their core principles back to Taba's (1962) curriculum model. The initial goal for this curriculum was the creation of conflict resolution methods for children. This was not limited to physical, life or even social sciences, but was meant for all interactions students would have. The model eventually evolved several characteristic and separate structures. The first was to leverage teachers in order to identify a group of skills that students struggle with and to limit the standards to only those which the teacher deems necessary. The second was to use curriculum experts to pair these skills with the appropriate concepts and topics (Taba, 1962). Finally, there was an iterative process added to the learning that helped drive students towards developing their own learning objectives (Taba, 1967). Taba also placed an emphasis on socio-emotional skills, noting that in many cases these skills were more important than the academic goals.

Taba's model helped to create an effective inquiry-based curriculum. The unique class problems were identified and focused on by teachers; professional help was leveraged to fix and support these problems with concept-driven curriculum, and finally the process was re-evaluated and the cycle started anew with the identification of new problems (Krull, 2003). This not only helped to present a familiar and meaningful curriculum, but the subsequent curriculum moved beyond the older creation into new learning zones.

The Taba model is difficult to implement. Few teachers are given the opportunity to create their own curriculum and even fewer are provided with the necessary professional help to satisfy the requirements of the Taba Model. That being said, for this project some very important features of this model have been taken into account: the skills that students need to improve have been identified and used as the basis for the curriculum and the standards have been reduced to those the teacher deemed necessary.

Understanding by Design (UbD)

Understanding by Design, UbD, is also conducive for an inquiry-based curriculum. The first basic step as outlined by Wiggins and McTighe (2011) is to identify desired results. The identification of these results should be focused on the transfer and usage of important learning goals and not on covering curriculum. Once these results are identified, it is suggested that they link to some big questions that will help to drive the discovery process (Wiggins & McTighe, 2011). The next stage in UbD requires the teacher to select their assessment strategy. The assessment needs to be an appropriate match for the results identified in step one. Finally, Wiggins and McTighe suggested the teacher should plan the learning cycle to ensure that students will either transfer, make meaning of, or acquire new knowledge.

Understanding by Design incorporates some familiar features of Taba’s model. Both models require teachers to identify learning objectives before going through the process of curriculum creation. However, in UbD teachers are expected to come up with their results from a prescribed set of standards as opposed to the identification of student needs. Also, UbD has less structure inherent in the planning process since teachers are expected to create the curriculum without the support of outside professional help.

These models are known as backward design because they start with the identification of outcomes and then pattern the curriculum in order to meet those outcomes. Though both of these are meant for use with inquiry-based curriculum, they are really for use in guided inquiry. True inquiry would be completely student-centered and generated. Taba's model comes close to a student-centered model, though it would still be considered as guided inquiry. These models suggest a reduction in the breadth of knowledge as well as a focus on independent student work.

Project Description

I have created a hybrid curriculum sequence that takes into account some of the beneficial concrete-abstract sequencing that an inquiry-based curriculum provides as well as some of the abstract-concrete sequencing that an Atoms First approach provides. I started by using the Taba model to initiate goal identification. However, I do not have a source of professional developers like Taba's model requires, so I switched to UbD steps for the curriculum planning stages. The project has a sequence outlined by the misconceptions identified in the goal selection, and four large units. Each unit has been mapped both internally by subunits and between the larger units themselves. The subunits and units are both outlined and details are provided with examples on how to support the learning with modeling, questioning, and experimentation. In order to initiate the identification of problem areas, as Taba suggests, it was also important to outline the demographics of my school.

School Variables

This curriculum is intended for a small private Caribbean school. There are about 90 students in each grade level. The chemistry course is a requirement for graduation, and the entire student body must enroll and participate in the course by their sophomore year. The classes are a mix of freshmen and sophomores. There are two teachers that split the course load for chemistry, and each teacher typically has two or three classes between twelve and twenty students. This allows for collaboration and experimentation. Another significant influence comes from the culture in which the school is embedded. The Latino culture of the school is goal-oriented as opposed to having a growth mindset. This culture is also heavily influenced by technology and social platforms. These aspects allow students to be highly connected with each other, the school to be well resourced, and teachers highly supported and independent. Outside the goal-orientation, this is an almost ideal setting for curriculum creation.

