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THE INFLUENCE OF TEACHER CURRICULAR KNOWLEDGE AND ORIENTATIONS TO THE TEACHING AND LEARNING OF SCIENCE ON SECONDARY CHEMISTRY CURRICULA

MICHAEL B. BURT

157 Pages

Efforts to understand changes in teacher curricula following the adoption of reform-based standards, such as the *Next Generation Science Standards* (NGSS) remain incomplete and prior scholarship has identified several topics in the standards (e.g., nuclear chemistry and kinetics) that remain infrequently addressed in teachers' introductory chemistry classes. This study provides an initial insight into how teachers decide what to teach, how they teach it, and why it might be valuable to include in their curriculum. To accomplish this, two teachers' units on nuclear chemistry and kinetics were explored as part of a case study methodology. The research questions sought answers to help understand why some topics found in the standards remain marginalized in many teachers' curricula while other topics receive extensive attention and coverage. Similarly, the study attempted to understand how teachers' curricular knowledge and orientations to the teaching and learning of science influence their curricular decision-making process around the topics of nuclear chemistry and kinetics. Findings suggest that subject-matter knowledge as well as curricular knowledge plays a significant role in shaping how teachers understand a particular topic and what type of knowledge students should be developing. Both participants independently sought learning opportunities (e.g., professional development) to augment their subject-matter knowledge and curricular knowledge around a unit on nuclear chemistry but did not do so for a unit on chemical kinetics. Similarly, individual teachers' orientations to the teaching and learning of science were generally consistent across the topics studied but differed greatly between the two participants. Both teachers also reported a desire to bring chemistry as it relates to the "real world" into their classes, though their understandings of what "real world" means differed significantly as did their subject-matter knowledge about each topic. For the goals underlying standards such as NGSS to be realized, further work must be done to understand barriers to implementation and for targeted professional development to be designed and offered to support those needs.

KEYWORDS: Science Education; Chemistry; Nuclear; Kinetics; PCK; Curriculum

THE INFLUENCE OF TEACHER CURRICULAR KNOWLEDGE AND ORIENTATIONS TO THE TEACHING AND LEARNING OF SCIENCE ON SECONDARY CHEMISTRY CURRICULA

MICHAEL B. BURT

A Dissertation Submitted in Partial
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for the Degree of

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M. B. B.

CONTENTS

TABLES

FIGURES

CHAPTER I: INTRODUCTION

As a classroom teacher at the secondary level, I have had the opportunity to collaborate with many other chemistry teachers in professional developments, task forces, assessment writing sessions, and other contexts at the local, state, and national levels. These experiences have been profoundly impactful in helping me develop from a novice to an experienced teacher and continue to influence me to this day. Two experiences that stand out relate to discussions about what content should be taught in an introductory chemistry classroom and whether certain topics should always be marginalized in comparison to other, seemingly more deserving topics.

In a year-long professional development workshop that was designed to allow teacher-leaders to become oriented to the draft form of the *Next Generation Science Standards* (NGSS), I was speaking with a university chemistry professor about the topic of electron configuration. While this topic had always been one that I had dutifully taught in my classes in much the same way that I had learned when I was in high school, I always had a feeling that its impact on my students was marginal at best. It seemed that the concept served a very limited role in my larger introductory chemistry curriculum and the larger goals I had for my students. During one conversation, this professor offhandedly suggested that he thought it would be reasonable to simply “stop teaching it”. I was shocked that I had received “permission” to modify a topic taught in my chemistry course. As I reflected, it occurred to me that I had the ability to trust my professional judgement to add, remove, or modify more than just the design of student learning activities or the style or wording of assessments. It meant that I, as the high school teacher, might also have the ability to question the accepted canon of chemistry knowledge or the nature of the curriculum that I had taken for granted as being an “essential” part of the introductory chemistry experience.

A second meaningful experience took place in a department-level conversation about modifying a district’s common chemistry curriculum to accommodate the expectations of NGSS, the state’s adopted science standards. When I brought up the need to include topics that were explicitly found in those standards (e.g. bond energy, equilibrium, and intermolecular forces), several colleagues were quick to point out that, in their view, those topics were “too advanced” for introductory chemistry students and only useful in classes at or near the Advanced Placement (AP) level. I quickly sought clarification about why those teachers felt those topics were so challenging for students that they were deemed entirely inappropriate for an introductory course, but it was not an idea that was subject to debate or further discussion. Just as in the case of being given “permission” to reduce the emphasis on a certain topic, it seemed that others felt a similar pressure to stay with topics that were “allowed” at the expense of those that were perceived inappropriate because it was, as they put it: “what’s best for kids”. It was unclear whether those teachers chose to avoid topics they weren’t as confident in teaching or simply viewed those topics as not being relevant to an introductory chemistry course. Instead, those discussions seemed to point toward a dominant view that introductory chemistry might have been understood to be a proving ground better suited to developing strong dimensional analysis and stoichiometry skills.

As time passed, I encountered the notion of pedagogical content knowledge (PCK) in a journal article that I had been reading as part of my efforts to stay in touch with the chemistry education research. PCK is viewed, largely, as the knowledge unique to teachers that allows them to transform their subject matter knowledge for learning in the classroom (Shulman, 1986).

This concept, including such ideas as orientations to the teaching and learning of science and its intersection with subject matter knowledge and other forms of pedagogical knowledge, seemed to me to explain many of the interactions that I have had with colleagues as we have (productively and unproductively) attempted to translate science into digestible units that students would be able to meaningfully engage with.

Statement of the Problem

Previous scholarship has suggested that secondary chemistry teachers are concerned with what topics ought to be covered in chemistry courses at the high school level (Deters, 2003). Despite this concern, it appears that certain topics in chemistry (e.g., stoichiometry, classifying types of reactions and predicting products) are routinely incorporated into introductory courses while others (e.g., equilibrium, kinetics, nuclear chemistry) are more likely to be marginalized or entirely left out (Boesdorfer & Staude, 2016; Burt & Boesdorfer, 2021). Efforts to understand this phenomenon are still incomplete.

In recent years, with more and more states adopting NGSS as their science standards, the expectation that all students have opportunities to engage with these topics and relevant natural phenomena becomes even more important. Prior work by Burt and Boesdorfer (2021) suggests that many of these standards are still not actively being incorporated into the curricula of teachers. Instead, it appears a belief that introductory chemistry serves to prepare students for future chemistry classes (in high school or college) limits the inclusion of some of the core ideas presented in NGSS and values other topics that are perceived to be more important to success in future coursework.

Despite this evidence, it is not clear why those specific topics may not be more intentionally integrated into introductory chemistry classes. Further exploration of the way that teachers transform their own chemistry knowledge for instruction is required to better understand these findings. Teacher PCK, or more specifically, enacted PCK, represents the specific PCK that is revealed while creating and implementing instructional segments in the classroom (Mazibe, 2018). Obtaining a deeper exploration of how this professional knowledge base influences the structure and purpose of teachers' curricular segments for essential topics like nuclear chemistry and kinetics would help begin to bridge the current gap in the literature.

Purpose of the Study

Many studies have attempted to understand the nature of the teacher PCK (reviewed in Chan & Hume, 2019). These studies have been able to capture differences between teachers' PCK and have identified many distinct ways that teachers make instructional decisions to support student learning. Similarly, a teacher's PCK for one topic has been shown to not necessarily relate to their PCK for another (Veal & Makinster, 1999). This idea suggests that exploring teachers' PCK more generally may not reveal differences between PCK at the level of individual topics. Exploration of teachers' topic-specific PCK for select topics may provide a deeper insight into not only the composition of teachers' curricula, but also the way that it is implemented in the classroom (enacted PCK). Several studies (e.g., Danisman & Tanisli, 2017; Mavhunga & Rollnick, 2013) have attempted to examine topic-specific PCK, though some use the Magnusson et al. (1999) model while others favor the Geddis et al. (1993) model as the basis for their understanding of topic-specific PCK of teachers. Considerably fewer have used the more recent consensus model (CM) described in Gess-Newsome (2015) that places a greater emphasis on science teacher orientations than previous models.

Understanding the influence that teachers' orientations toward science teaching may have on their curriculum development and subsequent instruction holds promise for resolving questions around the "...lack of coherence of teachers' orientations toward science teaching and the focus on the curricular materials" (Magnusson et al., 1999, p. 104). In order to adequately understand teachers' strategies for curriculum structure and composition, it would be important to understand how teachers believe successful student learning should look in a given topic as well as the purpose and method(s) in which students receive or develop that knowledge. Previous research has explored the introductory chemistry curriculum of Illinois chemistry teachers (Burt & Boesdorfer, 2021) following the state's adoption of standards-based reforms and in Iowa (Boesdorfer & Staude, 2016) prior to the adoption of new curricular standards. Each of these studies identified several topics that received considerably less focus in teachers' curricula than others. It was also noted that chemistry teaching may be influenced by a canon of knowledge as well as science teacher orientations (Burt & Boesdorfer, 2021). Consequently, it seems useful to further probe the nature of teacher topic-specific PCK in order to better understand the differences in attention afforded to certain topics in chemistry compared to others. The purpose of this study is to gain a deeper insight into how elements of PCK (curricular knowledge and orientations to the teaching and learning of science) shapes the structure and enactment of units on nuclear chemistry and kinetics, which are part of NGSS but have not traditionally been taught in introductory high school chemistry.

Research Questions

This study was guided by the following research questions:

1. Why do certain topics included in the standards (nuclear chemistry or kinetics) receive differing levels of attention across different experienced teachers' introductory chemistry curricula?

2. How do teachers' curricular knowledge and orientations to the teaching and learning of science influence their decisions relating to their chemistry curricula (a form of their enacted PCK)?

To understand the role that elements of teacher PCK play in the planning and continued development of secondary teachers' chemistry curricula, this question was more thoroughly explored using two topics in chemistry: nuclear chemistry and kinetics. Two sub-questions that were intended to further clarify the second research question are:

2a. How do teachers' curricular knowledge and orientations to the teaching and learning of science influence their enacted curriculum with respect to the topic of nuclear chemistry?

2b. How do teachers' curricular knowledge and orientations to the teaching and learning of science influence their enacted curriculum with respect to the topic of kinetics?

Overview of Methodology

Since this study intended to explore how teachers construct portions of their chemistry curricula and understand the influence that their PCK plays in those decisions, a qualitative methodology was appropriate (Plano Clark & Creswell, 2010). The research questions required an understanding of the processes that shape teachers' chemistry curricula; thus, a case study methodology lent itself to being able to more deeply probe elements of teacher understanding and decision making (Creswell, 2008; Yin, 2018). This case study method selected two experienced teachers to participate that teach introductory chemistry. These participants were chosen to represent contrasting perspectives using maximal variation sampling (Creswell, 2008). To aid in establishing the reliability of the findings from this study, participants provided member checking following the collection and analysis of the supplementary qualitative data.

Initial data relating to teachers' perspectives was obtained using a semi-structured interview as well as to create and examine documents pertaining to their units or learning segments on nuclear chemistry and kinetics. One such document, the content representation (CoRe) developed by Loughran et al. (2004), offered insight into teachers' subject matter knowledge, curricular knowledge, and orientations to the teaching and learning of science (elements of PCK). This allowed the teachers to distill a given topic into individual concepts and connect those to the larger curricular purposes served by an individual unit of study (nuclear chemistry or kinetics). A second type of document, student assessments, provided a unique perspective that highlights how much focus teachers place on each of individual topics within a unit as well as their interrelationships and connections to larger phenomena being studied in their introductory chemistry course.

Following the completion of each element of the case study methodology, the presence of multiple sources of teacher knowledge allowed for triangulation which enabled the development of a more coherent understanding of how each individual approaches the process of translating their knowledge of a given chemistry topic for student learning (Bowen, 2009). Prior to making cross-case comparisons between participants, member checking served as a referent to enhance validity of data analysis and ensure that the participants' perspectives have been sufficiently characterized (Creswell, 2008; Plano Clark & Creswell, 2010).

Significance of Study

This study has the potential to help contextualize teachers' orientations to the teaching and learning of science as well as their curricular knowledge in a way that offers insight into how those elements of PCK influence and shape the ongoing structure, design, and modification of individual teachers' curricula. By focusing on a topic like nuclear chemistry that has been shown to receive less extensive coverage (in terms of class time) than other topics (Boesdorfer & Staude, 2016; Burt & Boesdorfer, 2021), potential explanations arise to clarify this observation. General questions considered include: is less time being spent on a topic because it simply requires less time? Is a topic less well-understood by teachers and, thus, more difficult to translate for instruction? Is a given topic more challenging to horizontally sequence into the existing chemistry curriculum? An answer to any of those questions would helped to address elements of the research questions offered and presented an opportunity to consider potential means to remedy those issues to allow students to learn about nuclear chemistry and develop meaningful understanding. The replication of the design described above with kinetics, another topic covered in the typical secondary chemistry curriculum, provided an opportunity to examine differences in teacher PCK between different topics. The result of this work has implications for professional development and developing teacher PCK.

CHAPTER II: REVIEW OF THE LITERATURE

This study explored the nature of the professional knowledge utilized by secondary science (chemistry) teachers as they create, implement, and revise chemistry curriculum for two specific topics: nuclear chemistry and kinetics. As a result, it was necessary to review scholarship relating to curriculum, the teaching of nuclear chemistry and kinetics, and pedagogical content knowledge (PCK), particularly as it relates to curricular knowledge and orientations to the teaching and learning of science.

Understanding Curriculum

By 1973, at least 119 definitions of ‘curriculum’ had been offered in the research around education and schooling (Portelli, 1987) and that number has assuredly increased in the years that have followed. The large number of potential definitions suggests that different areas of curriculum study may contextualize the notion of curriculum differently. Regardless of the specific definition chosen, curriculum might generally represent “...what we choose to remember about our past, what we believe about the present, what we hope for the future” (Pinar, 2004, p. 20). The decisions made by curriculum designers (teachers, researchers, governments, or other organizations) might prioritize a view that reifies the knowledge of the past or values solely looking to the future as well as numerous other potential permutations. This includes the unique knowledge derived from a given curriculum (the “what”), the way that students will learn it (the “how”), the purpose it serves (the “why”), and who benefits from this structure.

Multiple, complementary attempts have been made to distill the basic elements of curriculum. Portelli (1987) explains that, at its core, curriculum can be understood in terms of content, activities, and its overall plan. In this view, content is analogous to “the what” and activities a proxy for “the how” of curriculum. Walker (2017) insists that any curriculum structure must articulate its purpose, content, and organization to be usable. This suggests that each curriculum is distinct from another based on how each component might be interpreted and operationalized.

Forms of Knowledge

Morris and Hamm (1976) explain that curriculum is unique because, at its core, its “...primary concern is with neither teaching nor learning but with knowledge itself…” (p. 299). The first decision that must be made in the development of a curriculum, then, is the decision about the type of knowledge that results from learning. Greene (2017) summarizes this as “...an arrangement of subjects, a structure of socially prescribed knowledge...” or, alternatively, as something that offers “...possibility for [the learner] as an existing person, mainly concerned with making sense of his own life-world” (p. 253). In short, this knowledge can be represented by (1) the acquisition of a body of already-developed factual information, (2) prescribed skills or understanding deemed worthy of production by society, or (3) the process of constructing understanding relevant to their life.

Knowledge as Content

A curriculum that prioritizes the acquisition of predefined factual information actively positions the teacher as a ‘knower’ and students as ‘not-yet knowers’ of that information. In this type of curriculum, “...we engage in it for its own sake rather than as instrumental to some extrinsic purpose or purposes” (Kelly, 2004, p. 47). The content itself becomes the beginning and end of the purpose for learning. This view reinforces the primacy of historical knowledge and presumes its everlasting value for the learner. As a result, the knowledge of the past is perpetually placed in a higher regard and greater value than that of the present. As many other scholars have identified (e.g., Au et al., 2016; Kincheloe, 2010; Rata, 2012), this approach dramatically underrepresents the role that politics and social class play in the construction of knowledge and in the development of curriculum.

Knowledge as Product

The idea that knowledge is derived from a predetermined end, or product, is often associated with the presence of ‘objectives’ or ‘targets’ that serve as instruments that indicate the results of successful education (Kelly, 2004). Tyler (2013) argues that knowledge sought from educational objectives can “...represent the kinds of changes in behavior that an educational institution seeks to bring about in its students” (p. 6). This represents a shift from knowledge as an existing set of facts or concepts to one that prioritizes changes in behavior that might accompany understanding. As a result, the development of a curriculum that conceptualizes knowledge as a product must separate the knowledge from the process of learning. In the Tylerian approach, the act of “...determining objectives, stating them in proper form, devising learning experiences, selecting and organizing learning experiences to attain given outcomes, and evaluating the outcomes of those experiences” represents the essence of curriculum development using the knowledge as product paradigm (Walker, 2017, p. 137). The learning achieved (and knowledge gained) in this model is evidenced through the completion of each objective. In practice, “it has the function of training every citizen...not for knowledge about citizenship, but for proficiency in citizenship...not for a mere knowledge of abstract science, but for proficiency in the use of ideas in the control of practical situations” (Bobbitt, 2017, p. 11-12). These objectives are known in advance by students and teachers alike and mark a finite endpoint to student learning.

Grundy (1995) explains that a teacher using a product-driven conception of knowledge might reject a curriculum design that encourages students to solely obtain correct answers. For similar reasons, that teacher may also ignore each student's ability to independently construct meaning and generate potential solutions to a problem. As a necessary feature of the 'curriculum as product' model, the outcomes of learning are predetermined and out of the students' control. The use of knowledge as a product in curriculum design has potential to overstate the importance of the 'ends' of learning at the expense of the 'means' where learning takes place.

Knowledge as Process

Conceiving knowledge as a process is to shift the emphasis placed on the result of learning (as in the knowledge as content or product frameworks) to one that emphasizes the process of learning. Gilbert (2005) explains that knowledge should be viewed as "...something organic, something that is always developing and always in process...as a series of systems that have particular ways of doing things" (p. 175). As a result, learning may not have as clear of an endpoint and, instead, be ongoing. The notion of "...'curriculum as practice'...gives precedence to contemporary action, and allows for contradictory, aberrant or transcendent action in relation to proactive definition" (Goodson, 1995, p. 14). Student knowledge derived from the 'process'-oriented knowledge base should be immediately able to put that learning into practice.

Dewey (1897) argues that for society to become transformed and shaped by its modern citizenry, education must be provided with an eye toward the cultivation of critical and social awareness. To accomplish this, he suggests that education should provide a framework for understanding one's experience. Embracing the notion of process, curriculum "…should focus on the construction of knowledge and encourage students to produce the information that has value or meaning to them in order to develop new skills" (Alismail & McGuire, 2015, p. 151). In much that same view, Hildebrand (2007) suggests that “critical activism requires the development of critical thinking skills, including how to: identify salient claims, analyse assumptions, be skeptical of evidence sources, evaluate alternative perspectives, seek warrants for conclusions, distinguish between belief and evidence...” (p. 58).

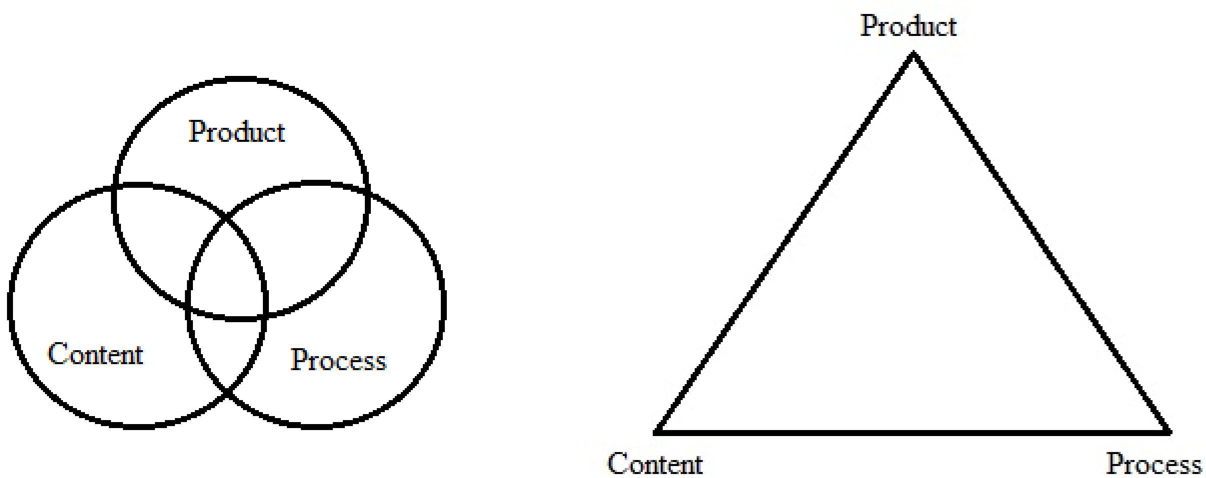


Figure 1. Revised Model of Knowledge Conceptions. Adapted from Kelly, A. V. (2004) and Greene (2017).

While all curricula may not be derived from a singular view of the aims of knowledge (content, product, or process), its knowledge proposition can be understood as a hybrid of one or more of those elements (knowledge as content, product, or process). Depending on the degree of emphasis, it could be conceptualized on a three-level Venn diagram or ‘plotted’ within the bounds of a triangle (See Figure 1). As an example, a curriculum created by *Teacher A* might prioritize the value of knowledge equally as content and product while ignoring the importance of knowledge as a process. Another option might be a curriculum, created by *Teacher B*, that uses targets to guide student learning, but those objectives prioritize knowledge as process. In practice, teachers are unlikely to construct curricula that reify a single view of knowledge. By determining the extent that a given curriculum or curricular unit emphasizes each view of knowledge, it can be possible to understand how it differs from another teacher's curriculum (See Figure 2 for each example visualized). This flexibility allows for greater precision when attempting to identify the knowledge base valued in a curriculum. Despite that, for a curriculum to be developed and put into practice, it needs to do more than signal the type of knowledge that ought to result from student learning.

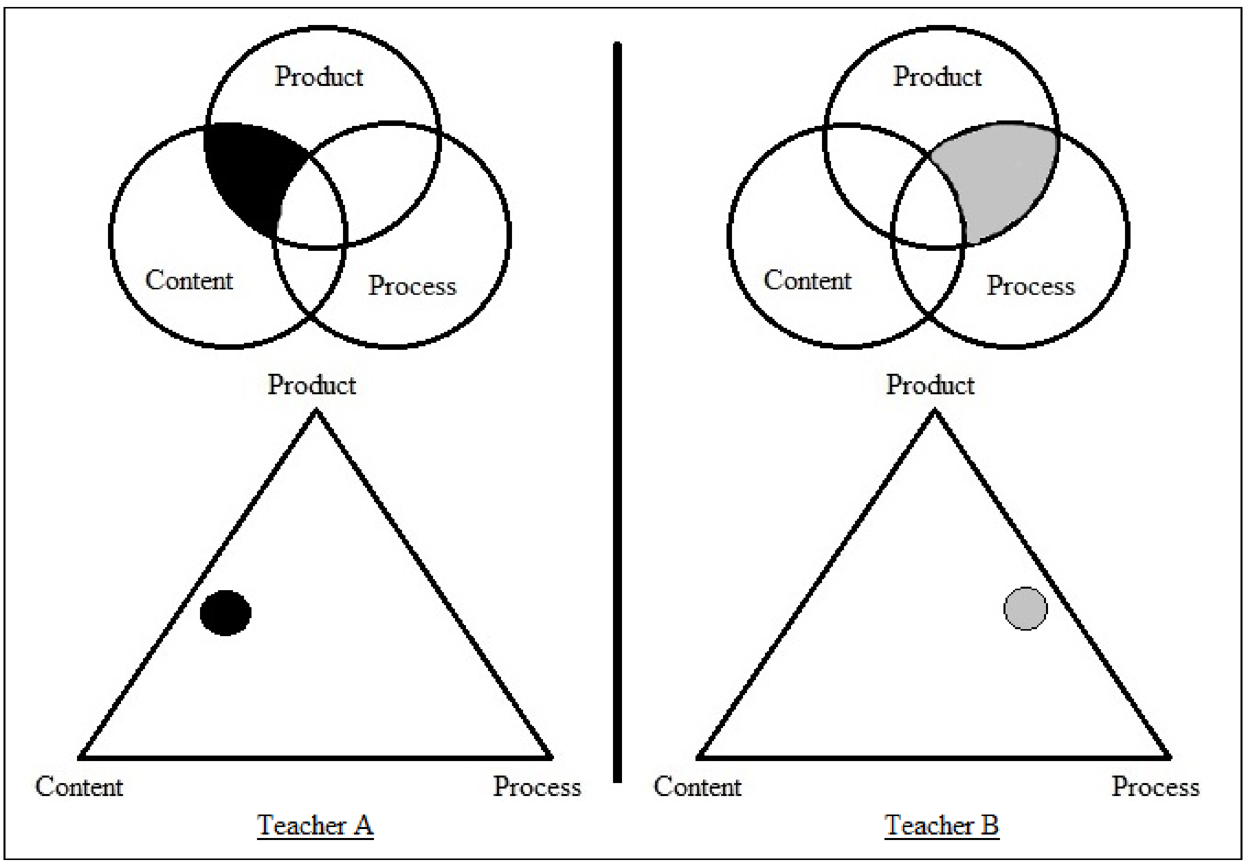


Figure 2. Applied Model of Knowledge Conceptions. Derived from Figure 1.

How Knowledge is Learned

Once the basis for knowledge is determined, the way in which it is developed in students becomes the focus. Johnson (1967) observes that "the nature of a particular intended learning outcome limits the range of possible learning experiences and thus guides instructional planning" (p. 130). Views of knowledge that center content require some form of transmission for learning to occur. Schiro (2012) describes that, in this model, "the purpose of education is to help children learn the accumulated knowledge of our culture: that of the academic disciplines" (p. 4). In doing so, this knowledge is effectively transmitted from the knower to the learner. At the end of learning, the knowledge of students and that of the teacher should look remarkably similar. This means that the act of learning results in a student acquiring a fixed set of knowledge and allows for teacher effectiveness to be measured by the extent that the knowledge was successfully transferred to the learner.

A teacher pursuing a product-oriented knowledge goal must select the optimal way for students to realize those goals. The curriculum consists of a series of learner experiences that "...includes not only that which is implied or specified in the curriculum, but also a large body of *instrumental* content selected by the teacher, not to be learned, but to facilitate the desired learning" (Johnson, 1967, p. 131). The instrumental content essentially acts as a conduit by delivering the student to their destination (achieving the learning objective). A curriculum that reinforces a view of learning as a product requires the teacher to preemptively determine what successful learning looks like. To do so does not typically require the input of students. Pinar et al. (1996) cautions that this approach serves to reproduce class structures of the workplace inside of schools.

The use of a process-oriented view of knowledge requires teachers to help students develop—in a much broader sense. This approach embraces the subjective nature of human experience where knowledge is neither static nor is it necessarily concrete. Bodner (1986) explains that “construction is a process in which knowledge is both built and continually *tested*” (p. 875, emphasis original). In a constructivist understanding of the learning process, the teacher and student cannot have a transactional relationship in which a discrete body of knowledge is transmitted to the learner; rather, it must be actively constructed by the learner using the lens of their own personal context. Learning in this form of curriculum requires students to examine their understanding and continually refine it upon examination, though that approach is not exclusive to the ‘knowledge as process’ model. Dewey (1897) explains that true education can only be attained through the intersection of social situations and the exercising of an individual child’s agency. The argument presented is that education is defined by the extent that a child can situate oneself in their community and develop their ‘power’. This demands a relevant, practical curriculum centered on experiences that foster individual agency over the whims of the educator.

Why Knowledge is Valued

The form of knowledge selected for a curriculum is predicated on the primary purpose that knowledge serves. Some of the potential purposes include perpetuating the dominant culture, ensuring one’s ability to compete in the economy, and allowing an individual to pursue self-fulfillment as a positive contributor to society. For those that favor knowledge as content, learning reproduces “...the culture of society...in terms of what is regarded as being best or most valuable...among the intellectual and artistic achievements of society” (Kelly, 2004, p. 49). To others, learning ought to be “...geared to economic productivity and the curriculum planned to promote forms of learning which are regarded as useful, in terms both of future employment for individuals and the continued economic growth of society" (Kelly, 2004, p. 54). Situating the purpose for schooling and student learning in the context of the Cold War and *A Nation at Risk* offers a view of students as future engines of economic development and key to remaining competitive internationally (Sleeter, 2002). Both purposes serve society at large, particularly the dominant cultural group that determines what knowledge has value.

In contrast, an "...understanding of knowledge as subjective means that it is always tied to some group's interests" (McPhail & Rata, 2015, p. 56). While embracing the process of learning and understanding the individual's ability to construct their knowledge occurs as a function of their own experiences, it increases the number of groups whose interests may be advanced through education. Anyon (2017) argues that a given curriculum can be traced to the maintenance of social class structures. Individual-oriented views of knowledge, emblematic of the curricular views that position knowledge as a process might be thought of as analogous to higher-status jobs in which those individualized outcomes might be more valued.

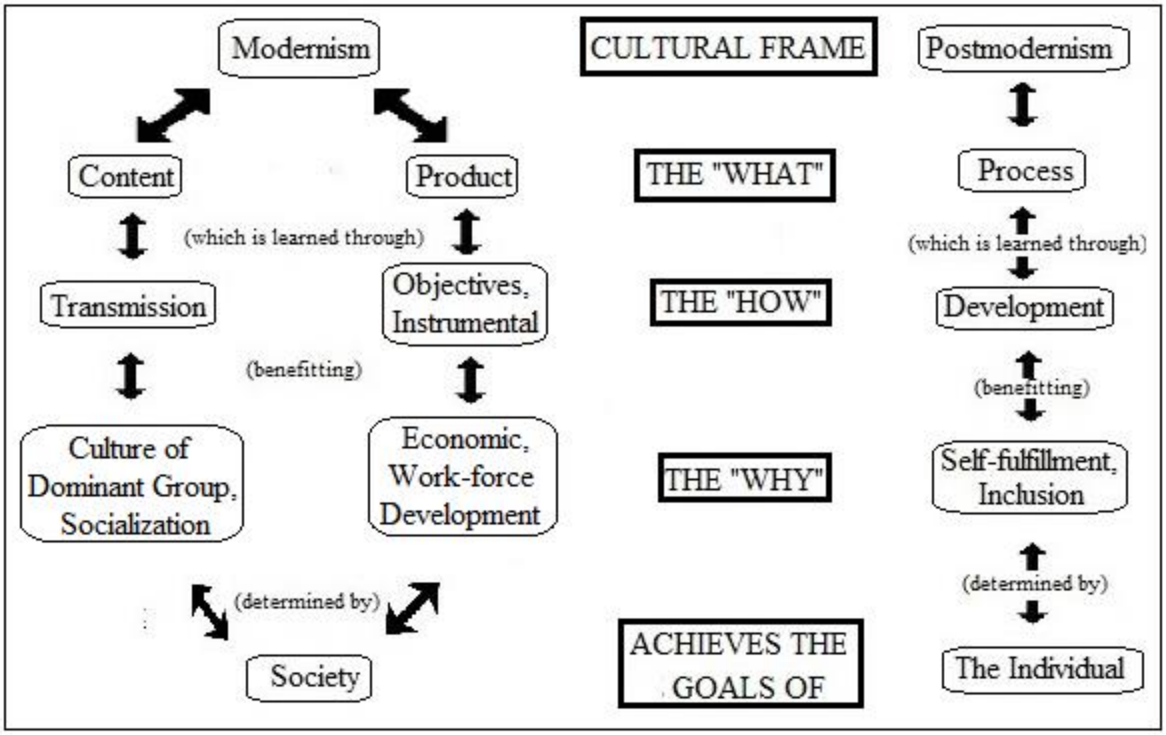


Figure 3. Visual Summary of Curriculum Construction. Adapted from N. J. Gehrke et al. (1992), A. V. Kelly (2004), and P. Slattery (2006).

Figure 3 presents a larger summary of the various forms of curricular considerations synthesized from the body of research discussed throughout this manuscript (Gehrke et al., 1992; Kelly, 2004; Slattery, 2006).

The Secondary Science Curriculum

Based on the National Research Council's (NRC) *Framework for K-12 Education*, the *Next Generation Science Standards* (NGSS) presents a three-dimensional set of student learning standards to support student outcomes in science classroom (NGSS Lead States, 2013; NRC, 2012). These standards include Performance Expectations (PEs) constructed from Science and Engineering Practices (SEPs), Disciplinary Core Ideas (DCIs), and Crosscutting Concepts (CCCs). Each standard aligns with one of four domains: physical science, life science, Earth and space science, and engineering. Each standard, or PE, represents "…what students should know and be able to do" (NGSS Lead States, 2013). These standards have been adopted in part or in its entirety by 44 of the 50 states in the United States and, as a result, serve as a useful starting point for considering what might shape teachers' ideas about what "should" be taught in classrooms across the country (NSTA, n.d.). The extent that these standards have been enacted by teachers was explored using two topics included in NGSS: nuclear chemistry and kinetics.

Nuclear Chemistry

Given that many of the states within the United States uses NGSS (or created ones derived from NGSS), it would be reasonable to begin with how those standards treat the topic of nuclear chemistry. As part of the PE labeled HS-PS1-8, students are expected to be able to "develop models to illustrate the changes in the composition of the nucleus of the atom and the energy released during the processes of fission, fusion, and radioactive decay" (NGSS Lead States, 2013). In the process of meeting this PE, students will model the composition of atomic nuclei before and after each process occurs while also accounting for relative changes in energy as well as the nature of each form of energy released. Within the NRC's (2012) *Framework for K-12 Education*, the learning of nuclear chemistry provides students with opportunities to understand "…the formation and abundance of the elements, radioactivity, the released of energy from the sun and other stars, and the generation of nuclear power" (p. 111). Through these contexts, students ground their learning using relevant phenomena.

As one of the leading scientific societies in the United States, the American Chemical Society (ACS) published a plan for teaching chemistry to all students, loosely based on the NGSS, in which nuclear chemistry is a key concept within two of its four 'core ideas' that are believed to be essential parts of any high school curriculum (ACS, 2018). Those two ‘core ideas’ include: “energy” as well as “matter and its interactions”.

Despite its relevance in standards and acknowledgement as a core component of chemistry, its marginalization in chemistry classrooms has been noted in chemical education research literature as early as the 1970s (Halsted, 1979; Streitberger, 1977). Not surprisingly, given its lack of traditional inclusion in typical secondary chemistry curricula, nuclear chemistry is undertheorized in the research (Tekin & Nakiboglu, 2006) and a widespread understanding of common alternative conceptions of students and teachers alike is lacking along with techniques for effective teaching. As a consequence, further exploration of the nature of nuclear chemistry education at the secondary level is warranted.

Chemical Kinetics

As part of the PE labeled HS-PS1-5 in NGSS, students are expected to be able to “apply scientific principles and evidence to provide an explanation about the effects of changing the temperature or concentration of the reacting particles on the rate at which a reaction occurs” (NGSS Lead States, 2013). In achieving these goals, students are asked to use kinetic molecular theory to demonstrate the connection between molecular collisions and reaction rate to better understand the nature of chemical reactions. Within the NRC’s (2012) *Framework for K-12 Education*, the learning of kinetics provides students with opportunities to consider the ways that molecular motion can be used to understand the nature of the forces that drive chemical reactions.

The American Chemical Society (ACS) includes kinetics as a key concept within two of its four ‘core ideas’ that they believe as essential components of any high school curriculum

(ACS, 2018). Those two 'core ideas' include: "matter and its interactions" as well as "motion and stability: forces and interactions".

For secondary students as well as undergraduates, physical chemistry topics like kinetics present difficulty due to its conceptual nature as well as potential mathematical demands on higher-level problems (Marzabal et al., 2018). In general, kinetics is concerned with chemical reactions and focuses on "…how fast the reactants are consumed, or the products are formed…[and] provide a means for predicting the rate of processes and to find the influencing factors that promote a desired reaction or inhibit an undesired one" (Job & Ruffler, 2016, p. 401). As described in the PE referenced above, the ability to understand the role that factors such as temperature and concentration have on the progression of chemical reactions and influence on reaction rate align well with this definition.

Despite its obvious place in chemistry standards as a key avenue for students to develop a deeper understanding of the nature of chemical reactions, kinetics is undertheorized in the chemistry education research. The research that exists is often focused on the topic's perceived difficulty by students and teachers as well as to discuss common forms of alternative conceptions (e.g., Cakmakci, 2010; Nicoll & Francisco, 2001; Sozbilier, 2004). Similarly, Sozbilir et al. (2010) describe a belief that some of the perceptions around the topic's difficulty and the lack of conceptual understanding of students and teachers, alike, might be linked to the time dedicated to "algorithmic problem solving" rather than deepening conceptual understanding (p. 118). Ultimately, limited research has been done to meaningfully characterize the nature of teachers' understanding of kinetics and how it shapes their teaching practice (Justi, 2002). As a result, further exploration is needed both at the secondary level and beyond.

Theoretical Framework

The framework of pedagogical content knowledge (PCK) has demonstrated utility in conceptualizing the cognitive strategies that teachers use as they attempt to transform their content and pedagogical knowledge to influence student learning (Shulman, 1986). Geddis et al. (1993) suggest that an individual's PCK provides insight into an educator's ability to facilitate learning for a student. An individual teacher's content (subject-matter) knowledge and pedagogical knowledge are modulated by their orientation towards science teaching (Gess-Newsome, 2015; Magnusson et al., 1999; Friedrichsen et al., 2011).

Models of PCK

This professional knowledge can be conceptualized at the general, discipline-specific, or topic-specific levels (Veal & MaKinster, 1999). As a result, PCK can be discussed broadly (general PCK), about a particular discipline such as chemistry (domain specific PCK), or at the most granular level (topic specific PCK). The ways in which teachers operationalize their content knowledge as they create support to enhance student learning can be examined at each level of PCK (See Figure 4).

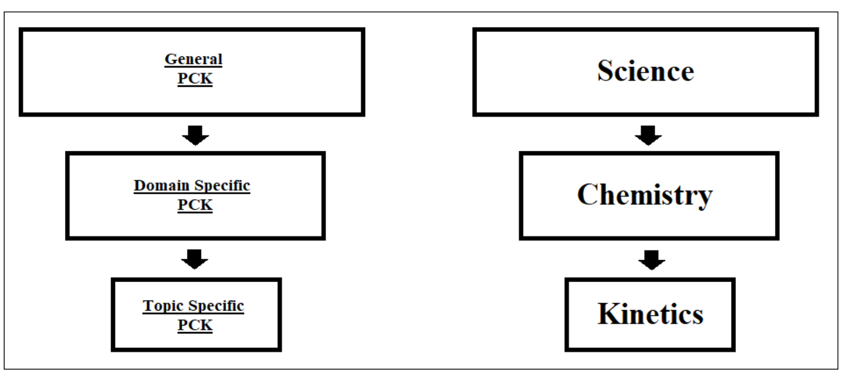


Figure 4. Revised Model of PCK. Adapted from Veal & Makinster (1999).

Pedagogical knowledge relates to teachers' knowledge of the science teaching, curriculum, student understanding, assessment, and instructional strategies that can be utilized by teachers to make their content knowledge accessible to students (Magnusson et al., 1999). Differences in teacher knowledge relating to any of those forms of pedagogical knowledge or variances in orientations to the teaching and learning of science would result in different ways of translating content knowledge for students in the classroom.

Curricular knowledge represents one element of teacher PCK included in the consensus model (CM) alongside assessment knowledge, pedagogical knowledge, content knowledge, and knowledge of students that, together with orientations to the teaching and learning of science, form the basis for teacher professional knowledge (Gess-Newsome, 2015). These elements of general and domain specific PCK are largely the same elements that operate at the more granular level when examining how teachers approach the teaching of individual topics. From there, teacher orientations to the teaching and learning of science play a role amplifying and filtering those forms of pedagogical and content knowledge as it is shaped for the classroom context (See Figure 5).

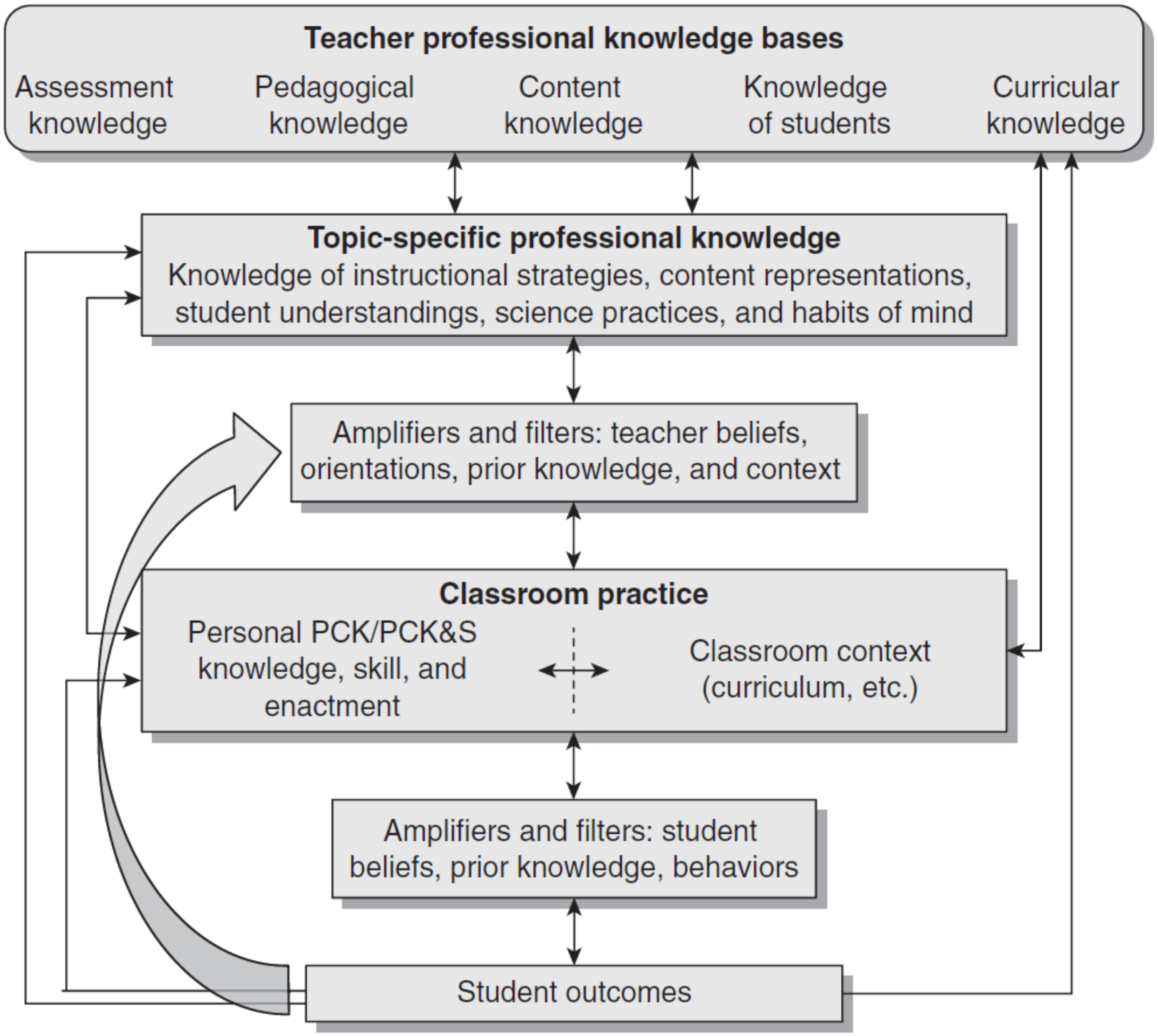


Figure 5. Consensus Model (CM) of PCK. From *A model of teacher professional knowledge and skill including PCK: Results of the thinking from the PCK Summit* (*p. 31*) by J. Gess-Newsome in A. Berry, P. Friedrichsen, & J. Loughran (Eds.) Re-examining pedagogical content knowledge in science education, 2015, New York, NY: Routledge.

Among the various models of PCK that have been presented over time is the notion of its existence as an 'integrative' or 'transformative' model of teacher knowledge. Gess-Newsome (1999b) explains that PCK includes the separate development of pedagogical knowledge, content knowledge, and knowledge of the specific educational context before those individual knowledge bases can be integrated into a single entity, PCK. Kind (2009) discussed the transformational model as a view that teachers begin with an existing body of subject-matter (content) knowledge and it is repackaged and intentionally *transformed* for students using elements of pedagogical knowledge, such as curricular knowledge. The Magnusson et al. (1999) model would be one such example of a transformative model of PCK.

Curricular Knowledge

Curricular knowledge as described by Gess-Newsome (2015) or in the Magnusson et al. (1999) model characterizes teachers' knowledge of curriculum as an essential element of PCK. This knowledge operates at the larger (domain) scope as well as at the narrower topic level and is sometimes referred to in the literature as curricular saliency (Geddis et al., 1993; Mavhunga & Rollnick, 2013). The knowledge and skills required to produce saliency within the curriculum include the selection, connection, and coherence of big ideas as well as the accuracy of the content itself (Chan et al., 2019; Geddis et al., 1993). This suggests that individuals' knowledge of curriculum itself may reciprocally shape their orientations to the teaching and learning of science as it relates to individual topics within the curriculum. This may be due to individual teachers' perceived value and subsequent sequencing of certain topics within their curriculum as well as the depth expected within a particular learning sequence.

Any effort to gain insight into teachers' curricular knowledge at the domain or topic levels requires an exploration of the elements of teachers' curricula. In addition, teachers' views of how curriculum should be constructed and the beliefs and attitudes that shape it provide a great deal of potential for insight. Grossman (1990) explains that "knowledge of content refers to knowledge of the major facts and concepts within a field and the relationships among them" as well as an "...understanding of the canons of evidence and proof within the discipline, or how knowledge claims are evaluated by members of the discipline" (p. 6). This provides teachers with an opportunity to identify core concepts and minimize trivial ideas that might interfere with student learning (Park & Oliver, 2008).

An individual teacher's knowledge of curriculum represents "...a teacher's understanding of how to help students understand specific subject matter and includes how a subject matter's topics, problems, and issues can be organized, represented, and adapted to the diverse interests and abilities of learners…" (Magnusson et al., 1999, p. 96). This knowledge of curriculum could be a particularly useful construct when considered at the topic-specific level as well as with the larger subject area or discipline as a whole. Magnusson et al. (1999) presented two categories that constitute knowledge of curriculum: knowledge of specific science curricular programs and knowledge of science goals and objectives.