There are some other unique aspects of this student body. According to the past several iterations of the school handbook, the school population comprises between ten and twenty percent of special needs students. The student body is primarily English Language Learners, ELLs. However, they have been immersed in English curriculum since kindergarten. These students are also wealthy, and there are no students at or near the poverty line; all families enrolled are located in the upper percentile in the country. As such, students at the school enjoy the benefits of economic privilege. The student body performs near or above average on standardized tests in English according to past college board reports. This population appears to be receptive to an inquiry-based approach. However, there are still misconceptions about science concepts that arise due to cultural, economic, educational and societal experiences which will need identification.

Parameter Based Methods

The parameters outlined above appear to have several common themes and have resulted in helping to create a path forward.

Step One. The most important theme is the identification of prior knowledge and viable areas of growth. This was apparent from a theoretical perspective on learning as well as from the methodologies. The Taba Model was used for guidance in this step which required the observation of the student group that the project was designed for. The first step, therefore, was to examine past strengths and weaknesses from student assessments as well as collaboration with teachers from the students' prior grade levels. The eighth and ninth grade teachers and I discussed areas where underlying causal effects are not related well, an indication of poor concrete to abstract connections. We also looked for common misconceptions, areas where the theoretical foundations were either incomplete or inaccurate.

Step Two. The next important theme is the reduction of standards to a group of core beliefs. This theme was present in the learning theories, cognitive studies, methodologies and even from the NSES. This step goes against the habit of looking up standards from a prescribed list and mapping them out. In order to create this group of core standards, the focus areas were compared for sequencing and prevalence. Those areas that did not appear to be well sequenced with others, or were not likely to be required for other concepts, were considered non-essential. Those areas that were identified with high amounts of linkages to other problem areas, and whose usage appeared to be consistent throughout the course, were considered with the highest importance. This required some value assessment for each area as well as some mapping of possible sequence structures. The value assessment was completed with input from other teachers as well as an additional literature review outlined in the project.

Step Three. The sequencing of the curriculum was the third step. Ideally, if using UbD as a model, the next step would have been to determine the type of assessments. However, since the assessments will need to be highly contextualized, model intensive, and inquiry-based, the real driving force behind the sequencing was the growth and development of models. This required proper sequencing with respect to model growth. This was a very large factor that separated science learning from other disciplines, and aided in cognitive studies. Modeling is perhaps the single most important feature of science learning. Piaget (1952), Baddeley (1992), Driver et al. (1994), and Chi (2005) all stressed the importance and uniqueness of mental models to science learning. So once the core ideas were generated, I looked at the historical modeling sequences that scientists used when those core ideas were first discovered and communicated. This required research into the scientists that first developed the core concepts, most of which incorporated some simple modeling in their papers. Once prominent model sequences were identified, in order to meet the learning theory parameters, the sequence steps were broken down into their minutiae and mapped out in smaller steps, from units to subunits.

Those were considered the fundamental building blocks for the curriculum, as they were the foundational building blocks for those scientists' initial learning cycles as well.

Step Four. After the sequence was complete, and the prominent models as well as their evolutions identified, their delivery into the curriculum began a round of question creation. This step allows for student-driven inquiryas well as the social interactions necessary to create theory-driven explanations and a scientific culture in the class. These questions help students to connect observations and experimentations from class with mental model creation and analysis. This step also required the appropriate selection of experiments and demonstrations and followed more of a guided inquiry process than a true inquiry process.

Step Five. To fill in the curricular picture, a group of relevant support materials was created. These materials included spatial modeling supports as well as descriptions assisting teachers through the probing questions and experiments outlined in step four. This last step will be a life-long process, and so a part of this step is also out of the immediate scope of this project.