Knowledge of Curriculum: Specific Programs

The extent of a teacher's knowledge of specific curricular approaches to a given discipline or topic can be understood in terms of general learning goals as well as published materials that represent the ways in which other teachers or curriculum writers have organized and constructed their curriculum (Magnusson et al., 1999). Examples of some of these programs include the Chemical Bond Approach (Strong & Wilson, 1958), *Chemistry in the Community* (ACS, 2011), or CLUE (Cooper & Klymkowsky, 2013). This type of curricular knowledge signals an awareness and understanding of the various ways that a topic or discipline has been successfully represented in terms of sequence and purpose. Similarly, this knowledge is indicative of the similarities and differences as well as the strengths and weaknesses of various learning goals held throughout the field. This includes the activities and/or materials that can be used to support those types of learning. Gess-Newsome (1999a) affirms the idea that "...textbooks, curriculum guides, and standardized assessments...interact with teacher cognition by reaffirming or challenging what is known and believed and may ultimately shape what is practiced" (p. 58). As a result, teachers that have only taught from the scope presented in a textbook or a single curriculum may be less inclined to consider alternative ways of teaching while those that have revised their curriculum at multiple points in time may be more aware of the strengths and weaknesses of various approaches available for teaching a given topic.

Knowledge of Curriculum: Science Goals and Objectives

Teacher knowledge of science goals and objectives begins with an understanding of the sources of national, state, or local documents that guide science curriculum and instruction (Magnusson et al., 1999). These types of guiding documents provide a reference and, in some cases, expectation for what teachers should be addressing in their classrooms.

The sole consideration of the curriculum related to a single topic is not sufficient for capturing a teacher's understanding of larger curricular goals and objectives. Grossman (1990) suggested the importance of understanding teachers' knowledge of vertical and horizontal curriculum. Knowing what students have already learned from other teachers and what they will be learning in later courses undoubtedly offers a meaningful context to visualize the role an individual teacher's curriculum should play in that student's learning (vertical curriculum). Similarly, the ability to integrate between and among individual topics within a discipline or domain, the horizontal curriculum, requires a far greater emphasis on the learning context (Maton, 2009). The purposive placement of each individual topic necessitates an understanding of which topics form natural sequences or present opportunities for teachers to build in necessary structures to ensure the progression between topics to support student learning. This suggests the importance that individual decisions play in the sequencing of learning for coherence while also fulfilling the larger goals or objectives for the learning. To accomplish this, teachers must, consciously or unconsciously, select a form of knowledge that must be valued, the way it ought to be learned, and its purpose for asking that students acquire or develop it.

National policy documents include sources such as ACS (2018), NRC (2012), or AAAS (1990). These types of documents often retain a much more macroscopic perspective than state or local guidelines would. State or local decrees often focus on compliance and adherence to narrower goals or detailed policy outcomes (Mehta, 2013) while advocacy and professional organizations are not similarly constrained in their purpose. Knowledge and understanding of these guidelines allow a teacher to contextualize their own curriculum on a more vertical level—especially between elementary, middle, and high school. State documents drawing from sources such as NGSS Lead States (2013) offer a more detailed vision of the various goals and purposes a potential curriculum might have in a given classroom at a certain grade level.

Schneider (2015) summarized knowledge of curriculum in terms of scope, standards, resources, and sequence (p. 170). This reinforces the need for a teacher to have a well-articulated understanding of the importance of certain content ideas and their relationship(s) to the standards crafted by governing bodies. For an individual teacher or school, the navigation of available resources and the potential organization of ideas might change in response to modifications of the existing standards and scope of a curriculum.

Science Teacher Orientations

Positioned uniquely to address questions about 'why' teachers enact their content and pedagogical knowledge in the way(s) they do, orientations to the teaching and learning of science provides a tool to gain further insight. Friedrichsen et al. (2011) clarified the model of

PCK presented by Magnusson et al. (1999) with an emphasis on the role of teacher orientations (attitudes, beliefs, views) toward the teaching and learning of science. Gess-Newsome (2015) suggests that these orientations give teachers the "…opportunity to embrace, reject, or modify new knowledge, skills, and practices" as they transform their own content knowledge for student learning (p. 34). These orientations have the capacity to exert significant influence on the ways that teachers' pedagogical knowledge (including their curricular knowledge) is operationalized and transformed depending on an individual's perception of (1) the goals or purposes of science teaching, (2) the nature of science, and (3) science teaching and learning (Friedrichsen et al., 2011). Lotter et al. (2007) described these orientations as ranging from amassing information to develop[ing] problem-solving skills; fact-driven to process-driven; limited student ability to expanding student ability; transmission of information to encouraging independent thought (See Figure 6). As a result, attempts to characterize the curriculum design of an individual teacher would be incomplete without attention to the contribution(s) that science teacher orientations play in transforming pedagogical and subject matter knowledge for the classroom setting.

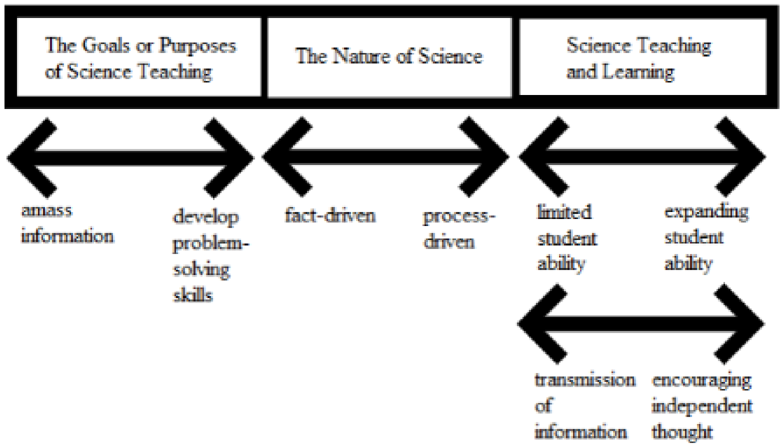


Figure 6. Revised Model of Teacher Orientations in Practice. Reprinted from “The implementation of reform-based standards in high school chemistry classrooms influenced by science teaching orientations” by Burt, M. B. & Boesdorfer, S. B., 2021.

Neuman et al. (2018) suggests that these orientations play an important role in shaping student learning. Of those is the relationship between teacher beliefs and curricular innovation, which was investigated by van Driel et al. (2008) and found that, for chemistry teachers, beliefs strongly favored fundamental chemistry (knowledge as content) and chemistry, technology, and society (knowledge as either product or process) while holding knowledge development in chemistry (knowledge as process) in the lowest regard. Borko and Putnam (1996) characterized orientations to the teaching and learning of science as a type of conceptual map or framework that teachers use as they assess, among other things, the value of curricular materials. Gess-Newsome (1999a) explains that “once established, orientations act as gate keepers for the acceptance or rejection of teaching material…” (p. 78). Given that knowledge of curriculum serves as the basis for the selection and development of teaching materials in a salient curriculum, the idea that teacher orientations may serve to influence those choices is significant.

Measuring PCK in Teachers

Previous studies have been done to better understand the nature of PCK in pre-service, early career, and experienced teachers (Chan & Hume, 2019). These studies generally have used one or more combinations of direct classroom observation (e.g., Boesdorfer & Lorsbach, 2014), interviews (e.g., Luft & Roehrig, 2007), artifacts from learning sequences (e.g., Mavhunga & Rollnick, 2013), and/or surveys (e.g., Sorge et al., 2017). Depending on the nature of each study and the research questions being explored, data relating to teacher knowledge, action, and beliefs might be collected. The alignment between each type of research question and the type of data collected can be visualized in Table 1.

Table 1

Data Collection Strategies in PCK Studies. Adapted from Chan & Hume, 2019.

	Questions of Teacher Knowledge	Questions of Teacher Reasoning	Questions of Teacher Action
Written Responses (e.g., Tests or Questionnaires)	X	X	
Artifacts (e.g., Lesson Plans or Assessments)	X	X	X
Interviews (e.g., Structured Conversations or Informal Discussions)	X	X	
Classroom Observation (e.g., Field Notes or Videos)			X

Few studies have attempted to characterize the interactions between teacher orientations to the teaching and learning of science and individual elements of PCK (Ekiz-Kiran & Boz, 2019). This suggests a gap in the literature that should be pursued to better understand how teachers' actions in and out of the classroom might be shaped by individual components of PCK.

Synthesis for this Study

In this study, curriculum specifically represents the knowledge that an individual teacher decides should be acquired or constructed by a successful learner. This includes explicit and hidden curriculum as well as the idea that curriculum can be broken into simpler elements relating to: (1) the type of knowledge students are asked to develop, (2) the way that learning is intended to occur, and (3) its reason for inclusion. I define curriculum by those three elements. To explore the curriculum of teachers, it is useful to consider questions such as "(1) why should we teach this rather than that? (2) who should have access to what knowledge? (3) what rules should govern the teaching of what has been selected? and (4) how should the various parts of the curriculum be interrelated in order to create a coherent whole?" (Kliebard, 1977, p. 262). The answers to these types of questions offer deeper insight into the nature of an individual teacher's curriculum and provide an opportunity to understand how it might continue to be shaped by their curricular knowledge as well as orientations to the teaching and learning of science (See Figure 7).

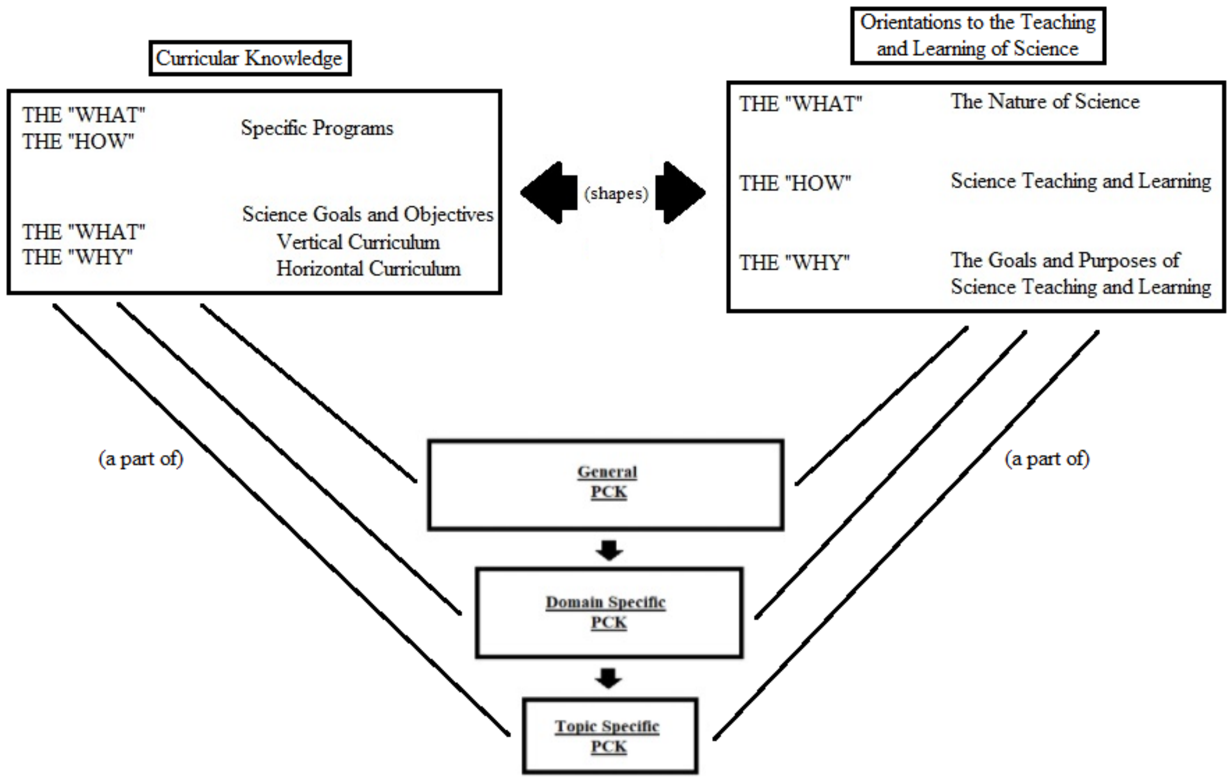


Figure 7. Relationship between Elements of PCK and Curriculum. Adapted from P. Friedrichsen et al. (2011), J. Gess-Newsome (2015), A.V. Kelly (2004), S. Magnusson et al. (1999), and W. R. Veal & J. G. Makinster (1999).

Focusing on the "why" of teacher curriculum, the purpose for student learning, as well as the form(s) of knowledge demanded are particularly useful in understanding how teachers' curricular decisions (enacted curriculum) are shaped by their curricular knowledge. Orientations to the teaching and learning of science, particularly teachers' understanding of the purpose for science teaching and learning provides a clear link to the "why" of the composition of their curricula and has already been explored at the whole curriculum level (Burt & Boesdorfer, 2021) in chemistry classrooms in Illinois. In that study, several topics represented in the state standards (e.g., equilibrium chemistry, kinetics, nuclear chemistry) were not widely represented in teachers' curriculum while other topics not explicitly covered in the state standards (e. g. nomenclature, predicting products & classifying types of reactions) received a much greater depth of emphasis in general. Differentiating between the curriculum at the domain or macro-level (year-long) and the topic-specific level (individual learning segments) allows for greater precision in attempts to understand how teachers' science teacher orientations shape the ways that they operationalize their content knowledge and knowledge of curriculum in their enacted curriculum. In this study, nuclear chemistry and kinetics will serve as the topics that will be examined in greater depth to better understand how they are shaped by teachers' curricular knowledge and orientations to the teaching and learning of science.

CHAPTER III: METHODOLOGY

As described previously, efforts to understand the nature of teachers' chemistry curricula require a deeper examination of the enactment of individual topics in practice as well as its intersection with the specific professional knowledge employed in those efforts. Using a qualitative design (Plano Clark & Creswell, 2010), multiple forms of qualitative data were collected to explore how several components of PCK (subject matter knowledge, curricular knowledge, science teacher orientations) play a role in the composition of a nuclear chemistry unit compared with one relating to the topic of kinetics. A qualitative approach utilizing multiple sources of data: (1) semi-structured interviews, (2) the completion of a content representation (CoRe) tool, and (3) document analysis of unit assessment(s) afforded a greater understanding of questions relating to "how", which is central to the research questions posed (Yin, 2018). The case in this context would represent the teaching of introductory chemistry at the high school level, particularly in terms of nuclear chemistry and kinetics. Institutional Review Board (IRB) approval was obtained prior to starting the collection of data and participants completed an informed consent to participate.

Research Questions

This study was guided by the following research questions:

1. Why do certain topics included in the standards (nuclear chemistry or kinetics) receive differing levels of attention across different experienced teachers' introductory chemistry curricula?

2. How do teachers' curricular knowledge and orientations to the teaching and learning of science influence their decisions relating to their chemistry curricula (a form of their enacted PCK)?

In order to understand the role that elements of teacher PCK play in the planning and continued development of secondary teachers' chemistry curricula, the second research question was able to be more thoroughly explored using two topics in chemistry: nuclear chemistry and kinetics. Two sub-questions that will further clarify the second research question are:

2a. How do teachers' curricular knowledge and orientations to the teaching and learning of science influence their enacted curriculum with respect to the topic of nuclear chemistry?

2b. How do teachers' curricular knowledge and orientations to the teaching and learning of science influence their enacted curriculum with respect to the topic of kinetics?

Definition of Terms

The following terms will be used throughout the study and are derived from the literature and research described in the preceding chapters.

1. Curriculum includes the form(s) of knowledge prioritized, the way that learning is structured to develop that knowledge, and the purpose for student learning.
2. Enacted curriculum refers to the specific content included or excluded from the cycle of learning experiences as well as the set of material resources and assessments offered by a teacher.
3. Pedagogical content knowledge (PCK) refers to the specific knowledge required to teach science or any domain within the field (e.g., chemistry) and includes the influence of

subject matter knowledge, science teacher orientations, curricular knowledge, knowledge of students, pedagogical knowledge, and assessment knowledge.

4. Subject matter knowledge, a component of PCK, refers to an individual's knowledge of specific chemistry concepts, the interrelationships amongst chemistry concepts, and broader relationships between those concepts and other topics in science.
5. Curricular knowledge refers to a teacher's knowledge and understanding about the specific science goals and objectives, the structure, composition, and purpose of existing curricular programs, and their ability to assess the coherence of a given curriculum.
6. Science teacher orientations, or orientations to the teaching and learning of science, refers to a teacher's understandings or beliefs about (a) the goals and purposes of science teaching, (b) the nature of science, and (c) science teaching and learning.

Data Collection

In order to understand the nature of PCK's influence on the teaching of nuclear chemistry and kinetics, elements of individual chemistry teachers' reported PCK were explored using a multiple, or collective, case study (Creswell, 2008; Yin, 2018). For each topic, individually, teachers participated in a semi-structured interview, completed a CoRe tool, and submitted copies of the assessment(s) intended for use during that unit in their class. These sources of evidence (interviews and artifacts) are among the most common forms of evidence used in case study research (Yin, 2018). The process of document analysis offers the unique ability to assist in triangulation with other forms of qualitative data already collected (e.g., semi-structured interviews) and serves as an important check against biases inherent to qualitative research (Bowen, 2009). A short follow-up interview was conducted following the completion of data analysis to serve as an opportunity for member checking to aid in establishing trustworthiness and validity of findings for each participant in the case study prior to undertaking cross-case analysis (Creswell, 2008; Plano Clark & Creswell, 2010). See Table 2 for a visualization of the data collection timeline for each participant.

Table 2

Data Collection Timeline for Grace & Ellie.

Participant: Grace	
Sequence/Order	Event
1	Nuclear Interview (Semi-Structured Interview)
2	Kinetics Interview (Semi-Structured Interview)
3	Nuclear CoRe (CoRe Document Completion)
4	Nuclear Assessment (Assessment Collection and Submission)
5	Kinetics CoRe (CoRe Document Completion)
6	Kinetics Assessment (Assessment Collection and Submission)
7	Member Check (Nuclear Chemistry & Kinetics)
Participant: Ellie	
Sequence/Order	Event
1	Nuclear Interview (Semi-Structured Interview)
2	Nuclear CoRe (CoRe Document Completion)
3	Nuclear Assessment (Assessment Collection and Submission)
4	Kinetics Interview (Semi-Structured Interview)
5	Kinetics CoRe (CoRe Document Completion)
6	Kinetics Assessment (Assessment Collection and Submission)
7	Member Check (Nuclear Chemistry & Kinetics)

Semi-Structured Interviews

The use of a semi-structured interview is ideal because it allows for greater consistency between data collected from individual cases while maintaining flexibility to ask additional questions if unexpected information is offered (Brinkmann & Kvale, 2015; Corbin & Strauss, 2015). During a telephone interview, teachers were individually asked to respond to questions eliciting information about their curricular knowledge (vertical and horizontal as well as knowledge about specific curricular programs and the goals and objectives), science teacher orientations (particularly the goals and purposes of science teaching and science teaching and learning), and subject matter knowledge. As part of the interview, participants were audio recorded and asked to identify the important ideas or concepts that are covered in nuclear chemistry and kinetics units which will represent the first part of the CoRe tool completed for each topic (See Appendix B).

To address potential inconsistencies or structural problems with the qualitative method, a truncated pilot study took place beforehand. The interview protocol was conducted with a pilot case to identify and correct potential issues with the protocol (Yin, 2018), though no changes were made in this instance. After receiving the case study participants' completed informed consent forms, they were asked to individually participate in a semi-structured interview in which they answered approximately 11 open-ended questions designed to elicit information about elements of teachers' PCK (See Appendix A for interview protocol). Science teacher orientations, subject matter knowledge, and knowledge of curriculum were all addressed in the questions and were adapted from earlier studies (Burt & Boesdorfer, 2021; Luft & Roehrig, 2007).

CoRe Document

Completing the content representations (CoRe) tool requires teachers to answer questions about a specific topic and includes: (1) what is the importance of learning about this topic?, (2) what are some difficulties or limitations in teaching this topic to your students?, (3) what other factors influence your teaching of this topic?, (4) what are your procedures for teaching each topic within this unit (and why?)?, and (5) how do you know when students understand or are experiencing confusion while learning this topic? Kind (2009) described the CoRe as "…the most useful technique devised to date for eliciting and recording PCK directly from teachers" (p.

195). Since this tool allows teachers to offer evidence of their topic-specific knowledge and beliefs as well as how they view a given topic fitting into their larger curriculum, it holds a great deal of promise for uncovering teacher PCK that relates to the teaching and learning of nuclear chemistry and kinetics.

After completing the semi-structured interview for a nuclear chemistry (the first topic explored), teachers were sent an electronic version of the CoRe tool (See Appendix B for a blank template) pre-populated with the major topics they identified during the semi-structured interview. Participants were instructed on how to complete each section of the tool and given a timeline for submission. A new CoRe tool was sent to each teacher for the topic of kinetics after the respective semi-structured interview was complete. In this study, the specific nuclear chemistry and kinetics topics identified were somewhat unique to each individual and allowed participants to be responsive to the components they believed to be core to a nuclear chemistry or kinetics unit.

Class Assessments

Following completion of the CoRe tool, teachers were asked to provide copies of any relevant assessments (e.g., tests, performance assessments) that relate to the topics of nuclear chemistry and/or kinetics. Obtaining and analyzing copies of major assessments given during each unit as well as final exams served as critical artifacts for analysis as part of the larger case study methodology. These took the form of multiple-choice, short answer, or practice-based performance assessments and were analyzed using a similar coding scheme as the semi-structured interviews (Bowen, 2009; Yin, 2018).

Follow-up Interview

A brief follow-up interview over the telephone was conducted individually with each participant to discuss the preliminary analysis based on their initial interview, CoRe template completion, and/or assessment(s) provided for both nuclear chemistry and kinetics (See Appendix C for sample protocol). This interview provided a critical opportunity for member checking (Creswell, 2008; Plano Clark & Creswell, 2010) and ensured that the data collected and analyzed was considered by each participant to be complete, realistic, and the themes that emerged were complete. Based on those conversations, there were opportunities to seek additional clarification or allow participants to clarify any data that was presented that they felt may not accurately reflect their attitudes, beliefs, and/or practice. Given the iterative approach inherent to qualitative research, this step allowed for any significant gaps in understanding to be filled as well as to correct any researcher misunderstanding (Yin, 2018).

Data Analysis

Prior to the coding and analysis of interview data, a preliminary research memo was drafted to preserve impressions following each interview (Corbin & Strauss, 2015). This allowed initial impressions, observations, and further questions generated as part of the dialogue to be preserved and referenced for subsequent analysis or used during the member check. Analysis did not occur on the same day as each of the interviews. Data collected from interviews was transcribed verbatim and analyzed using preliminary exploratory analysis (Creswell, 2008). To ensure participant confidentiality and privacy, individual identities were kept anonymous by destroying initial audio recordings after being transcribed and pseudonyms were used throughout the data analysis and reporting. Following the initial coding, themes were developed based on the relationships to the key components of the research question (e.g., curricular knowledge and science teacher orientations) and their relevance to individual elements of PCK and curriculum. While responses to each interview question varied, Table 3 depicts the areas of study intended to be addressed in each question. Responses relating to nuclear chemistry were analyzed separately from those relating to kinetics, though the final analysis includes a comparison of the findings related to each topic in context of the larger chemistry curriculum of teachers.

To address the first research question, teachers' perceptions of the complexity of intended student learning, reasons that students should be learning about the topic, and the topic's role in their larger chemistry curriculum were of particular importance. The follow-up interview provided a necessary opportunity to confirm teachers' perceptions about each topic's relative importance and the amount of class time needed to adequately support student learning. Cross-case analysis enabled comparisons to be made between the time and depth allocated to each topic and were used as the basis to understand potential differences between topics that may be more prominent in a particular teacher's curriculum compared to those that might receive comparably less emphasis. Answers to these questions were used to develop a description of the teacher's goals and teaching practice related to each topic.

Table 3

Alignment of Interview and CoRe Tool Questions with Research Questions.

Component of PCK	Interview Question	Element of Curriculum
Semi-Structured Interview Questions		
Knowledge of Curriculum (KoC): Specific Programs	Are you aware of any other approaches to teaching (*topic*)?	----------------------------------
KoC: Goals & Purposes Science Teacher Orientations (STO): Goals & Purposes	What do the standards say about (*topic*)?	----------------------------------
	How do you decide what to teach in this unit?	Type of Knowledge, Why Knowledge is Valued
	What do you believe is the purpose of a unit relating to (*insert topic here*)?	Type of Knowledge, Why Knowledge is Valued
	How does this unit fit into your chemistry curriculum?	----------------------------------
	How would you respond to a student asking, 'when will we ever use this?'	Type of Knowledge, Why Knowledge is Valued
STO: Science Teaching & Learning	What do students already know that they will need to use or apply?	----------------------------------
	How do you know when learning is occurring?	Type of Knowledge, How Knowledge is Learned
----------------------------------	Tell me about your (*topic*) unit.	How Knowledge is Learned
CoRe Tool Questions		
Subject Matter Knowledge (SMK)	Big Idea A, B, C, etc.	Type of Knowledge
	What else do you know about this idea (that you do not intend students to know yet)?	----------------------------------
KoC: Goals & Purposes	What do you intend the students to learn about this idea?	Type of Knowledge, How Knowledge is Learned
STO: Goals & Purposes	Why is it important for students to know this?	Why Knowledge is Valued
STO: Science Teaching & Learning	What are the difficulties/limitations connected with teaching this idea?	Type of Knowledge, How Knowledge is Learned
	What is your knowledge about students' thinking that influences your teaching of these ideas?	Type of Knowledge, How Knowledge is Learned
	Specific ways of ascertaining students' understanding or confusion around this idea.	How Knowledge is Learned
	What are your teaching procedures (and particular reasons for using these to engage with this idea)?	How Knowledge is Learned

Note: The use of (topic) refers to either nuclear chemistry or kinetics, depending on the interview being conducted.

For the next layer of analysis, responses to understand how the teacher's intended curriculum were collected from an individual teacher's semi-structured interview and CoRe document. These transcripts were duplicated and, on the duplicated copy, each statement from the interviewer was removed while each sentence that was spoken by the participant separated into individual segments (one segment per sentence). Each of the segments were coded as either "x", "1", "2", or "3" (See Table 4 for a list and explanation of codes). The total numbers of each code were added, and frequencies calculated without using excluded (x) segments. Based on the results of the analysis of the semi-structured interviews, similar codes for each topic were developed for participant responses provided on the CoRe tool and data tallied, presented individually as well as in aggregate with those obtained from the semi-structured interview throughout chapters four and five. This represented an initial data point to begin to understand how each participant understood and defined student knowledge for each unit. These themes serve as a basis for understanding the nature of teachers' curricula as well as elements of PCK.

Table 4

Codes, Definitions, and Sample Responses for the Analysis of Individual Teacher Statements (collected from Semi-Structured Interview and CoRe).

Code	Definition	Sample Response
x	Not related to concept of knowledge	"Yeah" "You've got me thinking"
1	Content: Identification of knowledge as discrete chemistry content	"We go through, and we start with alpha, beta, and gamma decay and talk about that" "$E=mc^2$"
2	Product: Identification of knowledge based on pre-determined outcomes	"We look at the nuclear reactor and how the control rods absorb some of the neutrons and so it slows down the reactions, so we look through a lot of the things like that, so the kids have an idea what nuclear is used for" "...evaluation of energy like where it's coming from and where it's going and how you know qualitatively how much it is"
3	Process: Identification of knowledge based on personal relevance	"...it's your future ability to assess information and decide how that affects you" "In researching the same topic from various perspectives or roles, students begin to shape their research to fit what they are looking for"

Initially, assessment documents for each topic were examined and coded based on the type of knowledge it intended to elicit from students to help gain insight into how each teacher portrays the nature of nuclear chemistry or kinetics within their chemistry curriculum. Initial assessment coding steps involved assigning a code based on the type of question that students were asked to respond to—either factual/recall, algorithms, or conceptual questions (See Table 5 for a list and explanation of codes). The totals for each of those categories were used to calculate frequencies and presented in chapters four and five, as appropriate.

Table 5

Codes, Definitions, and Sample Responses for the Analysis of Individual Teacher Summative Assessments.

Code	Definition	Sample Response
Factual/Recall	Requires students to recognize or identify key vocabulary words or static relationships (Anderson, Krathwohl et al., 2001; Koufetta-Menicou & Scaife, 2000)	Half-life is a. the time it takes for half of the atoms to decay b. half the time it takes for all the atoms to decay c. half the time it takes for 1 atom to decay d. half the time that you need to worry about storage of the waste The energy released in a nuclear reaction comes from a. electrons b. bonds c. positrons d. nuclei
Algorithms	Procedures for getting "right" answers to routine tasks or problems (Herron, 1996; Nurrenbern & Pickering, 1987)	When balancing nuclear equations, what do you use to determine which element is produced? a. number of protons b. mass number c. what type of particle is released d. it's the same as the original element The Cs-131 nuclide has a half-life of 30. years. After 150 years, 3.0 grams remain. The original mass of the Cs-131 sample is closest to a. 167 g b. 42 g c. 96 g d. 292 g
Conceptual	Requires students to justify, predict, or explain using deeper analysis and critical thinking (Zoller & Tsaparlis, 1997)	If a loved one was diagnosed with cancer after increased radon exposure and is strongly opposed to radiation treatment, what information might they need to further understand the cause and treatment of their disease? A question you have written to answer to improve and demonstrate your knowledge of nuclear chemistry topics but that appeals to your interests, experiences, curiosities, etc.

Assessment questions were also coded for alignment to each of the big ideas a given teacher identified in their semi-structured interview (See Tables 8 and 11 in chapter four and Table 16 in chapter five). Questions that related to more than one of the big ideas identified were counted and the frequency data used to represent the percentage of questions that relate to each of the big ideas for each teacher and within each unit.

Additionally, the assessments collected provide further insight into the way that science teacher orientations influence the way that teachers' curricular knowledge is operationalized in the form of their curriculum plan. As one source of data within a larger case study, the presence of teacher assessments offers an opportunity to assist in triangulation to enhance the validity of data collected in the study (Bowen, 2009). Each individual teacher's interview, CoRe tool responses, and assessment serve as opportunities to understand the nature of each participant's view of a nuclear chemistry and kinetics unit as well as its role in their larger chemistry curriculum as intended, prior to engaging in classroom instruction.

Participants

Based on the collective case study method, participants were identified using convenience sampling (Creswell, 2008). The purposive identification of participants represented a two-phased approach to screening (Yin, 2018). The potential pool of participants was initially reduced by using criteria of years of experience, gender, setting, and whether they currently teach a unit on nuclear chemistry or kinetics. Using homogeneous sampling (Creswell & Plano Clark, 2018), participants were selected that are both experienced (having taught chemistry for five years or more) and currently teach nuclear chemistry and kinetics in their classes to *some* extent (more than zero days of class time). Two participants were selected to enable cross-case analysis to occur more readily and provide greater opportunities to address the research question and provide theoretical replication, aiding in reliability of findings (Yin, 2018). The same data was requested from each of the participants. These participants were selected, initially, using data collected from a previous study in which the extent of topic coverage was elicited (Burt & Boesdorfer, 2021) and who had indicated that they would be willing and interested in being contacted to participate in future research.

Participant #1 (Grace)

Grace primarily teaches chemistry (and is the only chemistry teacher in her building), but occasionally teaches biology, AP chemistry, and other courses. Her initial bachelor's and master's degrees were in athletic training, but she completed an alternative certification pathway that allowed her to begin teaching at the high school level. She has completed 20 years of teaching and currently teaches at a large rural high school in Illinois. Prior to teaching at her current school Grace taught for several years at a separate, smaller rural high school in the same geographic area.

Grace's formal chemistry education largely included the requirements for her degrees in athletic training, but she did mention that her teacher certification program required an additional chemistry course to pursue state licensure, which she completed. She cited her own independent learning and participation in professional developments as her only other significant opportunities to develop additional chemistry content knowledge beyond her university education.

Participant #2 (Ellie)

Ellie currently teaches chemistry (and is the only chemistry teacher in her building) at a small rural high school in Illinois and has completed ten years of teaching, nine at her current school and one at a comparably sized school in the same geographic region. Four years after starting at her current school, she took a six-year break from the classroom and returned to teaching and has continued to work there for the past five years. Her current school uses a block schedule. Ellie's educational background includes a bachelor's degree in chemical engineering and a master’s degree in agricultural biosystems engineering before later completing an alternative certification program for teaching. After completing her master’s degree, but before pursuing licensure as a teacher, Ellie worked in technical sales and in related work to her engineering background.

Since becoming a teacher, she has completed additional coursework, particularly courses that related to a certificate in leadership education that she is in the later stages of completing. While none of her formal post-certification coursework has related to the teaching of science or chemistry, Ellie cited her own independent research and professional developments, such as the National Science Teaching Association’s (NSTA) annual conference, as her primary forms of post-graduate learning that relates to the teaching of science and chemistry.

Human Subject Protocol

Prior to data collection, approval was obtained from the Institutional Review Board (IRB) to ensure the ethical treatment of participants and minimize potential risks of undertaking this study. All participants signed informed consents prior to the beginning of the data collection.

CHAPTER IV: FINDINGS (NUCLEAR CHEMISTRY)

Participant #1 (Grace)

Overview

Grace identified the origin of her unit on nuclear chemistry as the direct result of several professional development sessions and explained that the unit was added to her chemistry curriculum following the state's adoption of NGSS. She identified four "big ideas" that guide student learning within the unit: conservation of mass, reactions, atomic structure and the Periodic Table of the Elements, and energy. Grace explained that for students to engage with the unit, they needed to already know about the composition of the nucleus (protons, neutrons, electrons), have an ability to navigate the structure of the Periodic Table of the Elements, and understand atomic mass along with its relationship to a given isotope's number of neutrons. She believes that, at its core, the unit serves to reinforce the ideas that everything is made of atoms, that energy comes from breaking those atoms apart, and that the quantity of atoms or particles is uniquely important. Grace suggested that the unit had relevance to the real-life consequence of radiation exposure, such as with radon.

This unit takes place during the first semester of her introductory chemistry course, follows a unit on the Periodic Table, and precedes a unit on chemical bonding. Within her nuclear chemistry unit, Grace primarily uses lecture and whole-class discussion to engage students with the content, organizing it in "...a packet of all the [activities] together" (Member Check). Activities used were sourced from textbooks, professional developments, PhET (n.d.) simulations, process oriented guided inquiry learning (POGIL) activities from Trout (2012), and others. Grace identified concepts included in her unit such as alpha, beta, and gamma decays, writing and balancing nuclear equations, half-life, penetrating power, and the equation for mass-energy equivalence's relationship to energy involved in nuclear processes. The unit is primarily assessed through a forced-choice multiple question test that Grace said she got "...from a textbook company and I picked out questions from that" (Member Check).

The Nuclear Chemistry Curriculum

Grace typically starts her unit on nuclear chemistry with a video on the bombings of Hiroshima and Nagasaki that includes a brief description and visuals of the bombs used. Following the video, she asks students to sketch out the processes taking place and collects the models. At the end of the unit, she repeats this activity with students and provides their initial models for comparison. Grace said that "[by the end of the unit] it's a riot how much it changes because they kind of understand what's going on now" (Nuclear Interview). For Grace, this form of understanding represents the successful mastery of the content she includes within the unit. She reports that students tend to enjoy this unit and is one that she uses to wrap up the first semester in her introductory chemistry classes.

During the initial semi-structured interview, Grace was asked to explain how nuclear chemistry fits within her entire chemistry curriculum, and she suggested that it "fits right after talking about atomic structure because students can relate it to the atomic structure after we've talked about electrons, protons, neutrons and we just tie it into that, and it makes a lot of sense" (Nuclear Interview). This explanation reinforces her view that the curriculum should be organized to allow new learning to be utilized in subsequent units as her students progress through the year's curriculum. Grace repeatedly referred to student knowledge in terms of discrete content, with 57.9% of her statements made throughout the interview and the self-completed CoRe document focusing on knowledge as content compared to either knowledge as product or knowledge as process (Table 6). Similarly, she described student knowledge in terms of process in only 2.6% of her statements.

Table 6

Codes, Definitions, Sample Responses, and Frequencies for Grace's Descriptions of her Unit on Nuclear Chemistry and its Purposes and Structure.

Code	Definition	Sample Response	Frequency
Content	Identification of knowledge as discrete chemistry content	"Everything [that] exists is atoms" "We've talked about conservation of mass and talked about atomic structure and it's almost a review for them to go through that material again"	57.9%
Product	Identification of knowledge based on pre-determined outcomes	"One particle breaking has a little bit of energy, but if you have million particles breaking apart, we have these huge explosions so that definitely ties into energy" "We tested for radon in our basement, and we had a huge high level of radon, so you guys need to understand that if you breathe that in, what is that going to do to your body?"	39.5%
Process	Identification of knowledge based on personal relevance	"Looking at the nucleus and looking all the way up to relating it to the nuclear reactors and things that are actually used in real life"	2.6%

Through her semi-structured interview and CoRe (See Appendix D for full CoRe), Grace identified four separate "big ideas" that students should be engaging with throughout the unit. "Big Idea #1" related to the Law of Conservation of Mass, where Grace explained that she hopes students learn that “the nucleus that is at the beginning of the reaction will break into smaller nuclei that will add together to have the same # of protons and neutrons” (Nuclear CoRe). She went on to explain that this idea can be challenging for students in certain contexts such as “when neutrons break into a proton and [an] electron” during beta decay. She elaborated to say that she sees this as ‘conceptual’ which causes students to “have a hard time visualizing what is really going on” during similar types of radioactive decay.

Grace identified reactions as a second “big idea” within the unit, explaining that at its core, she wanted students to be able to understand that a reaction starts with “reactants and end[s] with products” (Nuclear CoRe). She connected this idea with a later topic, balancing chemical equations, citing lack of familiarity as a reason she perceived nuclear equations to be challenging for her students. She explained that this is “very conceptual and [students] have not balanced any equations yet, so this can be difficult for them” (Nuclear CoRe). To address these issues, Grace uses “worksheets with examples of nuclear equations and have them balance them…[and]…once we draw them out, they start to catch on” (Nuclear CoRe).

The third identified “big idea” related to atomic structure and the Periodic Table of the Elements. Grace explained that students need to be able to use the periodic table to understand that “larger elements that contain more protons and neutrons are the ones that are more unstable” (Nuclear CoRe). In doing so, it appears that students are largely asked to identify the numbers of protons and/or neutrons in an element already presented as being unstable and undergoing a form of radioactive decay.

“Big Idea #4” was related to the role of energy in nuclear processes and was one that Grace quickly tied to $E = mc^2$ where she explained that “it basically proves the law of conservation of mass (energy) and shows how a nuclear reaction can give off so much energy”

(Nuclear CoRe). She suggested a natural connection to the topics of fission and fusion and used those as examples of how students engage with this idea. Because she viewed the math that relates to this idea (e.g., mass defect or nuclear binding energy calculations) to be incredibly difficult for students to perform and understand, Grace said that she does not incorporate these topics when assessing this "big idea".

Student learning throughout the nuclear chemistry unit is summatively assessed in the form of a 60-question forced-choice paper test that relates to much of what students were taught and asked to learn. Questions were initially coded and classified as either factual/recall, algorithmic, or conceptual (See Table 7). The factual or recall-based questions that require students to simply recognize or identify key pieces of information that relate to nuclear chemistry account for 56.7% of questions asked. Algorithmic questions require students to apply a formula or patterns to make a prediction or interpret a result, such as what a decay product would be if a given isotope underwent a particular form of radioactive decay. On this assessment, 36.7% of items asked questions requiring the use of some type of algorithm relating to nuclear chemistry. Only 6.6% of questions were coded as conceptual in nature and where students would be asked to justify, explain, or predict beyond the simple use of an algorithm or the recollection of simple facts or relationships. No questions overlapped multiple categories.

Table 7

Codes, Definitions, Sample Responses, and Frequencies for the Questions Included on Grace's end of Unit Assessment on Nuclear Chemistry.

<table>
<tr><th>Code</th><th>Definition</th><th>Sample Response</th><th>Frequency</th></tr>
<tr><td>Factual/Recall</td><td>Requires students to recognize or identify key vocabulary words or static relationships (Anderson, Krathwohl et al., 2001; Koufetta-Menicou & Scaife, 2000)</td><td>The nucleus left over after a nuclear reaction is called the
a. daughter nucleus
b. secondary nucleus
c. smaller nucleus
d. nuclear nucleus

What does the 4 in equation $^{4}_{2}He$ represent?
a. the mass number
b. the atomic number
c. the number of protons
d. the number of neutrons</td><td>56.7%</td></tr>
<tr><td>Algorithms</td><td>Procedures for getting "right" answers to routine tasks or problems (Herron, 1996; Nurrenbern & Pickering, 1987)</td><td>What particle does argon-39 (atomic number 18) emit when it decays to potassium-39 (atomic number 19)?
a. neutron
b. electron
c. proton
d. alpha particle

When uranium-238 (atomic number 92) decays by emitting an alpha particle, it becomes ____.
a. thorium-234
b. radium-236
c. uranium-234
d. radium-234</td><td>36.7%</td></tr>
<tr><td>Conceptual</td><td>Requires students to justify, predict, or explain using deeper analysis and critical thinking (Zoller & Tsaparlis, 1997)</td><td>In a nuclear reaction, unstable nuclei that change their number of protons and neutrons,
a. give off large amounts of energy, and increase their stability
b. give off small amounts of energy, and increase their stability
c. give off larger amounts of energy, and decrease their stability
d. give off small amounts of energy, and decrease their stability

Table 1 Half-lives of Several Radioactive Nuclides
<table><tr><th>Nuclide</th><th>Half-life (years)</th></tr><tr><td>carbon-14</td><td>5.71×10^{3}</td></tr><tr><td>potassium-40</td><td>1.26×10^{9}</td></tr><tr><td>radium-226</td><td>1.60×10^{3}</td></tr><tr><td>thorium-230</td><td>7.54×10^{4}</td></tr><tr><td>uranium-235</td><td>7.04×10^{8}</td></tr></table>
According to Table 1, the appropriate radioactive isotope to use to estimate the age of a rock from a rock formation believed to be a billion years old is
a. carbon-14
b. potassium-40
c. radium-226
d. thorium-230</td><td>6.6%</td></tr>
</table>

The summative assessment that Grace uses in this unit was also coded based on its alignment to each of the "big ideas". "Big Idea #1" accounted for 30.0% of the questions asked while the second "big idea" was represented in 41.7% of all questions (See Table 8). The most well-represented, "Big Idea #3", accounted for 48.3% of questions, but none of those problems required students to determine whether a given element was stable or unstable, a characteristic of the "big idea" that had been identified in the CoRe. Instead, those questions largely focused on using the Periodic Table and knowledge of atomic mass to determine the number of various subatomic particles. Of the four "big ideas" that Grace offered, the fourth was the least represented on the summative assessment with only 5.0% of the questions coded related. Any question that related to more than one "big idea" was able to be coded multiple times.

After analyzing the coded questions on the summative exam, 31.7% of the questions were not specifically tied to any of the four "big ideas" that Grace named (See Table 8). These questions related to topics such as half-life, penetrating power of radiation, and others. While these topics are not directly related to any of the stated ideas in the way that Grace explained them, the peripheral connections do not appear to be made with students within the unit itself either. When asked about this, Grace mentions that she uses half-life to "...show how nuclear is used in real life" (Member Check) in the context of carbon dating and topics like penetrating power of radiation to talk about why "...when you go to the dentist the put that lead cape on you to protect you from x-rays..." (Member Check).

Table 8

Codes, Definitions, Sample Responses, and Frequencies for the Questions Included on Grace's end of Unit Assessment on Nuclear Chemistry and Alignment to Grace's Identified "Big Ideas".

Code	Definition	Sample Response	Frequency
Big Idea #1	Conservation of Mass	The nucleus left over after a nuclear reaction is called the a. Daughter nucleus b. Secondary nucleus c. Smaller nucleus d. Nuclear nucleus What does the 4 in equation ${}^{4}_{2}He$ represent? a. The mass number b. The atomic number c. The number of protons d. The number of neutrons	30.0%
Big Idea #2	Reactions	To what element does polonium-208 (atomic number 84) decay when it emits an alpha particle? a. ${}^{210}_{82}Pb$ b. ${}^{210}_{82}Po$ c. ${}^{204}_{82}Pb$ d. ${}^{214}_{86}Rn$	41.7%
Big Idea #3	Atomic Structure, Periodic Table of the Elements	When balancing nuclear equations, what do you use to determine which element is produced? a. number of protons b. mass number c. what type of particle is released d. it's the same as the original element Alpha particles consist of a. 2 protons and 2 neutrons b. 2 neutrons and 2 electrons c. Energy d. 2 protons and 2 electrons	48.3%
Big Idea #4	Energy	The energy released in a nuclear reaction comes from a. electrons b. bonds c. positrons d. nuclei An unstable nucleus ___. a. increases its nuclear mass by fission b. increases its half-life c. emits energy when it decays d. expels all of its protons	5.0%

(Table Continues)

Table Continued

None	Not specifically aligned to any identified big idea(s).	What is the half-life of an isotope if 125 g of a 500 g sample of the isotope remains after 3.0 years? a. 1.5 years b. 2.5 years c. 3.5 years d. 4.5 years Which of the following materials is necessary to stop an alpha particle? a. three feet of concrete b. three inches of lead c. single sheet of aluminum foil d. single sheet of paper	31.7%

Note: An asterisk (*) is used to indicate a question that relates to more than one "big idea".

PCK

Subject-Matter Knowledge

Grace was able to identify many of the discrete content elements included in the DCI of the relevant NGSS PE relating to nuclear chemistry, such as alpha or beta decay, fission or fusion, or the importance of energy. During the semi-structured interview, she explained that most of her curricular materials (and content knowledge) for this unit came from a professional development workshop held at a local nuclear plant. She said in the member check interview that she "never really thought about [nuclear chemistry]" when planning her chemistry curriculum each year before the state's adoption of NGSS and before attending the professional development she mentioned. She went on to explain that she knew that nuclear reactors existed and that a nuclear bomb had "gone off", but that was largely the extent of her knowledge. She clarified that she began to fill in those gaps in content knowledge at that initial professional development workshop and continued to develop her understanding as she began (and continued) to teach the topic in her classes.

Knowledge of Curriculum: Specific Programs

When asked to consider alternative ways of teaching nuclear chemistry, Grace suggested that putting greater emphasis on energy might be a viable option. She explained that "I could probably do more with the reactions…and go through more with endothermic, exothermic, more tie it into thermo too maybe" (Nuclear Interview). While energy had previously not been an area of emphasis on her summative assessment for the unit (see Table 8), Grace was not able to specifically articulate what an assessment with greater emphasis on energy might look like. Textbooks, POGIL activities sourced from Trout (2012), and assorted materials from a professional development activity done at a local nuclear plant serve as the major resources available to her. She also cited some phenomena that she thought could be incorporated such as "level[s] of radon…medical procedures…" (Nuclear Interview). No other ways of teaching this unit were able to be identified aside from explaining that she sometimes does not have enough time for students to complete a radiation exposure inventory and other activities she had in her resource binder for the unit.