Timeline

The project has taken roughly two months to complete, though the mindset for it has been developing for several years. The first two steps took approximately one month to complete. This included the research, meeting with colleagues, the identification of common misconceptions, and the mapping out of those misconceptions with their core concepts. Step three required far less time than anticipated, as the mapping of the original misconceptions with their historical connections helped lay the groundwork for the process. The content and model sequencing for the large units and the subunits took only two days. This also allowed for an overview of the project to be shown which helped guide the last process. It is possible the concept sequencing was simple due to the fact that these initial units appear to be much better sequenced and modeled historically than units that will come into the curriculum that are outside the scope of this project. Creating the unit descriptions with details of misconceptions, sequence comments, modeling, experimentation, questioning and expectations was extensive. There were 19 subunits and four units, and this accounted for a majority of the project. This last step took about five weeks. Step five was partially incorporated into step four, and what was not will be left for future endeavors.

Summary

Creating a chemistry curriculum is a complex undertaking. Without using specific parameters for building in meaningful experiences, the vastness of options create chaos. Therefore, there are parameters to be used. The first parameter is based on cognitive learning theories. These created requirements for prior knowledge activation, identification and valuation of relevant information through highly contextualized spatial models, referencing and improvement of these models through social discourse. This parameter also requires the reduction of curriculum to a series of steps needed to develop understandings of these models. This should help students to understand how and why models are generated as well as how and why they are used.

Current curriculum sequence parameters helped to set up some requirements. Atoms First sequencing, though not followed closely in this project, requires the identification of concepts that are better introduced with an abstract theory as opposed to a concrete observation. This approach also creates the requirement that students create a scientific culture by engaging in social discourse. Inquiry-based models help to create the requirement that students generate interest in finding answers to questions by conducting real life experiments. A further requirement of inquiry was to use important questions whose answers bring up new sets of important questions, thereby driving a cycle of learning.

The Taba Model and UbD were both useful in creating the curriculum as a fusion of their methods was utilized in this project. Step one was from Taba's model, creating teacher-generated topics based on problem areas. Step two was from both models, a reduction of the curriculum down to the core ideas generated from step one. Step three was from UbD, though placed earlier in the sequence, and also somewhat unique to this project. This step generated the curriculum sequence using the historical context of model development related to the core concepts. Step four was from UbD, the generation of big questions and experiments to help place the learning goals into a presentable learning format. In the future, more effort will be added as assessment, materials and analysis are created to enhance the curriculum.

Chapter four of this paper focuses on the results of the steps outlined in my project. One notable insight discussed the results of using scientist and student misconceptions as the rationale for the valuation and ranking of concepts. The research and the mapping itself also generate some new insights into how curriculum should be sequenced, as well as a small paradigm shift in how science curriculum should be viewed. There were multiple pathways discovered through the curriculum, shedding light on the fact that there might not be a single unified sequence that is right for everyone. Finally, there is some anticipation into how this project will be used in the future. A curriculum has been sequenced, now it needs to be analyzed. With it will come some changes to how people approach science education and some ideas are given for sharing this information.

CHAPTER FOUR

Reflection

Introduction

In an effort to improve students' abilities to make informed decisions regarding concepts in a high school chemistry class, I have tried to create a curriculum sequence that is guided by some model-based, lab-based and question-based supports. The question that guided me in this project was: *How is an effective high school chemistry curriculum sequence created?* I wanted the sequence itself to be unique, but more importantly, I wanted there to be rationale behind each step. This rationale would include research into science education and chemical concepts, both historically and recently, as well as an analysis of the current misconceptions in the chemistry students at my school. Once the rationale was completed, I also wanted to create guidelines for the sequencing process. Though it helped to look through the curriculum design models from Taba and UbD, I wanted this part to be unique as well. Once all of these were in place and the sequence was mapped out, the models and experiments were added. The model and experiment selection became straightforward, as the research and sequence pointed in specific directions and moments in time. Lastly, questions were included, in an attempt to bring out misconceptions and allow for an inquiry-styled progression from one concept to the next. This chapter is a reflection of what was learned in that process.