Knowledge of Curriculum: Science Goals and Objectives

Grace's nuclear chemistry unit is intentionally structured to allow students' prior knowledge, developed in the unit on the periodic table, to be used to make sense of the inputs and outputs of radioactive decay. She did not mention any concerns about performance in later science courses, collegiate success, or any other context as a concern that continued to guide her unit structure or decision making related to her nuclear chemistry unit.

Following this topic is a unit on chemical bonding that Grace suggests is tied in as an extension of nuclear chemistry. When questioned more about this horizontal alignment between nuclear chemistry and chemical bonding, Grace said that "[I] need to work on that and relating it more to bonding. I think I relate it more probably later when we get into chemical reactions" (Nuclear Interview). After additional questioning during the interview, she was unable to provide any concrete connections she uses or thinks of when relating nuclear chemistry to chemical bonding despite her initial suggestion that those topics were closely aligned (horizontally).

The relationships between each topic or idea within the unit appear to be largely separate from one another. For example, students are not using half-life as a tool to understand relative stability nor are they crafting models to make predictions about the relative stability of a given isotope. In that sense, students appear to learn about each type of radioactive decay in isolation from one another, about half-life as a means to determine the age of certain objects, and penetrating power as a characteristic of radiation, but unconnected to previous topics.

After Grace explained that she began incorporating a nuclear chemistry unit following the adoption of NGSS, she cited a series of professional development sessions she had attended that served as the primary resource for this unit—as well as a significant source of her knowledge about the topic in general. She went on to explain that "NGSS really relates [nuclear chemistry] to conservation of mass" and emphasized its connection to the nucleus and atomic structure in general (Nuclear Interview). Grace did not mention any science and engineering practices or crosscutting concepts that play a role in her construction or understanding of the unit. She repeatedly identified the Law of Conservation of Mass as a significant driving force behind the unit. She also explained that it served to reinforce past material as "…it's almost a review for them to go through that material again…and it's a good tie for the semester and wraps everything up" (Nuclear Interview). Similarly, in the CoRe document that she completed, Grace stated that energy is important to discuss because "it basically proves the law of conservation of mass (energy) and shows how a nuclear reaction can give off so much energy". Despite this, Grace only holds students accountable for the role of energy in only 5.0% of the questions found on the summative assessment.

The process of developing a unit related to nuclear chemistry was one that Grace clarified was more coincidental than by an explicit need she identified following the state's adoption of NGSS. She explained that she received an email solicitation out of the blue for a professional development workshop hosted by a local nuclear plant and "...it just happened at the same time [as NGSS being adopted] because I need to be teaching this anyway and they had quite a program [at the professional development workshop] set up. They had a whole packet there for us with all kinds of labs and they had it set up nicely for teachers" (Member Check).

Science Teacher Orientations

Grace's views about the goals and purposes of science teaching and learning that relate to nuclear chemistry appeared to be more aligned to students amassing information rather than problem solving. She repeatedly explained in the interview and throughout the CoRe document that students had ample opportunities to show how the Law of Conservation of Mass is related to nuclear processes, but also structures her unit as a series of discrete ideas (radioactive decay, fission/fusion, half-life, and characteristics of radiation). In her CoRe document, she mentioned the Law of Conservation of Mass five separate times out of nine explicit statements relating to goals for the unit. She did not discuss the intersections and overlap between these ideas or concepts within the unit. Similarly, these ideas are largely assessed as factual pieces of information or through the application of isolated algorithms (See Table 7).

For each of her responses to the question about what difficulties she associated with teaching this topic, Grace cited the challenge of these ideas being highly "conceptual" with each of the "big ideas". Specifically, she said "It is conceptual, like most of chemistry, and they have a hard time visualizing what is really going on" or "again, this is very conceptual...so this can be difficult for them" (Nuclear CoRe). This provides added insight into her view of knowledge as content or knowledge as product potentially being limited by a view that students' capacity for success with this topic is limited in certain respects. Despite the limitations noted above and in her responses in the CoRe document, four of the five statements made in the semi-structured interview that specifically address student capacity are positive, emphasizing that "...they evolve" and "...it's kind of a neat thing [when they make connections in the unit]" (Nuclear Interview).

Since Grace emphasized factual knowledge—or knowledge as content (see Table 2), her unit seems to reflect that in the conception of the nature of science presented as more of a fact-based than a process-based endeavor. Her beliefs about science teaching and learning manifest themselves in how she provides opportunities for students to engage with topics that relate to the unit. By and large, student learning arises from practice in the form of worksheets or teacher-driven discussions or lectures. Consistent with a view of knowledge as content and knowledge as product, Grace appears to favor information transmission over independent thought as student activities seem to be largely designed to practice algorithms such as completing a nuclear equation to ensure that mass and/or atomic numbers are conserved and constructing a simple explanation for a chain reaction or nuclear process in terms of products or reactants. On her CoRe document, Grace highlighted the use of specific activities to accomplish each goal, such as a computer-based simulation for students to visualize a chain reaction or her walking students through the steps required to determine the identity of a given daughter nuclei or the calculations needed to determine mass defect or nuclear binding energy. She did not cite any opportunities for students to construct their own understanding in terms of larger societal issues or other illdefined phenomena that required an application of science and engineering practices or crosscutting concepts in addition to any relevant disciplinary core ideas.

Discussing Grace's Nuclear Chemistry Curriculum

Much of Grace's nuclear chemistry unit appears to be structured around helping students interpret and negotiate the completion of balanced nuclear equations that depict various forms of radioactive decay. The use of mass numbers and the atomic numbers of relevant isotopes provide essential information to determine the resultant daughter nuclei (or parent, depending on the problem). Each of the first three "big ideas" that she presented (the Law of Conservation of Mass, reactions, and atomic structure) seem to be complementary and support students navigating decay equations while also situating that type of knowledge as the preferred outcome of the unit. In her responses throughout both the interview and while completing the CoRe document, Grace almost always defined knowledge through her statements using either the content (57.9% of the time) or product lens (39.5% of the time). This suggests that she believes that nuclear chemistry should be taught (and learned) as a set of discrete information or pre-determined outcomes that students should be able to realize by the end of the three- to four-week block of time that she allocates to nuclear chemistry within her year-long chemistry curriculum (See Figure 8).

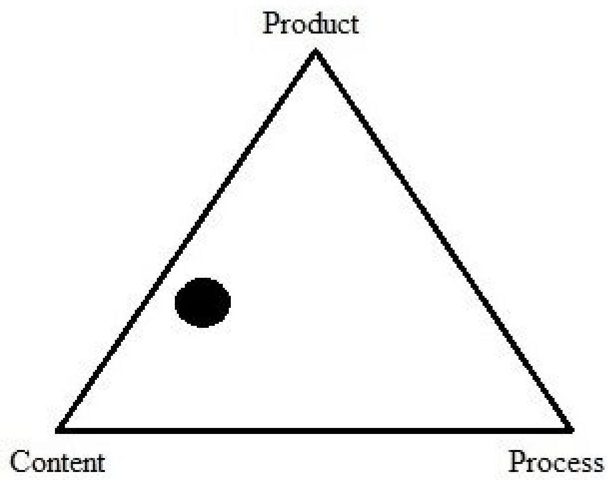


Figure 8. Characterization of Grace's View of Knowledge in a Nuclear Chemistry Unit.

Grace's summative assessment aligns with her view of knowledge as content (and secondarily, product) as the questions students were largely factual or recall-based (represented by 56.7% of all questions). This further reinforces Grace's view that nuclear chemistry is an accumulation of information that students come to "know", such as how many protons or neutrons a given isotope has or what the name of a primary decay product is. Though Grace did mention tying the unit to larger ideas like the bombing of Hiroshima and Nagasaki, it does not appear that students use that phenomenon (or others) for anything other than an opportunity to describe the science behind the chain reaction and subsequent release of energy. Similarly, Grace discussed student learning about nuclear chemistry in terms of knowledge as process only 2.6% of time, and only 6.7% of the questions on her summative assessment were characterized as conceptual. This was the only time that students were asked to engage with the concept of stability where it was necessary for them to determine what it meant for an atom to become more stable (or less stable).

Grace's summative assessment also included a significant number of questions (31.7%) that she was not able to clearly connect back to the main ideas she presented in either the initial interview or CoRe document she completed. Among those were several references to penetrating power which, while undoubtedly related to energy, students do not experience the concept in terms of energy. Rather, Grace explained that she wants students to know:

> ...you can protect yourself from those with alpha if you just have a shirt on it's going to stop it, but if you're getting into gamma then you've got to make sure you're protected, and we talk about...when you go to the dentist, they put that lead cape on you to protect you from x-rays and talk about it that way. (Member Check).

Grace presented this as fact-laden information where students are told what types of materials stop each form of radiation as they use that to identify the material used to protect a person or object from certain types of radiation produced from radioactive decay. In her view, this fulfills her vision for establishing real-world connections with the content for students. Based on Grace's explanations about her unit's structure and purpose, any further connections or integration of learning beyond that would be purely coincidental. Interestingly, Grace identified energy as the last of her "big ideas" which aligns with the crosscutting concept "energy and matter" associated with HS-PS1-8 from NGSS (NGSS Lead States, 2013). Based on the assessment data provided, the matter portion of this crosscutting concept was represented, at least in part, by the first three "big ideas" while the fourth "big idea", relating to energy, was only represented by 5.0% of all questions. This suggests that Grace sees the role of energy in nuclear processes as much less important than matter's role despite the prevalence of both in the standards. The ACS Guidelines for Teaching Middle and High School Chemistry include references to nuclear chemistry being relevant to the chemical principles of "matter and its interactions” and “energy” (ACS, 2018). Like NGSS, this shows that the subject matter included in Grace’s unit disproportionately minimizes energy’s role.

The conception of knowledge as content and knowledge as product inherent to Grace’s nuclear chemistry unit appears complemented by the way the unit is structured. She described the use of worksheets and class discussions as foundational ways that students engage with the ideas presented in the unit. When discussing her teaching procedures in this unit, she repeatedly used phrases such as “I use” and “I teach” or “I have them do...” which suggest a teacher-centered view that aligns with the forms of knowledge presented. This also aligns with Grace’s concerns about the potential confusion from students working with topics she sees as being highly conceptual and difficult to understand.

Grace explained that she believes this topic is important to learn because the Law of Conservation of Mass is inherently important on its own. Each of the four “big ideas” that she identified can be tied back to this idea that the unifying impetus behind this unit is that it serves to develop student understanding of the Law of Conservation of Mass. Absent from this justification is how students are expected to use the ideas that Grace finds interesting or real-world examples of the topic. Those ideas, such as carbon dating or radon testing in residential settings, do not align well with the “big ideas” that she offered.

Participant #2 (Ellie)

Overview

Ellie’s nuclear chemistry unit was created following the adoption of NGSS and was not something she taught prior to the existence of NGSS. She reported that this unit was her “favorite” of all her introductory chemistry units and identified four “big ideas” that she believes guide student learning within the unit: using science or research to evaluate a controversial topic, the role of energy and its relationship to nuclear reactions, the phenomenon of nuclear processes, and assessing information and determining its relationship to “you” as an individual. She explained that students ideally come into the unit with an understanding of what protons and neutrons are as well as what the atomic number represents. At its core, Ellie believes this unit on nuclear chemistry serves to develop students’ “...future ability to assess information and decide how it affects you”, or what she described as “consumer chemistry” (Nuclear Interview). In that sense, she sees a clear, real-world, personal connection available for students to make within the unit—both as an interesting phenomenon and an opportunity to practice “mak[ing] decisions in the face of potentially conflicting and still real information” (Nuclear Interview).

The unit takes place during the first semester of her introductory chemistry course following a unit on energy and fuels and precedes a unit on stoichiometry. Within this unit, Ellie reported allocating time for students to research the answers to a question that they came up with as well as bringing in a former student to speak about life on a nuclear submarine and his own experience with nuclear power. She also reported asking students to engage in classroom activities for “...modeling the radiation types...” or “...their analysis of what THEY think after they have had to adopt a role for the town hall meeting” (Nuclear CoRe, capitals in original). Students are asked to conduct a simulated town hall meeting around the potential benefits and drawbacks of a new nuclear plant being built in the community and take the perspectives of individuals with various jobs (environmental engineer, police officer, etc.) to argue for or against the plant’s presence. Materials for the unit were primarily sourced from the NEED Project (2020), and Ellie created or modified other supplemental activities as needed. She identified concepts in the unit that include “fission, fusion, and radioactive decay” (Nuclear Interview). The summative assessment for this unit involves an exam that primarily uses a constructed response format that Ellie created to allow students to demonstrate how they might apply their knowledge of nuclear chemistry.

The Nuclear Chemistry Curriculum

Ellie's unit on nuclear chemistry is structured to encourage students to examine their views and their relationship to nuclear chemistry. During the semi-structured interview, she explained that to begin class-wide conversations about nuclear chemistry, "I put on the board 'nuclear is...', 'nuclear is not...', and 'nuclear might be...' and have them throw out words that kind of fit in that. So, you know, just kind of survey their overall feelings" (Nuclear Interview). She uses this conversation to serve as an initial introduction to what students already know or think about the topic. These initial ideas are expanded upon while discussing alpha, beta, and gamma decays as well as fission and fusion. Ellie explained that understanding these topics is not necessarily what she hopes students get out of the unit; instead, she said that "...I don't think it's essential knowledge. I don't think that's useful in the grand scheme of things" (Member Check). She clarified that she wants students to "just [know] that different radiation affects individuals differently" and prefers to look for ways to apply the nuclear chemistry content (Member Check).

One of the ways she attempts to help her students apply what they've learned about nuclear chemistry is to allow them to participate in a class-wide town hall meeting centered on the benefits and drawbacks of a nuclear power plant being built in the area her school is located in. She explained that she has students:

> ...do different roles as townspeople because one person comes in as the nuclear scientist and gives the background and one person comes in and gives us, they're from the financial institution and talks about how much money overall you'll need. One person is

> from homeland security or law enforcement and their job is to tell us is this really a threat in those cases. The law enforcement finds that they're going to need to you know patrol in that area more and it changes kind of the town structure as it is. It's always interesting if you give three different people, a biologist, an environmentalist, or whatever and two of them are like yeah, it's really good for the environment and one is like it's not good for the environment. So, I really like how the real life is brought to them. (Nuclear Interview)

For Ellie, this form of understanding represents the successful mastery of the content she included within the unit.

During the semi-structured interview, Ellie explained that her nuclear chemistry unit followed a unit on energy and fuels and later clarified in the member check that after nuclear chemistry, "...we do a lot of stoichiometry". She explained that this unit "...kind of released me from the 'okay we're going to learn about the atom' and 'we're gonna learn about protons and neutrons and electrons' and I started looking at it and say if I wanted to teach about the atom, I can do it through isotopes and nuclear chemistry" (Member Check).

Ellie referred to student knowledge in a myriad of ways. During the analysis of the coded statements made throughout the semi-structured interview as well as the CoRe document she completed, 63.3% of total statements were excluded (e.g., "Yes" or "I still like it, but I have it take a lot of time"). Of the remaining statements that were included, knowledge as product was the most frequent type of statement with 43.7% and knowledge as content coded in 36.8% of all non-excluded statements (See Table 9). Statements that refer to student knowledge from the process perspective were represented by 19.5% of all included statements. Individual statements were not able to be coded for more than one descriptor.

Table 9

Codes, Definitions, Sample Responses, and Frequencies for Ellie's Descriptions of her Unit on Nuclear Chemistry and its Purposes and Structure.

Code	Definition	Sample Response	Frequency
Content	Identification of knowledge as discrete chemistry content	"Fusion takes place in the Sun" "But they're learning the mechanics that I'm checking still"	36.8%
Product	Identification of knowledge based on pre-determined outcomes	"Some kids aren't interested, but they're still probably learning but I don't know if they're learning the big skills that I'm telling them, opening the door kind of skill" "...evaluation of energy like where it's coming from and where it's going and how you know qualitatively how much it is"	43.7%
Process	Identification of knowledge based on personal relevance	"...it's your future ability to assess information and decide how that affects you" "...sharing of their ideas and experiences is valuable here"	19.5%

During her semi-structured interview, Ellie identified four separate "big ideas" that comprise the main ideas that students should be engaging with throughout the unit that were represented on her CoRe document (See Appendix E for complete CoRe). "Big Idea #1" related to "using science or research to evaluate a controversial topic", where Ellie explained that she hopes that students will become more proficient at "how to locate and assess sources of information" as well as their ability to use "...evidence to support an argument and communicat[e] this argument out to [the] community" (Nuclear Interview). She emphasized that this is a not a skill that students will use briefly, be tested on, and simply forget; rather, she said that “this is a life skill that will not stop at the school doors/graduation” (Nuclear Interview). She explained that students are often reluctant to engage with more than a few isolated sources of information or data and tend to avoid peer-reviewed scientific research due to it being perceived as much less accessible than other potential sources.

Ellie’s second “big idea” touched on energy and its relationship to nuclear reactions where she explained that she uses this idea to reinforce the importance of the Law of Conservation of Mass and Energy. She further explained that she wanted students to understand “the idea that energy is released when bonds are broken” to comprehend why more energy is released during nuclear processes than a “standard chemical reaction”, as well as how that energy can be controlled (Nuclear CoRe).

“Big Idea #3” included the phenomena of nuclear processes where students would be asked to consider the applications of fission and fusion in natural and human-directed contexts. She explained that she felt this idea was important for students to understand “...the differences and similarities in the mechanisms between radioactivity and nuclear fusion or fission in assessing risk and evaluating credibility to claims they might come across” (Nuclear Interview). Ellie acknowledged that students sometimes struggle with this topic because “without being able to SEE radiation and nuclear reactions, it can be difficult to differentiate between the various types” (Nuclear CoRe, capitals in original). She asks students to construct models to help visualize the changes that take place during these processes as well as to encourage them to “...solve/balance equations and predict products of reactions as they process these two subatomic particles and the idea that SOMETHING is conserved” (Nuclear CoRe, capitals in original).

The fourth “big idea” was related to the need to assess information and determine its relationship or relevance to “you” as an individual. Ellie explained that she hopes students come to understand how different forms of radiation are different and where a person might find them. In the end, she asks students to engage with the "claims [that] are made about risks and safety..." of these particles or forms of energy (Nuclear Interview). Ellie explains that because students all process risk differently, some may be inclined to dismiss those varying degrees of risk depending on the potential benefits coupled with exposure to those risky scenarios.

In order to assess the extent of student learning by the end of Ellie's nuclear chemistry unit, students are asked to complete a summative assessment containing five sections (two sections containing more than one open-ended question) with a total of seven potential questions to be answered. To satisfactorily complete this assessment, students are only required to complete three of the sections and may choose from the pool of five sections to respond to. Questions were initially coded and classified as either factual/recall, algorithmic, or conceptual (See Table 10). The factual or recall questions accounted for 14.3% of all questions asked while algorithmic questions were not represented at all, being 0.0% of questions included on the assessment. Conceptual questions were the basis for 85.7% of all questions on the assessment and required students to apply their knowledge in novel ways, often more than one possible answer for students to reach.

Table 10

Codes, Definitions, Sample Responses, and Frequencies for the Questions Included on Ellie's end of Unit Assessment on Nuclear Chemistry.

Code	Definition	Sample Response	Frequency
Factual/Recall	Requires students to recognize or identify key vocabulary words or static relationships (Anderson, Krathwohl et al., 2001; Koufetta-Menicou & Scaife, 2000)	How are you exposed to radiation each day?	14.3%
Algorithms	Procedures for getting "right" answers to routine tasks or problems (Herron, 1996; Nurrenbern & Pickering, 1987)	*(None)*	0.0%
Conceptual	Requires students to justify, predict, or explain using deeper analysis and critical thinking (Zoller & Tsaparlis, 1997)	Widget Inc is seeking permits to open a factory where they will be using radioactive materials to make their product (which is already determined to be safe). The manufacturing process they are using will cause their employees to be exposed to increased levels of radiation. Should Widget Inc be granted permission to begin production? State your reasoning, demonstrating your understanding of the effects of radiation exposure. How can nuclear chemistry be used to improve life on this planet and conversely, what harm might it bring to society? Provide 3 examples and descriptions of each.	85.7%

Ellie's summative assessment was also coded based on each question's alignment to each of the "big ideas" she named during the semi-structured interview (See Table 11). The first of the “big ideas” was represented on at least 57.1% of the questions while the second and third “big idea” were each invoked in 85.7% of the questions that students were asked to respond to. The fourth “big idea” was relevant for 100% of the questions that were found on the assessment. Questions relating to more than one “big idea” were coded as many times as necessary. For example, the question “If a loved one was diagnosed with cancer after increased radon exposure and is strongly opposed to radiation treatment, what information might they need to further understand the cause and treatment of their disease?” could be coded to each of the four big ideas.

Table 11

Codes, Definitions, Sample Responses, and Frequencies for the Questions Included on Ellie's end of Unit Assessment on Nuclear Chemistry and Alignment to Ellie's Identified "Big Ideas".

Code	Definition	Sample Response	Frequency
Big Idea #1	Using Science/Research to Evaluate a Controversial Topic	How can nuclear chemistry be used to improve life on this planet and conversely, what harm might it bring to society? Provide 3 examples and descriptions of each. If a loved one was diagnosed with cancer after increased radon exposure and is strongly opposed to radiation treatment, what information might they need to further understand the cause and treatment of their disease?	57.1%
Big Idea #2	The Role of Energy and its Relationship to Nuclear Reactions	What might you limit exposure to if you wanted to avoid increased exposure? How are you exposed to radiation each day?	85.7%
Big Idea #3	The Phenomena of Nuclear Processes	How are you exposed to radiation each day? Widget Inc is seeking permits to open a factory where they will be using radioactive materials to make their product (which is already determined to be safe). The manufacturing process they are using will cause their employees to be exposed to increased levels of radiation. Should widget Inc be granted permission to begin production? State your reasoning, demonstrating your understanding of the effects of radiation exposure.	85.7%
Big Idea #4	Assessing Information and Determining its Relationship to "You" as an Individual	How do you feel that this will affect you? A question you have written to answer to improve and demonstrate your knowledge of nuclear chemistry topics but that appeal to your interests, experiences, curiosities, etc. Your question MUST BE APPROVED by [*Ellie*] before you submit (and before you've researched an answer) this assignment.	100%
None	Not specifically aligned to any identified big idea(s).	*(None)*	0%

PCK

Subject-Matter Knowledge

Ellie identified many of the content-level elements relating to the DCI of the NGSS PE that she identified as related to nuclear chemistry. She included ideas such as fission, fusion, forms of radioactive decay (e.g., alpha decay or beta decay), and electromagnetic waves (which she mentioned was beyond the scope of her class). During the semi-structured interview, Ellie explained that she leans heavily on the curricular materials produced by the NEED Project (2020) and incorporates additional resources or brings in a former student that serves on a nuclear submarine while in the Navy. While completing her CoRe document, she reported that she emphasizes "the idea that energy is released when bonds are broken" despite that statement not being an accurate representation of the chemistry involved.

Ellie explained that she:

> ...really didn't do nuclear chemistry or learn much about it before I started teaching it and for a really long time, I always tried to skip it. It was kind of a thing you cover at the end and...I think we need to get to the end [of the semester] and use the basics with application which is what we shove at the end [of the curriculum] (Nuclear Interview).

During the member check, she clarified that her content knowledge relating to nuclear chemistry has "definitely grown since I started teaching [it]" but acknowledged that she didn't know much about nuclear chemistry prior to deciding to teach it in her classes.

Knowledge of Curriculum: Specific Programs

Ellie acknowledged that there were multiple ways that a unit on nuclear chemistry could be taught, but largely focused on the way(s) she could frame the context for students to learn about the topic. She explained that she has spent a lot of time working on her existing structure that emphasized nuclear power, but said they could "...look at nuclear proliferation...I mean there's probably always options, right? I believe that there are other options [for teaching the unit], but it doesn't mean that I would want to" (Nuclear Interview). The application of nuclear chemistry was a consistent concern of Ellie's through the unit and within the summative assessment she uses for her unit (See Table 10).

Ellie explained that she draws from resources like the National Energy Education Development, NEED Project (2020), or from several documentaries such as the PBS (2015) film, Uranium—Twisting the Dragon's Tail. In addition to the alternative phenomena that she felt could be incorporated into the unit, she seemed to acknowledge that she is most concerned about students getting practice with "...mak[ing] decisions in the face of potentially conflicting and still real information" that relates to nuclear chemistry (Nuclear Interview). She also cited Erik Francis' book, *Now That's a Good Question*, as a source of inspiration for the structure of her summative assessment for the unit.

Knowledge of Curriculum: Science Goals and Objectives

Ellie identified many of the elements present in the NGSS PE (and relevant DCI and SEP, but not CCC) relating to nuclear chemistry, HS-PS1-8. She described the DCI to include "fission, fusion, radioactive decay" and later explained that radioactive decay includes alpha decay and beta decay. She also pointed out that modeling was the primary SEP that needed to be addressed in a unit relating to nuclear chemistry and that energy played a significant role in nuclear processes but didn't specifically address it as the CCC used.

The goals of Ellie's unit on nuclear chemistry are something she acknowledges might be a bit different than they were earlier in her career. She explains:

> Because so much of what we've always done is like 'okay they're gonna learn this' and 'they're gonna practice this' and 'then they're going to do something with it' and I build them the other way. I have to re-learn or even learn things that I'm like when I discover them it's a lot more fun for me to be like 'I know, look at this!' because I get excited about this and am like 'I didn't know this!' so now I force [them] to learn it. (Nuclear Interview)

These approaches to unit design are also informed by Ellie's understanding of what students need to engage with the unit itself.

Ellie explains that students come into the unit, ideally, with an understanding of "...the parts of the atom..." and have "...identified that the atomic number is the number of protons" but acknowledges that students don't have to have the understanding to engage with the ideas included within the unit (Nuclear Interview). She mentioned that the topic of nuclear chemistry as a natural fit in the progression from a unit on fuels because she believes the link of energy and the Law of Conservation of Energy is present in both topics.

Science Teacher Orientations

Ellie's views about the goals and purposes of science teaching and learning that relate to nuclear chemistry appear to be closer to developing students' problem-solving skills than amassing information based on her statements made that identified knowledge constructed throughout the unit in terms of content less than 40% of the time throughout the interview and the CoRe document she completed (See Table 9). Similarly, her assessment of the topic of nuclear chemistry assessment was largely achieved through conceptual questions that require students to do more than recall facts or apply algorithms (See Table 10). Instead, Ellie explained that she values what "...captivates [students] and their interests [which] is more important than the mechanics" (Nuclear Interview).

When asked in the CoRe document to explain the difficulties or limitations associated with teaching the topic of nuclear chemistry, Ellie identified variance in students' risk awareness and "coping mechanisms [that] can lead students to dismissing actual risks because we've brushed off some low risk or even high-risk factors that we benefit from enough to take that risk" as important concerns that might be associated with the topic. Interestingly, these describe more of the process of engaging with scientific processes rather than the accumulation or categorization of facts. She went on to lament that "...students often use only a few sources that are summaries and pro/con lists, and it can be difficult to get them to reach beyond when peer-reviewed scientific research is so much less accessible" (Nuclear Interview). The only idea she identified that approached the understanding or use of factual knowledge as a means of doing science was when she highlighted the need for students to overcome their inability to concretely "...SEE radiation and nuclear reactions, it can be difficult to differentiate between the various types" (Nuclear CoRe, capitals in original). At no point in the interviews or CoRe document completion did Ellie suggest that her students might not be able to learn what she set out for them to learn and was exclusively optimistic about their ability to grapple with the ideas they were asked to confront. Her beliefs about science teaching and learning manifest themselves in the degree of autonomy she offers her students in the learning process as well as her repeated commitment to asking them questions, even on assessments, that allow them to bring their own experiences or perspectives to the table in order to address larger issues, such as the "big ideas" she had identified (See Table 8). She explained that:

> The summative questions I use to assess students' ability to communicate and defend a claim is written within questions I have specifically written to keep students and their own ideas involved in the processing...and I want to do more of this, but I need to solidify the feedback and rubric/expectations. (Nuclear Interview)

Discussing Ellie's Nuclear Chemistry Curriculum

Ellie's nuclear chemistry unit seems to be designed to help students apply nuclear chemistry concepts to various ways they might impact them throughout their lives or within their community. The use of a class-wide debate and efforts to bring people more directly impacted by nuclear power into student learning experiences help to directly connect two of the "big ideas" she offered (using science/research to evaluate a controversial topic and assessing information and determining its relationship to "you" as an individual), while a deeper exploration of the mechanics of nuclear processes ties in the remaining "big ideas" (the role of energy and its relationship to nuclear reactions and the phenomena of nuclear processes). In her responses throughout the interview and the CoRe document she completed, Ellie consistently defined knowledge of nuclear chemistry as a combination of knowledge as content (36.8% of the time), product (43.7% of the time), and process (19.5% of the time). This suggests that she believes nuclear chemistry should be taught (and learned) as a set of pre-determined outcomes involving specific content. This content, in Ellie's view, should have some relationship to students as individuals and can be fostered in students before reaching the end of the three-week timeframe budgeted for this unit within her chemistry curriculum (See Figure 9).

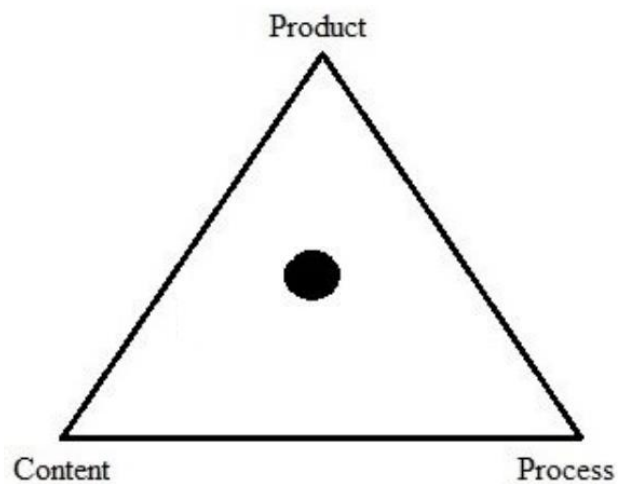


Figure 9. Characterization of Ellies's View of Knowledge in a Nuclear Chemistry Unit.

Ellie's summative assessment aligns with her view of nuclear chemistry knowledge as multidimensional (content, product, process) given that the questions she asks students to respond to are largely conceptual in nature (85.7% of questions) and require students to integrate various forms of knowledge to adequately address each question. Similarly, each of the "big ideas" that she had identified are represented on the summative assessment, with "Big Idea #1" being the least represented (addressed in 57.1% of all questions).

The concept of knowledge as an amalgam of content, product, and process inherent to Ellie's nuclear chemistry unit appeared to be structured in a way that reinforces this view. She described infrequent use of worksheets and less time spent on "...the boring parts of if there was a beta decay of calcium-48, what would happen? You know, what's the daughter?" than she might otherwise have (Nuclear Interview). Upon reflection, Ellie emphasized how much she enjoyed this unit and acknowledged that despite the flaws present in its current form, "it probably will still be more successful than the worksheets" she would be using if she taught in a way she described as being more traditional (Nuclear Interview). Ellie explained that:

> I felt like I never got to the application of science because I was always focused on the mechanics of naming and things that I was disappointed by. Then I left [the classroom] for six years and when I went back, the NGSS heled me make different choices (Member Check).

She conceded that this perceived shift allowed her to begin focusing on why students were learning what they were in class and:

> ...coming back in NGSS and skills-based grading and so the questions were more open-ended. It gave me kind of a better way to develop my units in a way that I could teach them the content with this stuff we never got to" (Member Check).

When discussing her teaching procedures in this unit, she repeatedly used phrases such as "students do" and "they should" or "they will" which suggests more of a student-centered view that aligns with the forms of knowledge presented. This also complements Ellie's goals for the unit that relate to students finding ways to connect nuclear chemistry to their personalized experiences today or what they might reasonably encounter later in life.

A Comparison of Grace and Ellie's Nuclear Chemistry Curricula

The units designed by Grace and Ellie are, to varying extents, intended to support students as they attempt to develop mastery of HS-PS1-8, which discusses developing a model that illustrates the change in composition of the nucleus and the energy involved during multiple nuclear processes, such as fission, fusion, and radioactive decay (NGSS Lead States, 2013). This standard is derived from NRC (2012), which emphasized the importance of engaging with the concept of radioactivity, stellar nucleosynthesis, and the role of nuclear power in energy generation. There was significant overlap in the “big ideas” identified by Grace and Ellie. The importance of energy and the phenomenon of nuclear reactions was addressed by both teachers and reflect their common understanding of the importance of a unit on nuclear chemistry to include common forms of nuclear reactions (e.g., fission, fusion, and radioactive decay) and the significance of the energy involved in those reactions (the crosscutting concept associated with HS-PS1-8). Grace’s “big ideas” relating to the Law of Conservation of Mass and the importance of navigating the information found on the Periodic Table of the Elements was also found in Ellie’s nuclear chemistry curriculum, albeit with a slight difference in level of emphasis. Two of Ellie’s “big ideas”, “Using Science/Research to Evaluate a Controversial Topic” and “Assessing Information and Determining its Relationship to ‘You’ as an Individual” differed from Grace’s unit in that both teachers had what appeared to be divergent views of what student relevance might mean. Grace’s desire to present interesting facts or ideas to students—or exposing them to ways that we use nuclear chemistry—appeared to fulfill her vision for making the learning relevant for students. Ellie differed in her approach, asking students to actively confront decisions (e.g., should a nuclear plant be built in the community, should a family member receive radiation treatment for cancer, etc.) related to common applications of nuclear chemistry in everyday life.

When comparing the differences in attention given to a unit on nuclear chemistry between Grace and Ellie’s chemistry classrooms, it appears that differences in perceptions about the standards themselves as well as each teacher’s own subject-matter knowledge played a significant role in determining the scope and depth that the topic was covered. Both teachers cited a limited understanding of nuclear chemistry prior to attempting to teach it in their classes and both went about developing that knowledge in similar ways (independent research and participation in professional workshops). This is likely an experience shared by more teachers than just Grace and Ellie as nuclear chemistry is infrequently taught at the undergraduate level, leaving teachers to find alternate resources to develop their subject-matter knowledge for the topic (Konkankit et al., 2021).

Grace's orientation to the teaching and learning of nuclear chemistry appears to be firmly rooted in the importance of the content that she believes to be core to NGSS and the topic of nuclear chemistry more generally, namely the Law of Conservation of Mass. In context of her unit on nuclear chemistry, Grace seems to view the nature of science to be more aligned with factual knowledge, which manifests in her perception of the goals of science teaching and learning as being more akin to amassing information about real-world phenomena than solving real-world problems. This can be seen in her interview and CoRe document where 57.9% of all coded statements she made were related to knowledge as content. Similarly, this is also noted in her summative assessment design in which 56.7% of questions required students to simply recall a fact or isolated piece of static information. Areas of study that Grace cited as a real-world connection of nuclear chemistry, such as penetrating power of radiation and half-life, do not align well with the "big ideas" she identified and suggest that she views these ideas as part of a "required" canon of nuclear chemistry knowledge that are required to successfully teach the topic.

Ellie's nuclear chemistry curriculum seems to reflect an orientation to the teaching and learning of chemistry that indicates a view that students should primarily work at developing problem-solving skills and find ways to connect the topic of nuclear chemistry to their personal lives. On several occasions, she said that following the adoption of NGSS, her approach to teaching and learning science shifted significantly. Ellie explained that she felt like teaching under the new set of standards gave her a natural opportunity to reflect, saying "...I feel like it released me" and that she realized she could deepen her students' understanding of the composition of the atom while using isotopes and nuclear chemistry to accomplish that goal in a more meaningful context (Member Check). As she went through her entire introductory chemistry curriculum, she recounted a similar approach she took and clarified that:

> Every year I tried to cut out more naming because I felt like it took so long to get students to really do a good job of it and then every year I was like 'but why?'. And so, I think that it took me a while to admit that that's what we knew, it's not like I felt like I am forced to teach this in this way, it was just kind of automatic. Oh, they need to understand what matter is and mixtures and compounds and elements and we move here. It felt standard and there were things that I'm like we spend too much time on this for it to be useful...I was just doing what I knew (Member Check).

Despite nuclear chemistry being a topic that often receive differing levels of attention across different experienced teachers' introductory chemistry curricula (RQ1), both Grace and Ellie indicated they added a unit on nuclear chemistry following the adoption of NGSS. Despite their willingness to add that unit to their existing curricula, both reported a very limited amount of relevant content knowledge that they could draw from as they developed their nuclear chemistry units. Throughout the semi-structured interviews and in the subsequent member checks, Grace and Ellie both indicated they were able to deal with this challenge by independently learning and accepting additional help in the form of area professional development workshops. Absent this specific and sustained effort, both Grace and Ellie acknowledged they would not necessarily have had the existing resources or subject matter knowledge necessary to facilitate student learning around the topic.

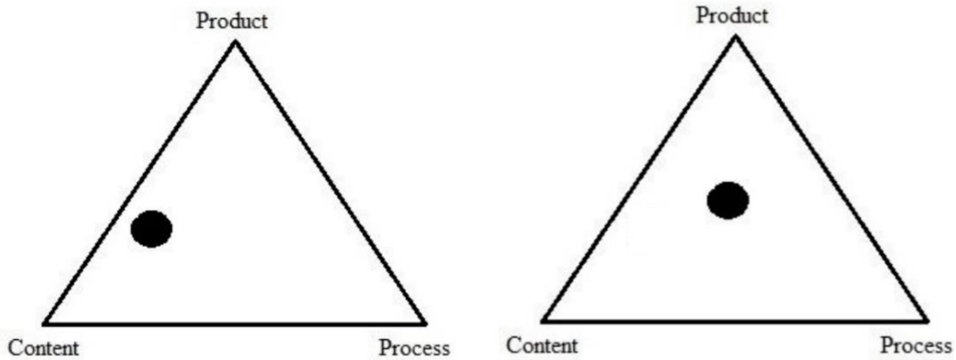


Figure 10. A Comparison of Grace's and Ellie's Views of Knowledge in a Nuclear Chemistry Unit.

The impact of teachers' curricular knowledge and orientations to the teaching and learning of science on their enacted curriculum with respect to the topic of nuclear chemistry (RQ2a), can be understood in terms of the elements of PCK discussed above. Grace and Ellie both independently created different nuclear chemistry units that appear to differ by the type of knowledge students are asked to construct (See Figure 10). For Grace, knowledge in the nuclear unit looks like the accumulation of facts, such as the idea that paper can stop an alpha particle while lead is required to block gamma radiation, or the mastery of algorithms such as how to predict the products in a nuclear equation or solve a half-life problem. For Ellie, knowledge constructed in a nuclear chemistry unit has some similar factual and procedural knowledge as Grace's, but it goes further by asking students to take some of those ideas relating to nuclear changes and pushing them to look for ways to apply those to their own lives or the lives of others within their community (See Table 12). Despite these differences between the nuclear chemistry units of both teachers, both Grace and Ellie's units aligned with their respective differences.

Table 12

Comparison of Grace and Ellie's Knowledge Statements and Summative Assessment Questions

Frequency of Statements Coded for Type of Knowledge		
	Grace	Ellie
Content	57.9%	36.8%
Product	39.5%	43.7%
Process	2.6%	19.5%
Frequency of Summative Assessment Questions Coded for Question Type		
	Grace	Ellie
Factual/Recall	56.7%	14.3%
Algorithmic	36.7%	0.0%
Conceptual	6.6%	85.7%

CHAPTER V: FINDINGS (KINETICS)

Participant #1 (Grace)

Overview

Grace explained that her approach to teaching kinetics in her introductory chemistry classes does not rely on a formal unit. Instead, she clarified that she "probably brings most of it in when we do chemical reactions and...how chemical reactions can change with grinding up things and heating them and I tie it more in like that" (Kinetics Interview). Grace described that while she viewed calorimetry to be a part of the topic of kinetics, she no longer includes it due to concerns she has about students' ability to navigate the math involved. She said that she "...know[s] it's not difficult math, but students don't ever really tie it together...and I just felt like they completely got lost" (Kinetics Interview). Grace believes that this topic is more advanced than is appropriate for students in an introductory chemistry course and, as a result, only exposes students to isolated ideas without assessing them summatively. The only assessment, albeit formative, she was able to articulate was a brief discussion she generally has with students after watching a video about the factors that make a reaction speed up or slow down. When asked to explain why the topic might be important for students to learn—or when they might be able to use that knowledge—she referenced a video that shows students walking through an increasingly narrow hallway, eventually resulting in collisions and books and papers flying around the hall. At several points during the semi-structured interview, Grace stopped and wondered aloud whether her approach toward the topic was the "right one" and whether some of her difficulty discussing the topic of kinetics might be due to her not emphasizing it in her classes. After reflection, she said “maybe I should teach it more often and then I’d remember [it], you know?” (Kinetics Interview).

The Kinetics Curriculum

Grace reports that she generally integrates kinetics concepts within a unit on chemical reactions but does not have a standardized way of doing this from year to year. Citing time constraints and concerns about students’ ability to understand mathematical applications of kinetics, she explains that she keeps discussions about kinetics to a minimum in her introductory chemistry course. Grace said that she believes that the topic includes “big ideas” such as the factors that influence a reaction rate, the Law of Conservation of Mass, and the role of energy in breaking down or forming substances. For Grace, this topic “...didn’t seem to fit anymore with the way I wanted things to flow” (Kinetics Interview), and she repeatedly referenced challenges due to the amount of time that she felt would be required to invest in the topic to ensure students had an opportunity to master it.

During the semi-structured interview, Grace was asked to further clarify her understanding of kinetics and the topic’s relationship to her unit on chemical reactions. She repeatedly cited energy and calorimetry as something she viewed as interchangeable with kinetics. She shared a story about guiding students through calculations relating to a lab about the energy density of various components of a trail mix and explained that they “...tried to take the numbers and crunch them and figure out the calories and I just felt like they completely got lost” (Kinetics Interview). She wondered whether it might have been something that she was doing that might have caused students to struggle or whether it might be the topic itself.

Grace referred to student knowledge in a couple of significant ways. During the analysis of the coded statements made throughout the semi-structured interview as well as the CoRe document she completed, 45.8% of her total statements were excluded (e.g., "Yeah" or "You've got me thinking"). Of the remaining statements, knowledge as product was the most frequent type of statement with 56.4% and knowledge as content coded in 43.6% of all non-excluded statements (See Table 13). Statements that refer to student knowledge from the process perspective were not represented by any of the statements she made on either the semi-structured interview or on the CoRe document that she completed.

Table 13

Codes, Definitions, Sample Responses, and Frequencies for Grace's Descriptions of her Unit on Kinetics and its Purposes and Structure.

Code	Definition	Sample Response	Frequency
Content	Identification of knowledge as discrete chemistry content	"...anytime we discuss reactions [students should know] that all matter is conserved" "We will not include anything on rate laws"	56.4%
Product	Identification of knowledge based on pre-determined outcomes	"They need to know this to help them to understand that reactions don't always run at the same rate and there are times when we need to slow down or speed up a reaction" "I think maybe more just a general understanding of reactions and why they change and the energy that we get from them"	43.6%
Process	Identification of knowledge based on personal relevance	*(None)*	0%

Of the coded statements, 11.1% could be described as negative, math-related statements such as "...they didn't understand the math a lot of times and I would go through it with them, and they still wouldn't get it" or "...I have some kids that are pretty low-level math too that are in chemistry" (Kinetics Interview). The topic of kinetics, as described by Grace, is not explicitly assessed in her class (summatively or formatively).

Grace was able to identify three distinct "big ideas" throughout her semi-structured interview that related to what students should be coming to better understand throughout the unit (in this case, the semester). These ideas were later elaborated on in her CoRe document (See Appendix F). The first "big idea" related to the factors that influence a chemical reaction (e.g., reaction rate) and Grace explained that "students need to understand that there are several factors that will make a reaction either speed up or slow down" (Kinetics Interview). In order to address why this idea is valuable for students, she explained that "they need to know this to help them understand that reactions don't always run at the same rate..." (Kinetics CoRe). Grace was unable to provide additional context or clarity for what this might look like—or more detail about the factors that she identified. She did go on to say that she uses a metaphor to communicate this idea with students, using the concept of finding a prom date and the factors that might lead a person to saying yes or no when asked to the dance. She cited her perception that this topic is "a very conceptual idea for the students just like most other chemistry topics. It is very hard for them to visualize what is actually happening" (Kinetics CoRe) and, in part, due to a lack of time, she does not assess the topic.

"Big Idea #2" related to the Law of Conservation of Mass where Grace explained that students need to understand that in all reactions, matter must be conserved. She clarified that students "need to understand that a reaction can speed up or slow down and the particles that are present are still present. They do not 'disappear' because the reaction goes faster or slower" (Kinetics CoRe). Grace explained that this "big idea" is not specifically assessed in this context.

The third "big idea" that Grace was able to identify related to the role of energy in breaking down or forming substance(s). She explained that "students need to understand that energy plays a role in chemical reactions and how the reactants form the products. And how fast/slow this happens" (Kinetics CoRe). Grace clarified her meaning here by saying that students "need to remember that bonds broken or made release or gain energy and this all ties into new products being formed" (Kinetics Interview). Time was again cited as a concern for this topic as well as it not currently being one that is formally assessed in her classes.

PCK

Subject-Matter Knowledge

During the semi-structured interview, CoRe completion, and subsequent member check, Grace struggled to connect the "big ideas" she had identified to the specific knowledge she hoped that students would leave her course having developed over the semester or year. When asked to consider a scenario where she had extra time available to spend more time on kinetics, she mentioned the possibility of including "…order of reaction, rate limiting [or]…maybe just the mechanism" (Member Check) but was unable to provide further detail when asked for clarification. Within that same conversation, Grace acknowledged that she "…probably know[s] even less about kinetics than [nuclear]" and at several points mentioned that it had been a long time since she had made a conscious effort to infuse kinetics-related topics into her introductory chemistry course. For those reasons, it appears that Grace's subject-matter knowledge relating to kinetics may be less than that of other topics that she regularly teaches.

Knowledge of Curriculum: Specific Programs

Grace was asked about potential alternatives to her current approach to teaching kinetics, and she responded by explaining that she had to think about what her students "could actually understand". She cited "...more basic enthalpy and entropy" before clarifying that it might "...be more rate laws and that kind of stuff or the AP stuff" (Kinetics Interview). When asked to clarify her understanding about the relationship between enthalpy and entropy and the larger topic of kinetics, she wondered whether she should think of them together. The only specific methods of teaching kinetics that Grace mentioned were references to activities she's done in the past, namely "Alka-Seltzer in the film canister". No other ways of teaching this unit were identified or references to previous ways that she went about teaching the unit (topic) were given, but she did clarify that she does teach kinetics (primarily rate laws) in her AP chemistry course.