Major Learnings

The greatest insight I gained from this project might be the importance of teacher-generated curriculum. The actual curriculum itself might not be as important as the teacher's familiarity with it. By generating one's own curriculum, a teacher ensures they are familiar and invested with it. This is something that seemed to be in opposition to the purpose of this project. I initially thought I would make a sequence that was going to be universally applied to chemistry education. What this new insight suggests, however, is that the sequence may not be that important. In a sense, there are dozens, perhaps hundreds of sequences to try in learning the same concepts. The one that is effective is the sequence that makes the most sense to the learner. Since the learning experience is so intertwined with the teacher's though, this means that the more effective sequence is most likely the one the teacher understands the best. Giving teachers a new and improved sequence would actually lead to struggle because it is unfamiliar. This idea reinforced the trend I see in science education: teachers are teaching students the same sequences and methods that they were taught. They repeat the experience that worked for them. One important way to improve the educational experience, therefore, is for educators to create their own sequence. This is what reinforced the idea that a teacher's familiarity with a curriculum sequence is more important than the sequence itself.

Another insight I gained was that there is no single, universal sequence. The more research I delved into, the further I got into creating the sequence, the more I realized the likelihood that pathways of learning, though similar, are different for us all. This might even apply to the learning process. The good news is, this is a healthy approach. After all, students are doing the learning, and teachers are providing the materials from which the learning develops. Recognizing students all have unique experiences means they will interact differently with materials. I think this likely causes different pathways. Multiple pathways might also be associated with increased proficiency after repetition throughout the year. Using a concept or model in multiple circumstances in multiple subsequent concepts allows for more possible pathways since more connections are attempted, increasing the number of students who will make meaningful connections. I started with the notion that there was a universal sequence in chemistry that worked best for everyone, but I realize that is highly unlikely. However, by providing means of building multiple pathways it is possible to improve everyone's chances.

Another insight is that accepting and dealing with mistakes is a part of science. Assuming that science is written in stone is a failure to recognize the scientific method, as well as the mindset which makes science unique. This is hard to place into a sequence. However, this is in line with the idea that there is no perfect sequence. Believing that students will build upon their knowledge base sequentially until they understand a concept like quantum mechanics is counterproductive and a cause for failure. Students should understand that not just making mistakes, but removing beliefs and revising them is a part of learning. We know that certain notions are going to eventually be removed and revised (Vosniadou, 2007). The longer students hold onto the idea that what they believe will not change, the more difficult and painful it will be for them in the future to update their knowledge. Building into the sequence topics and models that get changed, that get updated, is important. Providing a theory that is the explain-all, end-all to start the course does not allow for the fluid motion of ideas that science requires. Students should, at a certain point, question not just what they have learned, but what the teacher has told them. Faith in an infallible teacher, afterall, sounds more religious than scientific.

These are the paramount changes in my understanding of education when reflecting on the project and research work. They point to some big faults in my premise. However, I do not think they point to big faults in the product. The process worked even when implemented by a misconception-soaked individual like myself. This is a testament, perhaps, to the benefits of allowing oneself to be wrong, to the acceptance that there is more than one way to do something right, and in the importance of doing something oneself. Oddly, those were all the main faults in my initial thinking, and ended up providing perhaps the biggest benefits in the end.

Research Review

One of the most influential theorists for me was Piaget. Perhaps this is because he laid the foundation for subsequent cognitive learning theories and I enjoy learning about the foundations of theories. This was true in the research review for the science content as well, I thought Lavoisier was very influential. What struck me about Piaget at first was the description of the learning process as a group of individual concept segments, schema (Piaget, 1952). This was analogous to atomic theory, to quantum theory, this separation of a larger whole into its smaller parts. This idea also brings about the belief in a sequential learning process that everyone goes through, which was another of Piaget's theories (Piaget, 1952). These would lead me down a path that helped to produce a viable sequence, however, it provided too narrow of a description of how learning happens, and needed to be modified.