Knowledge of Curriculum: Science Goals and Objectives

Grace structures her year-long chemistry curriculum around the units she views as representative of the discipline but does not include a specific unit relating to kinetics. When asked about the horizontal alignment between kinetics and chemical reactions (the unit she said that the topic of kinetics appears within), she explained that she briefly includes allusions to some applications or contexts that relate to kinetics, but intentionally keeps them vague and fleeting because of her fear that students are not prepared for the math required. In her mind, Grace sees the importance of kinetics in relation to "...the energy they get out of food...[and] we can figure out by breaking down or heating a substance [so] we can figure out how many calories are in what and there's energy that comes from that" (Kinetics Interview). After making that observation, she was not able to provide additional clarification for how she links that idea to kinetics. Following additional questioning, she was able to identify rates of reactions and rate laws as being a part of kinetics but did not offer and meaningful connections that she believes could be made between the topic and phenomena that students could engage with.

In terms of vertical alignment, Grace did not mention any concerns about performance in later science courses, collegiate success, or any other context as a concern that guides her structure and decision making related to her absence of a kinetics unit. She mentioned that she teaches the topic in her AP chemistry classes but does not teach that course every year.

When discussing kinetics, Grace acknowledged that she does not have an explicit unit covering the topic and, instead, attempts to integrate relevant ideas from time to time throughout her unit on chemical reactions. When asked about the role of kinetics in NGSS, she expressed some uncertainty by saying "I'm sure there's something in the standards about it, but I can't remember" (Kinetics Interview). Grace did not mention any science and engineering practices or crosscutting concepts that play a role in her construction or understanding of the unit.

Science Teacher Orientations

Grace's view of the goals and purposes of science teaching and learning for the topic of kinetics appears to be limited by her stated belief that it is a topic more suited for advanced chemistry students. In that sense, Grace limits the amount of exposure and practice that her students have to those ideas by not spending much class time on them. Instead, she presents them in brief segments while also declining to assess the extent of students' learning around those concepts or topics.

Grace repeatedly described her perception that students will struggle with the topic of kinetics, citing the math she believed inherent to the topic. As a result, she explained, "…it would have to be really basic for my chem kids" and that "I would have to try and figure out a way to make the math work…but you know how that is where the math takes three times longer to do it" (Member Check). This suggests that Grace has a view that students have a limited ability to engage with the topic and as a result, influences her orientation with respect to science teaching and learning.

Discussing Grace's Kinetics Curriculum

Since Grace does not offer a specific unit on kinetics in her introductory chemistry class, it might be reasonable to assume that she does not believe this topic to be of particular importance for students. After extensively discussing this topic in a semi-structured interview, through the completion of a CoRe document, given the lack of an assessment relating to the topic, and after the subsequent member check it seems that Grace has a limited understanding of the topic (subject-matter knowledge). This appears to play a significant role in limiting her ability to structure meaningful learning opportunities for students to achieve the goals outlined in the relevant NGSS PE (HS-PS1-5), which is also discussed in key sources intended to inform secondary teachers' unit design (e.g., ACS, 2018; NRC, 2012). This standard asks students to connect differences in temperature and concentration with changes in a reaction's rate.

Based on her statements made on the CoRe document she completed and throughout her semi-structured interview, Grace's concept of kinetics knowledge appears to take the form of knowledge as content and knowledge as product. 56.4% of those statements conceived of kinetics as discrete content where 43.6% took the form of knowledge as product and generally aligned with Grace's view that the topic involves a tremendous amount of math that she finds challenging to teach and, in her experience, students find challenging to master (See Figure 11).

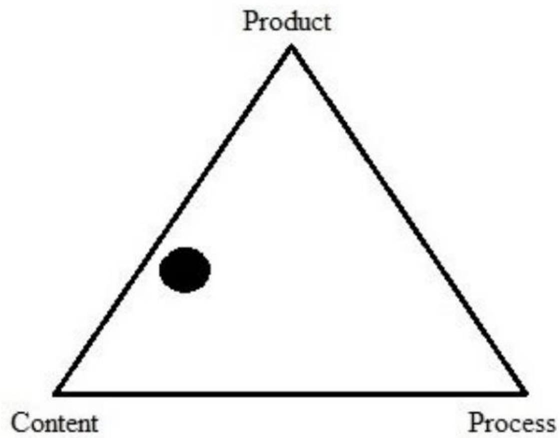


Figure 11. Characterization of Grace's View of Knowledge in a Kinetics Unit.

When given an opportunity to discuss kinetics in greater detail, Grace routinely integrated superficial elements of other topics, such as bond energy, entropy, or calorimetry, as potential concepts that might belong in a kinetics unit without providing insight into any existing relationship between those ideas. These topics perhaps more closely relate to other NGSS PEs, such as HS-PS1-4 or HS-PS3-4. She seemed particularly uncomfortable discussing connections between these elements and others, as well as their connection to the overall chemistry curriculum. Similarly, invoking ideas such as rate limiting steps and mechanisms in kinetics, which are beyond the scope of the NGSS PE, suggest that Grace is aware of a canon of knowledge that is related to the topic, but was not able to discuss them in any further detail. At multiple times, Grace wondered aloud whether she might be thinking about these connections "wrong" or if there might be other, better ways to do this. She also cited her perception that kinetics is challenging due, in large part, to math, which aligns with much of the research about the teaching of kinetics (e.g., Cakmakci, 2010; Marzabal et al., 2018) though she did not cite an awareness of that research at any point in the study. In the semi-structured interview, 11.1% of Grace's statements were coded as negative and largely focused on the math she believed essential to the topic. This aligns with Grace's decision to forego including this topic in a dedicated unit as she believes it to be a tremendous challenge for students, conceptually and mathematically, and acknowledged that her own understanding of the topic could use additional professional development or independent learning in order to be more able to sufficiently translate the topic for her introductory chemistry students.

Participant #2 (Ellie)

Overview

Ellie described her kinetics unit as one that she particularly enjoyed. Her unit is anchored around the phenomenon of cooling a cup of coffee or tea and the way that energy flows in or out of that system. She described this unit to be more singularly aligned with "...material structure...[and] structure and properties or structure and function of materials..." (Member Check). She acknowledged that she does not view it as the same as the part of the unit she considers "kinetics", but they are part of the same learning segment. She clarified that she is "...not going in and tying a full PE and saying it's all here" (Member Check). Much of her discussion for the unit related to controlling the transfer of energy and when asked why it might be important to know about that, Ellie said:

> Students will encounter in their lives a time when energy loss can be avoided with appropriate steps. It can be important in them as a consumer or even a person who must redesign or fix a problem (big or small). (Kinetics Interview)

Much of her ideas about what she believes to be kinetics appeared to be associated with her understanding or perception of the kinetic molecular theory of gases than the traditional conception of kinetics that relates to rates of reactions and changes in factors that influence them.

The Kinetics Curriculum

The two and a half to three week-long kinetics unit that Ellie described takes place just before her unit on nuclear chemistry and immediately follows a unit on energy and fuels that discusses the chemistry of fuel storage and use. During the semi-structured interview, she explained that she asks students to help her come up with "...what the best receptacle for a drink is..." (Kinetics Interview) as part of the initial conversation in the unit. She said that students tend to suggest containers like those made by Yeti and that allows her to pivot the conversation to what makes some containers better at insulating a beverage than another. Ellie reported that she "...hit[s] both metallic structure, conductivity of energy, both forms of energy and then the vacuum" (Kinetics Interview). She described challenges in students understanding what a vacuum is as well as how it works in the context of a Yeti-style container. Following this conversation with students, Ellie asks them to come up with some type of investigation to collect data about various factors that might lead to a particular material allowing more (or less) energy to transfer. She said that students often test the effectiveness of different quantities of ice, the impact of stirring or type of material a spoon was made from on the temperature of coffee or tea in the container. Ellie explained that these conversations serve as the basis for the unit, but she hopes to push students into the use of the equation for the heat gained or lost from a system ($q = mc\Delta T$) and initial discussions around the concept of a chemical reaction being endothermic or exothermic.

Ellie also described her students' use of energy bar charts, or LOL diagrams, throughout this investigation and as they attempt to make sense of their data. She explained that she hopes students apply these ideas to any scenario where energy could be gained or lost from a system but acknowledged that:

> The cooling of tea or the deep dive into the structure of cups is sometimes such a 'small' problem to some students that they don't find it at all important. On one hand it is totally accessible and demonstrates the scale of energy transfer problems from big to small but for some it is too small. (Kinetics Interview)

For Ellie, successful mastery of the content in this unit largely can be represented by students' understanding of what making a Yeti container better at insulating a beverage than another type of container and their ability to model and quantitatively track changes in energy within that system.

There were three distinct "big ideas" that Ellie brought up that she intends for students to explore throughout the unit that she discussed in her semi-structured interview and on the CoRe document she completed (See Appendix G for complete CoRe). The first "big idea" related to energy transfer and Ellie explained that she hopes students come to understand that "heat is transferred through materials differently based on structure" and that "energy moves from high to low [and] cold doesn't spread, heat does" (Kinetics CoRe). She elaborated to say that she uses this section as an opportunity to practice student modeling, depicting energy flows throughout a system.

Ellie's second "big idea" related to the Law of Conservation of Energy, where she explained that she wants students to know that "energy isn't created so it must come from somewhere. Energy isn't destroyed, so it must be transferred to something/somewhere else" (Kinetics CoRe). She clarified that she wanted students to come to better understand the concept of "...heat 'loss' without using 'loss'" (Kinetics Interview).

The ability to harness or control energy was the final "big idea" that Ellie identified. She stated that:

> Energy can be moved through materials quickly or more slowly depending on the structure and design of the materials used. “losing” energy is really just letting it go when you don’t want it to and [that] steps are often taken to help avoid this” (Kinetics Interview)

Ellie acknowledged that students achieve this when they “...suggest a new design or a fix to a problem [that] helps them see a variety of applications where we might want to ‘engineer’ something to encourage or inhibit energy transfer” (Kinetics Interview).

During the analysis of the coded statements made throughout the semi-structured interview as well as the CoRe document she completed, 30.9% of her total statements were excluded (e.g., “I guess” or “Okay”). Of the remaining statements, knowledge as product was the most frequent type of statement with 52.3% and knowledge as content coded in 35.1% of all non-excluded statements (See Table 14). Statements that refer to student knowledge from the process perspective were represented in 10.6% of all statements analyzed. Of the coded statements, none could be described as negative, math-related statements.

Table 14

Codes, Definitions, Sample Responses, and Frequencies for Ellie's Descriptions of her Unit on Kinetics and its Purposes and Structure.

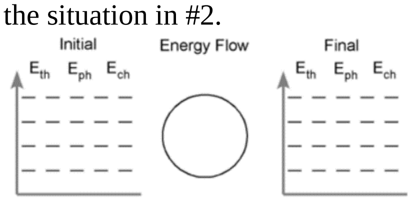
Code	Definition	Sample Response	Frequency
Content	Identification of knowledge as discrete chemistry content	"[I ask them] 'what is an insulator?'" "Energy isn't created so it must come from somewhere"	35.1%
Product	Identification of knowledge based on pre-determined outcomes	"We go through the whole scenario, and I ask for ice and I can't remember to bring something cold, so they have to design an experiment to help come up with a solution and they have to design an experiment to test it" "Many formatives asking for models of various situations and lots of opportunity for students to explain and revise their thinking"	52.3%
Process	Identification of knowledge based on personal relevance	"Students will encounter these problems in their lives where energy loss can be avoided with appropriate steps" "It can be important for them as a consumer or even a person who must redesign or fix a problem (big or small)	10.6%

The topic of kinetics, as described by Ellie, is assessed primarily through a four-question constructed response exam. The questions found on this exam were initially coded and classified as either factual/recall, algorithmic, or conceptual (See Table 15). The factual or recall questions accounted for 16.7% of all questions asked while algorithmic questions were represented on

33.3% of questions included on the assessment. Conceptual questions were the basis for 50.0% of all questions on the assessment and required students to apply their knowledge to a unique scenario that could not be reduced to simple recall or application of a rote algorithm.

Table 15

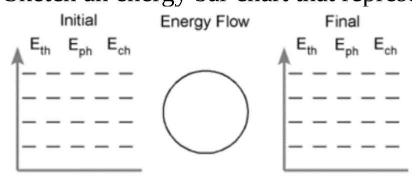
Codes, Definitions, Sample Responses, and Frequencies for the Questions Included on Ellie's end of Unit Assessment on Kinetics.

Code	Definition	Sample Response	Frequency
Factual/Recall	Requires students to recognize or identify key vocabulary words or static relationships (Anderson, Krathwohl et al., 2001; Koufetta-Menicou & Scaife, 2000)	Draw the movement of particles and energy in an example of a *conductive* heat transfer. Identify any objects that are exothermic and any that are endothermic.	16.7%
Algorithms	Procedures for getting "right" answers to routine tasks or problems (Herron, 1996; Nurrenbern & Pickering, 1987)	Draw models of the structure within a poorly insulated coffee cup and a well-insulated cup. a. Show movement of particles and energy inside the cup, through the cup and outside the cup. Sketch an energy bar chart that represents the situation in #2. 	33.3%
Conceptual	Requires students to justify, predict, or explain using deeper analysis and critical thinking (Zoller & Tsaparlis, 1997)	Draw models of the structure within a poorly insulated coffee cup and a well-insulated cup. b. Explain what makes your drawn cups different and how one insulates better than the other. In the coffee and cups investigation, a group, wanting to test how cool a hot drink could become in a span of time using different treatments, would want to control a number of variables to be certain the dependent variable (temperature) was reflecting only the treatment (like stirring) and not another variable. List and explain at least 3 of these variables they'd need to control.	50.0%

Each question on Ellie's summative assessment was also coded for their alignment to each of the "big ideas" she named during the semi-structured interview (See Table 16). The first of the "big ideas" was represented on at least 83.3% of the questions while the second and third "big idea" were each invoked in 100.0% and 50.0%, respectively, of the questions that students were asked to respond to. None of the questions included were unrelated to any of the "big ideas" presented.

Table 16

Codes, Definitions, Sample Responses, and Frequencies for the Questions Included on Ellie's end of Unit Assessment on Kinetics and Alignment to Ellie's Identified "Big Ideas".

Code	Definition	Sample Response	Frequency
Big Idea #1	Energy Transfer	Draw the movement of particles and energy in an example of a conductive heat transfer. Identify any objects that are exothermic and any that are endothermic. Draw models of the structure within a poorly insulated coffee cup and a well-insulated cup. a. Show movement of particles and energy inside the cup, through the cup and outside the cup.	83.3%
Big Idea #2	Conservation of Energy	Sketch an energy bar chart that represents the situation in #2.  Draw the movement of particles and energy in an example of a conductive heat transfer. Identify any objects that are exothermic and any that are endothermic.	100%
Big Idea #3	Harnessing (Controlling) Energy	Design a teapot for *[Ellie]*. This teapot must be able to heat and store hot water for tea. *[Ellie]* is more likely to use her stove than the microwave, enjoys her tea hot, but doesn't drink it very quickly and drinks only a cup or two each day. Describe as much as you can about the choices you would make and why. Draw models of the structure within a poorly insulated coffee cup and a well-insulated cup. b. Explain what makes your drawn cups different and how one insulates better than the other.	50.0%
None	Not specifically aligned to any identified big idea(s).	*(None)*	0.0%

PCK

Subject-Matter Knowledge

Throughout the semi-structured interview, CoRe document completion, and member check, Ellie repeatedly emphasized her view that kinetics and a unit on energy and heat transfer, what she described as “thermo”, were one and the same. Her characterization of the alignment between those ideas was not explicitly connected to NGSS or any other source on its own. When asked to consider a scenario where she had extra time available for her kinetics unit and she defined it, Ellie mentioned not currently distinguishing between the transformation of energy in chemical reactions and clarified that she only addresses the transfer of energy. When prompted to provide additional insight into how she might incorporate energy transformation into the existing unit, Ellie was not able to provide a clear answer.

Ellie explained that “...my content knowledge has definitely grown since I started teaching...[but] the kinetics less so since I did have the engineering background...” (Member Check). She reiterated that Google searches were her primary method of increasing her content knowledge.

Knowledge of Curriculum: Specific Programs

When asked to consider alternative ways that she could teach kinetics in her introductory chemistry class, Ellie suggested that she might consider using refrigerants as an anchoring phenomenon for the unit. After initially talking about what the standards say about the topic as currently constructed, Ellie was asked how she created the instructional materials used to support students’ knowledge development in this unit. She explained that her materials are derived from sources like the Next Generation Science Storylines (n.d.) and American Modeling Teachers Association (n.d.) to create her curriculum, “I cobble everything together” (Member Check).

Knowledge of Curriculum: Science Goals and Objectives

In her mind, Ellie believes kinetics is important because of its relationship to energy transfer and daily problem-solving that students may experience. She described the topic's intersection with the ideal gas law and thermochemistry but was not able to provide additional detail beyond the importance of connecting temperature measurements to the speed of particles and how that influences the readings given on a thermometer. In her mind, kinetics, at its core relates to how the addition and removal of energy influences the speed of particles. She did not mention rates of reaction or how energy might play a role in influencing the progression of a chemical reaction.

For vertical alignment, Ellie mentioned that this unit benefits from student learning in previous courses, like physical science, where students might have already considered aspects of the ideal gas law and use those relationships to incorporate the role of energy in changes to measurable properties like volume or temperature. She did not mention any issues she foresaw with students attempting higher level coursework in sciences or, specifically, in chemistry at either the high school or collegiate levels.

In terms of horizontal alignment, Ellie explained that she sees kinetics as a topic that encompasses "...regular energy, conservation of energy like the defying the conservation of energy and matter". Coming out of a unit on fuels, she views her unit on kinetics as a natural transitional unit before moving into nuclear chemistry where she talks about what she described in the semi-structured interview as exceptions to the Law of Conservation of Energy.

When asked to describe the role of kinetics in NGSS, Ellie was somewhat unclear on the specifics of what the standards said. She explained:

> My recollection is that the phrases we usually look for are hidden more. It's not as obvious but there is, I know that we use the one where the properties of, well see, I haven't looked at them for a while. It's the properties, the structure of a material. I think it might even be an engineering design or maybe it's not. It might just be [that] it's a physical science where the properties of a substance are based on the structure of that on a microscopic level or atomic level. Atomic structure. I can say it, but I can't. The crosscutting concept of energy, there are a couple of the elements there that I feel like we hit on but I can't tell you the wording on them. (Kinetics Interview)

Ellie's explanation went on to clarify that she felt this unit would be tied to students' understanding of macroscopic properties and its intersection with the Law of Conservation of Energy.

Science Teacher Orientations

Ellie's view of the goals and purposes of science teaching and learning for the topic of kinetics appears to be rooted in the notion that students should be working to develop problem-solving skills, but acknowledged that there were multiple potential ways of getting students to the same end goal, saying:

> It's about solving problems in general. So, I talk to them about how I use intentionally a problem that seems minor and unimportant to establish that we can solve our problems and we can step through steps for how to solve them and what we're willing to do, the constraints for a problem. (Kinetics Interview)

This view aligns with the design of Ellie's summative assessment, which includes 50.0% of all questions being conceptual in nature. Rote factual or recall styled questions were the least emphasized on the assessment and similarly reflects Ellie's view that mere accumulation of information is less preferable to the development of problem-solving skills.

In a similar vein, Ellie's design of her unit appears to draw student toward a view of science as one that relies more on the process of "doing" science compared to one that reifies facts. While this is shown in her assessment design, it also is reinforced to a certain degree in her statements made throughout the semi-structured interview and on the CoRe document, where only 35.1% of all statements about student knowledge could be understood as knowledge as content, or discrete blocks of information (See Table 15).

When discussing her approach toward designing and assessing students throughout this learning segment, Ellie did not once suggest that students had a good reason limiting their ability to engage with the ideas included. Of her statements made in the semi-structured interview and CoRe document, 0.0% were coded as negative or suggesting a limited student ability. When given an opportunity to more specifically address student ability on the CoRe document, answering the question "What are the difficulties/limitations connected with teaching this idea?", Ellie identified areas of conceptual difficulty, but did not use those as reasons not to invite students to grapple with those ideas in the unit. For example, she said "students sometimes refer to energy as particles and hold on to the idea that 'cold' can transfer" or "students see that metal is a conductor but continue to recommend a metal container for insulation without explaining the vacuum between two layers" (Kinetics CoRe). These types of challenges or alternative conceptions were framed as obstacles to overcome, that could be dealt with and further reinforce Ellie's view about science teaching and learning to include students' expanding ability.

Ellie also described giving students the space to plan and conduct investigations to collect data that allows them to test their ideas in real time. She explained that she allows them to explore most any variable and supports them in making sense of the data, which suggests that her view of science teaching and learning around the topic of kinetics as she understands it encourages students' independent thinking.

Discussing Ellie's Kinetics Curriculum

Ellie's kinetics unit appears structured to allow students to gain practice tracing the flow of energy into and out of systems as well as to explore some of the factors that might prevent or enhance that movement. The use of a more open-ended investigation allowing students to test the impact of various factors (e.g., stirring, amount of ice, types of materials, etc.) on the loss of energy from a system (a cup of coffee or tea). This provides students with opportunities to make connections between each of the "big ideas" that Ellie identified: transfer of energy, the Law of Conservation of Energy, and harnessing (controlling) energy.

In her responses throughout the interview and in the CoRe document she completed, Ellie consistently defined kinetics knowledge as a combination of content (35.1% of the time), product (52.3% of the time), and process (10.6% of the time). This suggests that she believes the topic of kinetics, as she understands it, should be experienced as a set of pre-determined outcomes that involve a set body of content that students are expected to be able to use and relate to themselves or their place in the world (See Figure 12).

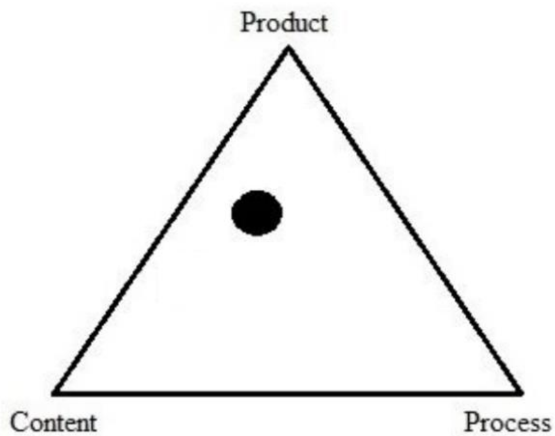


Figure 12. Characterization of Ellies's View of Knowledge in a Kinetics Unit.

The summative assessment that Ellie created to assess student learning at the end of her unit on kinetics appears to align with her multifaceted (in terms of knowledge as content, product, and process) understanding of what student knowledge should look like. Students are largely asked to respond to conceptual questions (50.0% of all constructed response items) that ultimately requires students to use specific content and the outcomes of classroom experiences together to sufficiently answer each of those types of questions. At the same time, the "big ideas" that she had identified during the semi-structured interview are well-represented on the assessment with "Big Idea #3" being the least represented in only 50.0% of all questions asked.

As Ellie discussed her teaching procedures in this unit, she exclusively described student actions (e.g., "Students measure...", "Students create...", or "Students determine...") which suggests a more student-centered view that aligns with the forms of knowledge emphasized in the unit. This also complements her stated goal of having students use their learning about the nature of energy transfer to harness it in chosen ways to solve a problem.