Another part of Piaget's work focused on the learning process itself. The accommodation and assimilation of concepts requires that concepts be modified or created through a process of cognitive conflict (Piaget, 1952). This was, and continues to be, a central focus especially in science learning. It is important to provide instances where our beliefs are challenged, where certain experiences show us that we are wrong and need to modify our understanding. It is not easy to incorporate this fallibility into teaching practices when teaching is centered around providing people with the right answers and judging their repetition of these correct answers. However, it is something that must be addressed and will be a large focus not just in how this project can be improved, but in how my teaching and perhaps science teaching at large needs to be improved.

Vygotsky (1978) was another influential theorist for me, another foundational theorist. His focus on the importance of interaction and practice of concepts through language, and on the progression through conceptual steps will probably always focus my efforts (Vygotsky, 1978). This obviously helped when considering important questions for support and pushed me to use smaller progressive steps in the sequence. Even more so, it has helped to change my focus in class to more student to student conversation, more explicit in-class discussion, and a pace that is focused enough on each step that it feels slower, methodical.

I remember watching Michelene Chi, Micki, give her 2017 NARST keynote presentation in San Antonio. I had assumed there were correlations between math and science, and knew student success in language arts did not translate into science. But I had never seen someone explain the details of why this occurs until Micki Chi did. She has since then changed her description of what emergent processes are, and how they are interpreted by students (Chi, 2005). I do not fully understand her new theories, but she has helped me to appreciate the unique character of science. Most importantly, she helped me to understand that it is the misconceptions in science that might define it the most. She used the term robust misconceptions (Chi, 2005), which I am still understanding more and more. This is the idea that certain misconceptions will pop up over and over, and even when addressed will remain due to methods Piaget outlined like disbelief, creating new concepts that don't exist, or adding information that isn't there (Piaget, 1952). I have seen this so often in class, and decided to make this a central point of the project. These misconceptions were identified, and there are repeated attempts to address them throughout the units. I have also increased my focus on the types of misconceptions in class, trying to identify where they are, and allowing those students more exposure to the material and related questions.

The historical texts from the scientists who described the original chemistry concepts I found really helpful. It is difficult to place oneself into another's viewpoint when trying to learn science concepts. However, I think both Lavoisier (1789) and Dalton (1808) provided some honest reflections of their struggles. Lavoisier discussed the difficulties with assigning correlations that are not present. In order to combat this, he spent countless years documenting lab work and perfecting separation techniques. Even then, his understanding of chemical reactions and mass conservation failed to help clarify atomic theory or intangible sources of energy. However, he did simplify his explanations and analysis. Dalton was able to capitalize on improved techniques, especially in gas measurements and separation, and yet had similar struggles to Lavoisier. Again, one of biggest strengths was to communicate his understanding with simple, clear ideas. Dalton added simple spatial diagrams as well. These diagrams I find are still helpful for visualizing atomic theory today, over 200 years later.

When I looked through the misconceptions and struggles for students at my school, I found similarities between our students and these older scientists. Their mental environment must not be so different. I thought the strengths of Lavoisier and Dalton would be helpful as a focal point for the curriculum as well. I tried to make the presentation of each step as explicit as possible. I also tried to incorporate a large amount of laboratory examples into the curriculum supported with simple diagrams that attempt to transition between Lavoisier and Dalton. In order to transition away from their way of thinking, guiding questions were added to try and point students into new ways of thinking, especially when looking at Joule's experiment. In this way, these old concepts could be introduced in a natural setting, and progressed through in small natural steps.

Possible Policy Implications

The sequence and scope of this curriculum appears to be connected to the theories and ideologies previously outlined in this paper. However, the implementation of this curriculum in real life, both in my school and at large, requires some long term planning. This planning should have several points of focus. The first is to realize that misconceptions have a meaningful knowledge base. The second is to provide multiple pathways from this knowledge base towards new ideas. The third is on vertical alignment, since several of these concepts appear to be appropriate for a middle school level course. Lastly, there is a need to increase teacher exposure to this curricular mindset, since there is going to be resistance to several aspects of this curriculum.

The misconceptions detailed in this project are typically due to either a scientifically out-dated concept or to an unrelated concept that was applied out of place. The first example of this was the confusion between separating particles into smaller particles, and separating particles into similar groups. The purpose of the separation was to separate them based on particle types. The separation into smaller particles, while not accurate, uses ideas that help to understand atomic theory and help to identify what an atom is. In this instance, the concept was out of place but could be used later to aid in understanding. Similarly in the last unit, the confusion with heat as a tangible particle is actually based on the older idea of caloric. Though the concept is too outdated for the goals of that subunit, it can be used to help express heat symbolically in the prior subunit. For the most part, common, robust misconceptions are not simply invented by students, but a consequence of prior knowledge.

Since misconceptions reveal knowledge and a level of understanding they can be used to build meaningful learning sequences. Students used prior understandings in order to arrive at these misconceptions, so it is no surprise that historically scientists shared these same misconceptions. Both the scientist and student used their prior knowledge and applied it somewhat naturally, though incorrectly. While the outcomes may not have supported a specific learning target, they support learning other beneficial learning targets. If students can be channelled into these alternative pathways when these misconceptions appear, these misconceptions can actually help the overall learning progression. However, as far as I know, that needs more research.

Modern teachers need to provide differentiation for a variety of learners. Using multiple pathways for the learning sequence could provide this differentiation. However, providing the materials and outline for students to select their path would require more resources and planning. Perhaps this could be achieved by providing materials and lab experiments based on student responses to guiding questions. A document would need to be provided for teachers that showed how each specific response would correlate with a specific pathway. This would also require further research and study in order to create with any confidence.

Teachers need more experience in order to confidently teach with the mindset used in this sequence. The two other teachers that used this sequence with me felt comfortable with using the modeling and the experimentation, however, they could only resist the introduction of atomic structure for so long. In both cases, they switched to atomic structure before the subunit on stoichiometry was completed. This shows how embedded the usage of atomic structure is to the storyline of teaching chemistry. Both teachers described needing more time with the curriculum to feel comfortable with it. However, the increased use of laboratory experiments and spatial models was appreciated by both, and they continue to use those throughout their curriculum.

Another important decision for the department and our school is to select which concepts are designed for a middle school class and which are geared for high school. It helped to sit down with the 8th grade teacher to discuss this. Currently, there is some crossover on the first three units. However, atomic structure is also introduced. Also, there are some difficulties in equation usage that might be due to math levels. The suggestion would be to drop the theoretical aspects in 8th grade, including the calculations in stoichiometry. Instead, a focus would be on the first two sections with more depth using modeling. The 8th grade teacher was very receptive to this idea, and I think this will be the decision that gets made going forward.

Limitations

The curriculum sequence that this project provides, as well as the materials and mindset, are largely untested. There has been an effort made to take misconceptions into account both historically as well as those found in our student body. However, more data should be taken to determine that these are in fact representative of the students this curriculum is designed for. Also, the implementation of this curriculum is limited due to the comfort of the teachers that will use it, as well as the materials available to them. All of these actions would increase the validity of this project.

Another limitation of this project is the curriculum itself. I made the assumption that misconceptions would be a driving force, and that the mapping of the sequence could be informed by them. This seemed intuitive, however, perhaps this intuition is fallible. There should be some further analysis of the steps, probably through assessment analysis, that shows evidence for their correlation. Again, this step would help to add validity.

The scope of this project is limited as well. This is designed as an outline for a curriculum with specific supports. There are no specific lesson plans included, or assessment materials. As such, teachers must provide these on their own. Since those teachers cooperating with me on this wanted more resources, the creation of these would help to make this curriculum more practical.

Future Research Recommendations

Due to the design of this new approach, there are several future research questions that need to be addressed. Some of these would help to improve the project itself, and some are there to evaluate the project.

To improve the project, the following recommendations are given. First, to provide more materials, especially assessments. This allows for teachers unfamiliar with this approach to have more familiarity and explicit expectations. Included with this addition should be possible alternate pathways based on misconceptions to help differentiate the curriculum and take advantage of the misconceptions themselves. This would require additional research as well as the time required to create the documents. Besides just adding resources, the curriculum should be vertically aligned between 8th grade and 9th grade classes. This would mean expanding the scope of the curriculum for the 9th grade class, and would be a multiple-year approach.

To evaluate the project itself, the following is recommended. There should be some assessment data to analyze for each unit and subunit. These subunits should be compared to each other to look for correlations across each. In other words, doing poorly in a previous subunit should have an effect on the subsequent subunits. Data about misconceptions from other classes, possibly other schools, needs to be taken. These misconceptions were taken as the focal point for the curriculum, so their prominence in the student body should be reviewed.

Communicating Results

The science department at Carol Morgan School has been working with me in various ways on this project. They will be the first group that this project is shared with under the intention of having the curriculum implemented. There are certain individuals, like the 8th and 9th grade teachers, who will be more affected by this since they teach chemistry concepts in their classes. Over the spring and summer, they will be given the curriculum documents, in the hopes of trying to start implementing either some or all of the units. I will also try to present this curriculum during one of our in school professional development days this coming spring.

I would like to communicate these results to a wider audience as well, however, I have less control over that option. I would like to either publish this project and/or paper. I would also like to present this project at an upcoming conference, perhaps NARST, in 2021.

Benefits to the Profession

This could be a new way of thinking about and understanding sequencing concepts in chemistry. Or, it could just be another new take on curriculum that is held by an individual teacher. Either way, this will change the way I teach classes, as well as the way in which students learn in those classes. Ideally, I would hope that this curriculum is part of a larger trend of change in chemistry curriculum design. I believe that the progress towards inquiry that is happening across the NGSS and AP standards will help increase the need for mindsets like the one presented in this project. I think this curriculum can support those who are still in need of guidance and wondering how a new approach can be made.

This could also help improve methods for using student misconceptions to produce meaningful curriculum. Teachers will be expected to produce curriculum that is tailored for their classrooms, and using misconceptions is an important first step. Not only does it provide insight into what students already know, it shows the pathway for what they need to learn. Hopefully this project helps someone else understand how that can be accomplished. The rules for creating sequences in the project were designed with that in mind.

Summary

Personally, the process of using misconceptions to create a model-based chemistry sequence helped to solidify a new way of approaching science curriculum. I now believe that a majority of science is taught on the premise that students will memorize a storyline that their teacher provides them. They are then expected to apply this storyline to situations in order to explain the outcomes they observe. This is the opposite process that scientific learning relies on. Observation should always come first, and should always be referenced in the explanation. It is those explanations that should reveal misconceptions, that should reveal student understandings. By examining the analysis that students have in interpreting events we determine what they know. If we tell them beforehand, then we are not capable of checking their or our own knowledge.

My research into this matter helped to provide support in understanding why these misconceptions exist, and how they can be resolved. The most important findings showed that students need to take small, simple steps. These steps are aided through simple, spatially-related diagrams. A constant review, a habit of referencing observations, will help students transition from what they see physically to how they interpret the phenomenon mentally.

The project helped to create a sequence map of the concepts students struggle with in chemistry. I learned in this project that misconceptions are similar between students and scientists. This makes sense. If we understand science to be a process of creating and comparing concepts, some right and some wrong, then we should anticipate that there are natural misgivings that people will arrive at when progressing through a discipline like chemistry. However, the project also taught me that students will not take the same concept paths when arriving at similar understandings. They need to be provided the opportunity to take their own unique pathway.

The project and the research both revealed that creating a curriculum is important for an individual teacher. Teaching someone else's curriculum, teaching a curriculum that I was taught, distances me from the curriculum. When I research the concepts and background, when I struggle with the actual sequence mapping, I acquire a whole new understanding of the concepts and curriculum. This understanding I would never have had without this experience.

I believe there were several novel ideas presented in this project. The prominence of simple spatial modeling, the usage and analysis of misconceptions, the process of creating the curriculum sequence, and the purposeful separation from an atomic-structure-storyline I think are all new ideas. The actual curriculum maps and overviews are as well. If any of these are recognized and utilized by someone else then this project would be beneficial not just to myself and my students, but to others out there as well.

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