A Comparison of Grace and Ellie's Kinetics Curricula

Within the scope of the NGSS PE most related to kinetics, HS-PS1-5, students should be asked to "apply scientific principles and evidence to provide an explanation about the effects of changing the temperature or concentration of the reacting particles on the rate at which a reaction occurs" (NGSS Lead States, 2013). A comparison of Grace's and Ellie's units on what they described as kinetics shows a significant divergence in subject-matter knowledge as well as the expectations of the standards themselves. While Grace cited a limited understanding of kinetics prior to teaching it in her classes, Ellie reflected on her engineering background to consider her level of comfort with the topic. Both teachers described supplementing their existing subject-matter knowledge with internet searches and described their level of comfort with the topic as improving over time. Despite that, Grace does not currently offer a formal unit on the topic nor was she able to articulate a clear vision supporting how one could be integrated into her existing curriculum and Ellie's unit does not appear to meaningfully relate to the topic of kinetics itself. Within Ellie's learning segment, students are asked to consider the flow of energy within a chemical system, which aligns much more with HS-PS3-4 in NGSS than a unit on chemical kinetics (HS-PS1-5). Neither teacher appeared to understand the idea of chemical kinetics as outlined by NGSS Lead States (2013) or ACS (2018).

Grace's orientation to the teaching and learning of kinetics appears to be firmly rooted in the importance of the content that she believes core to the topic (e.g., rates of reactions, the Law of Conservation of Mass, or energy's role in breaking down or forming substances) than applications of that content to the lived experiences of students or other pre-determined outcomes. In her unit, Grace understands that content to be forms of factual knowledge and preferentially requires that students gain knowledge in the form of new information than asking them to solve a particular type of societal problem. This can be understood in context of the statements made throughout the semi-structured interview and CoRe document she completed where 56.4% of all coded statements that she made related to knowledge as content. Grace's belief about the importance of this topic can also be inferred from the lack of any assessment relating to the topic.

Ellie's kinetics curriculum appears to reflect an orientation to the teaching and learning of kinetics that suggests a view that student growth should take place in the form of developing problem-solving skills and using them to interpret what she described as mundane, everyday phenomena like the structure and function of a coffee mug that keeps a drink warmer longer. Though she alluded to NGSS at several points, it is not clear that her approach to teaching this topic supports students in realizing HS-PS1-5, the PE that most closely aligned with the topic of kinetics. Despite this, she described revisiting her approach to teaching the topic she understands as kinetics in her class following NGSS adoption. Ellie explained that she did not necessarily include this topic early in her career and went on to clarify that:

> I would say that when I taught at the very beginning of my career, I did more introduce the atom, you do reactions, the types of reactions, the predicting reactions, the naming, the stoichiometry, and if you have time you get to the thermo and acids and bases. And I did that over and over again and got frustrated feeling like I wasn't getting to the cool stuff. You know, the stuff you can see. (Kinetics Interview)

Despite these changes, Ellie's unit on kinetics appears, instead, to be a unit more closely aligned with calorimetry or energy transfer in systems.

The reasons that Grace and Ellie offered to explain their inclusion (or lack thereof) of the topic of kinetics in their curricula provides needed context to understand why a topic like kinetics might receive differing levels of curricular focus than other topics in chemistry. Grace was not able to articulate the impact, if any, that NGSS had on her willingness to teach the topic as she explained that her understanding of the topic was not sufficient to confidently construct a learning segment that she feels makes sense in the context of her existing introductory chemistry curriculum. While she reported a willingness to seek out professional development or other related learning opportunities for other topics (e.g., nuclear chemistry) that she felt had been left out of her curriculum, that same level of interest does not seem to be present for kinetics so far. Ellie's kinetics curriculum appears to be limited by her understanding of the topic as well as a lack of awareness of the extent that the topic is included in NGSS. Though the unit she described included references to other PEs (e.g., HS-PS1-4 or HS-PS3-4) that seem entirely reasonable for an NGSS-based chemistry course, those do not necessarily align with HS-PS1-5 which more appropriately addresses chemical kinetics as a topic.

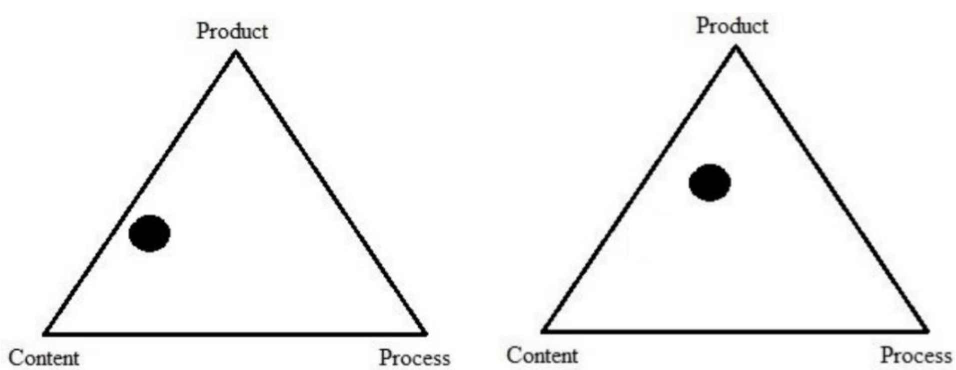


Figure 13. A Comparison of Grace's and Ellie's Views of Knowledge in a Kinetics Unit.

The impact of teachers' curricular knowledge and orientations to the teaching and learning of science on their enacted curriculum with respect to kinetics can be understood given the elements of PCK discussed above (RQ2b). Grace and Ellie both independently described their view of what it means for students to develop knowledge about kinetics (See Figure 13). For Grace, that knowledge in a kinetics unit more frequently takes the shape of the accumulation of a set body of facts, such as a list of factors that might influence a chemical reaction. In Ellie's unit, knowledge might mirror Grace's in that energy is a core component of her concept of the "big ideas" in the unit, but the knowledge developed by students might more accurately be represented as a combination of content, product, and process which requires students to synthesize ideas and apply them to distinct problems (See Table 17 for a comparison). As with their units on nuclear chemistry, Grace and Ellie's units on kinetics align to their stated purposes and appear to employ teaching and assessment practices that align with those goals.

Table 17

Comparison of Grace and Ellie's Knowledge Statements and Summative Assessment Questions for a Kinetics Unit

Frequency of Statements Coded for Type of Knowledge		
	Grace	Ellie
Content	56.4%	35.1%
Product	43.6%	52.3%
Process	0.0%	10.6%
Frequency of Summative Assessment Questions Coded for Question Type		
	Grace	Ellie
Factual/Recall	N/A	16.7%
Algorithmic	N/A	33.3%
Conceptual	N/A	50.0%

CHAPTER VI: DISCUSSION AND LIMITATIONS

Research Question 1

Research question #1 asks "why do certain topics included in the standards (nuclear chemistry or kinetics) receive differing levels of attention across different experienced teachers' introductory chemistry curricula?". Teacher content knowledge appears to play a significant role while knowledge of standards and understanding of available resources (curricular knowledge) and their understanding about the purpose (the "why") for teaching a given topic seems to be a lesser contributor to the amount of time that teachers are willing to dedicate to teaching the topic—or whether they are willing to teach it at all. Both Grace's and Ellie's nuclear chemistry units were rather new additions to their introductory chemistry curricula following the adoption of NGSS in Illinois in 2014. Grace stated that her inclusion of nuclear chemistry was coincidental with NGSS while Ellie cited the new standards as a driving force behind the changes her nuclear chemistry unit has undergone in the years since. In terms of kinetics, both teachers abstractly referenced NGSS and its relationship to kinetics but were neither able to articulate its connection to the topic nor were they able to describe any impact that those standards had on their teaching of the topic. For one teacher and one topic (Ellie and nuclear chemistry), the standards seemed to impact her choice to give attention to a topic though this relationship between standards and topic coverage was not uniform in Ellie's decisions nor were they across the teachers involved in this study. This aligns with existing scholarship that understands the complicated relationship between teachers' knowledge of standards and their interest or ability to implement those standards in their classes (e.g., Banilower, 2019; Roehrig & Kruse, 2005; Schmidt & Prawat, 2006).

By Grace and Ellie's own words, their respective knowledge of nuclear chemistry and kinetics prior to teaching those topics was limited. Both teachers referenced a lack of undergraduate coursework relating to nuclear chemistry as a reason for their limited knowledge base, which is consistent with previous studies (e.g., Konkankit et al., 2021). Grace and Ellie each cited a great deal of work that was done on their parts through professional development attendance and independent learning to develop sufficient understanding for themselves that could then be translated for student learning. Given this initial lack of subject-matter knowledge, it is unsurprising that a teacher might be less able to support student learning for nuclear chemistry than other topics that they might have more confidence in teaching due to greater subject-matter knowledge. For kinetics, Grace reported an initial lack of understanding about what the standards asked of students for the topic and went further to explain that she "...probably know[s] less about kinetics than [nuclear]" (Member Check). Because of her lack of subject-matter knowledge for nuclear chemistry, Grace chose to seek additional professional development. Either similar opportunities did not present themselves as readily for kinetics or Grace felt less inclined to remedy an area that she knew was not an area of strength in terms of subject-matter knowledge. The result is the lack of a formal unit on kinetics and a minimal infusion of the topic into her existing curriculum.

For Ellie, she referenced her background in engineering as a reason she felt better prepared than most to teach the topic of kinetics in her introductory chemistry classes. Despite that, and a general awareness of NGSS, the unit that Ellie identified as kinetics more closely aligned with calorimetry or heat transfer. This aligns with the existing scholarship on pre-service teachers and undergraduates (e.g., Cakmakci, 2010 and Sozbilier et al., 2010) that suggests many students ultimately graduate with superficial understanding of chemical kinetics and significant alternative conceptions relating to conceptual differences between physical chemistry and thermodynamics persist.

Teacher beliefs about the "why", or purpose for learning the knowledge in each unit appear to drive the topic's coverage as well. Grace and Ellie both reported a desire to help students connect their learning to the real-world and make that learning relevant. Grace articulated a view of nuclear chemistry's real-world application from a factual basis, simultaneously allowing students to receive what she viewed as canonical nuclear chemistry knowledge, but also one that she felt resonated with her own life experiences (e.g., having to test her home for radon before selling it). She did not seem to have the same "real life" connections for kinetics to include it in her curriculum. Ellie articulated a slightly different perspective by repeatedly citing individual students' needs and interests as the basis for the topic while also acknowledging their role in society as a separate, but still relevant, purpose for learning about the topic, but in this way she was able to include nuclear and her version of kinetics for her students.

Grace and Ellie appear to view the goals and purposes of science teaching and learning slightly differently. Both teachers seem to include a purpose that learning should relate to students' "real-lives" or help them to better understand the world around them. Grace seems to see that "why" as having facts related to real-life while Ellie is more interested in having her students engage with those topics in ways that she might expect of herself in the context of her daily life. Ellie's approach to bringing "real life" to students is a bit more in line with the existing scholarship on authentic learning (e.g., King et al., 2008 & Bulte et al., 2006) though Grace's strategy of using facts and algorithms to present students with genuine applications of chemistry is discussed in the literature as a common approach that does not appear to consistently succeed in supporting students' ability to retain what was learned over the medium or long terms (e.g., Avargil et al., 2012 and Ultay & Calik, 2011).

In short, teacher familiarity with the state standards (related to knowledge of curriculum: goals and purposes as well as knowledge of curriculum: specific programs) and their level of subject-matter knowledge, including how it relates to the "real world" appears to be two of the most significant factors that determine Grace or Ellie's willingness to integrate a new topic into their existing curriculum. Concurrently, teachers' views of the purposes for teaching and learning of science appear to play a significant role in influencing what Grace and Ellie each expect student knowledge to look like at the end of an instructional unit as well as their ability to translate their subject-matter knowledge for student learning. Their expectations for their students, while different, align with their personal views.

Research Question 2

Research question #2 asks, "how do teachers' curricular knowledge and orientations to the teaching and learning of science influence their decisions relating to their chemistry curricula (a form of their enacted PCK)?". As mentioned above, Grace and Ellie both reported a desire to help students connect their learning to the real world and make their learning relevant. Despite that shared goal, both teachers went about achieving it differently. For Grace, facts serve as the primary means to capture the real-world phenomena she is interested in sharing with her students while Ellie uses a series a relatable problems or issues (e.g., building a nuclear plant in your hometown or cooling down a hot cup of tea) to realize the same goal.

Research Question 2a

Research question #2a asks, “how do teachers’ curricular knowledge and orientations to the teaching and learning of science influence their enacted curriculum with respect to the topic of nuclear chemistry?”.

Understanding Curriculum

In terms of their understanding of curriculum, both teachers understood knowledge in the context of a unit on nuclear chemistry differently. Ellie’s unit included many of the same elements that Grace’s unit did, but also positioned her students at the center of the learning, asking that they also find ways to relate the topic to their interests, to their family, and to their community. In Ellie’s telling, nuclear chemistry is best learned through student action, and she hopes to support their ability to navigate complex social and scientific ideas that students find value in. Ellie defined knowledge as content and product in 80.5% of the statements she made compared to Grace with 97.4% of her statements over a similar time interval (See Table 9). These differences were similarly highlighted on the summative assessment given by both teachers as 56.7% of the questions asked by Grace could be interpreted to be simple facts or recall while 14.3% of the questions asked by Ellie could be labeled the same.

Table 18

Comparison of Grace and Ellie's Concept of Knowledge for a Nuclear Chemistry Unit

	Grace	Ellie
The "WHAT"	Content Product	Content Product Process
The "HOW"	Transmission	Development
The "WHY"	Canon of Chemistry Knowledge	Self-fulfilment

For Grace, that generally resulted in students being told about ways that elements of the topic (e.g., half-life) are commonly used in a factual manner. That is, students were often told what happens, and their experience was limited to what the teacher views as important or interesting. For Ellie, students were given a phenomena or real-world context with the purpose of asking them to seek meaning for themselves or their community. Students that achieve Grace's goals are largely able to converge on a specific skillset and knowledge base that mirrors that of Grace's own knowledge while students that achieve Ellie's goals might develop and use similar information but use it for different purposes and in much different contexts. As Tekin & Nakiboglu (2006) explain, nuclear chemistry is a topic with perpetual relevance in daily life, leaving teachers with innumerable opportunities to find relevance to their own experiences, to their own community, and to the world at large. See Table 18 for a visual representation of Grace and Ellie's concept of knowledge for a unit on nuclear chemistry.

Curricular Knowledge

For Grace, learning was intended to expose students to real-life applications of nuclear chemistry through the accumulation of facts. With that goal in mind, she structured her unit around herself as a 'knower' and the students being able to largely replicate her level of understanding through lecture and teacher-facilitated discussion necessary to transmit the requisite information (knowledge). While aware of the alignment between NGSS and the topic of nuclear chemistry, Grace did not indicate that her unit is driven by the standards, nor are they heavily influenced by an awareness of another specific program intended to support student learning around the topic. Her unit, instead, was most influenced by the accumulation of resources from assorted professional developments, independent research, and elsewhere. For Ellie, the NGSS PEs relating to the topic of nuclear chemistry were forefront in her mind and something that appeared to drive her unit design alongside her willingness to leverage other existing programs and resources design to support teachers in helping students learn more about the topic. The NEED Project (2020) served as her primary program and resource, but Ellie indicated that other sources were leveraged to lesser extents.

Table 19

Comparison of Grace and Ellie's Curricular Knowledge for a Nuclear Chemistry Unit

Elements of Grace's PCK for Nuclear Chemistry: Curricular Knowledge		
	Extent of Knowledge	Influence on Unit Design
Knowledge of Curriculum: Science Goals and Objectives	Aware of Standards	Does Not Explicitly Use Standards in Unit Design
Knowledge of Curriculum: Specific Programs	Aware of Existing Programs and Resources	Existing Programs and Resources Serve as Basis for Unit
Elements of Ellie's PCK for Kinetics: Curricular Knowledge		
	Extent of Knowledge	Influence on Unit Design
Knowledge of Curriculum: Science Goals and Objectives	Aware of Standards	Standards Drive Unit Design
Knowledge of Curriculum: Specific Programs	Aware of Existing Programs and Resources	Existing Programs and Resources Serve as Basis for Unit

The perspectives of Grace and Ellie mirror those described in the literature (e.g., Tekin & Nakiboglu, 2006; Unak, 2017) as teachers possessing lesser amounts of knowledge relating to the topic of nuclear chemistry tend to struggle creating systems to educate others on the topic. The added support that comes from a knowledge of the relevant standards and resources that currently exist to support the teaching of a topic like nuclear chemistry clearly allowed Grace and Ellie to both begin teaching the topic with comparatively less struggle than they might otherwise have had. See Table 19 for a visual representation of the components of curricular knowledge and their influence on each teacher's unit.

Science Teacher Orientations

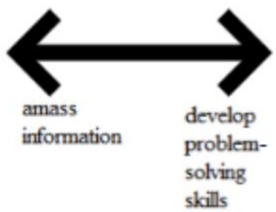
Grace's orientation to the teaching and learning of nuclear chemistry relies heavily on the assumption that accumulation of factual knowledge and students' ability to describe natural processes like radioactive decay are essential to realize her goals for students. She did not cite many barriers to student success in this unit and indicated that student success required her to transmit her set body of knowledge and understanding of established procedures for solving radioactive decay or half-life problems. Ellie, by contrast, repeatedly explained her view that the unit's purpose aligned with helping students to engage with and consider potential solutions to everyday problems (e.g., how to evaluate potential benefits and drawbacks of radiation treatment for cancer) while also asking students to develop a proficiency in the knowledge and procedures that Grace discussed in her unit. See Table 20 for a representation of Grace and Ellie's dominant orientations to the teaching and learning of science for a unit on nuclear chemistry, derived from Figure 6 and previously discussed in chapter four.

Table 20

Comparison of Grace and Ellie's Dominant Orientations to the Teaching and Learning of Science for a Nuclear Chemistry Unit

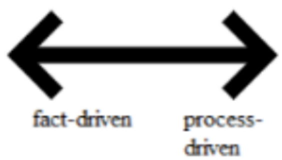
Teacher's Dominant Orientation to the Teaching and Learning of Science (Nuclear Chemistry)

The Goals or Purposes of Science Teaching



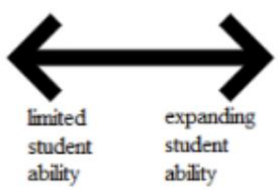
	Grace	Ellie
The Goals or Purposes of Science Teaching	Amass information	Develop problem-solving skills

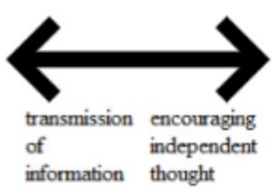
The Nature of Science



	Grace	Ellie
The Nature of Science	Fact-driven	Process-driven

Science Teaching and Learning





	Grace	Ellie
Science Teaching and Learning	Expanding student ability	Expanding student ability
	Transmission of information	Encouraging independent thought

The tension in Grace and Ellie's unit designs, centered around what "real-world" teaching and learning looks like must ultimately be confronted as students experience the unit and take time to provide evidence of their learning. While the existing literature on the topic of nuclear chemistry is relatively undertheorized, Tekin & Nakiboglu (2006) discuss the prevalence of what they describe as “rote learning” or “algorithmic problem solving” and emphasize the need to shift toward more conceptual tasks that require higher-order thinking. In this sense, it echoes many of the issues raised by Unak (2017), describing the implications of a comparatively lesser body of knowledge teachers may otherwise have to draw upon as well as the distinct differences in the way that Grace and Ellie have constructed their own units on nuclear chemistry.

Research Question 2b

Research question #2b asks, “how do teachers’ curricular knowledge and orientations to the teaching and learning of science influence their enacted curriculum with respect to the topic of kinetics?”.

Understanding Curriculum

Despite both teachers’ awareness of nuclear chemistry and its presence in NGSS, that same level of awareness was not nearly as apparent for kinetics. Grace’s view of knowledge remained factual and her understanding of what real-world applications look like mirrored that of nuclear chemistry, but her level of curricular and subject-matter knowledge appeared to be substantially different between the two topics. For Ellie, the unit she described did not align well with the topic of kinetics and suggests a similar misalignment between her nuclear chemistry and kinetics units.

Table 21

Comparison of Grace and Ellie's Concept of Knowledge for a Kinetics Unit

	Grace	Ellie
The "WHAT"	Content Product	Content* Product* Process*
The "HOW"	Transmission	Development*
The "WHY"	N/A, Not Currently Taught	Self-fulfilment*

Note: An asterisk (*) denotes where the evidence provided, regardless of its extent or influence, did not align with the substance of NGSS or the standards related to the topic.

Grace framed knowledge relating to chemical kinetics in terms of content or product in 100% of her statements made throughout the interview and CoRe document completion while Ellie described it in similar terms in only 89.4% of her statements made. To Grace, this topic is learned largely through accumulation of facts and the development of proficiency with the use of select algorithms, such as rate law calculations. Despite describing a unit that does not align with the concept of kinetics as described in NGSS, Ellie repeatedly emphasized the value she believed inherent to students attempting to engage with concepts that may not have a singular, clear solution (e.g., whether ice, vigorous stirring, or another intervention should be used to modify the temperature of a cup of tea). Grace's understanding of how a kinetics unit could operate echoes the cautions of Sozbilier (2004) in the concern about teachers' prioritization of algorithmic problem solving over more conceptual applications or understanding associated with the topic. See Table 21 for a visual representation of Grace and Ellie's concept of knowledge for a unit on kinetics.

Curricular Knowledge

The kinetics units of Grace and Ellie were different for multiple reasons, chief among them that Grace did not actually have a formal unit on kinetics while Ellie shared a unit that more closely aligned with the topic of calorimetry or heat transfer than kinetics.

Unlike her nuclear chemistry unit, the state's adoption of NGSS did not appear to influence Grace to consider changes to the way that kinetics is presented within her introductory chemistry class. Ellie cited NGSS as an opportunity to reconsider what she had previously taught and how she taught it but understood the topic of kinetics entirely differently than Grace. Neither teacher possessed sufficient curricular knowledge to meaningfully construct a unit that supports the expectations laid out in NGSS for the topic of chemical kinetics.

Table 22

Comparison of Grace and Ellie's Curricular Knowledge for a Kinetics Unit

Elements of Grace's PCK for Kinetics: Curricular Knowledge		
	Extent of Knowledge	Influence on Unit Design
Knowledge of Curriculum: Science Goals and Objectives	Minimal Awareness of Existing Standards	Standards do not Influence Unit (or lack thereof)
Knowledge of Curriculum: Specific Programs	Unaware of Specific Programs or Resources	Minimal Resources are Used
Elements of Ellie's PCK for Kinetics: Curricular Knowledge		
	Extent of Knowledge	Influence on Unit Design
Knowledge of Curriculum: Science Goals and Objectives	Unaware of Existing Standards*	Standards do not Influence Unit Design
Knowledge of Curriculum: Specific Programs	Aware of Existing Programs and Resources*	Existing Programs and Resources Serve as Basis for Unit

Note: An asterisk (*) denotes where the evidence provided, regardless of its extent or influence, did not align with the substance of NGSS or the standards related to the topic.

The challenges experienced by Grace and Ellie in constructing units that support students in realizing the goals of the standards is not unexpected given their stated lack of understanding of both the standards and the potential resources available to teach the topic. The work of Banilower (2019) found that as many as 16% of teachers surveyed reported not using state standards to drive their instruction. While a breakdown of individual topics was not discussed in that context, it may not be unreasonable to see that teachers may selectively choose which standards to attend to and which to either ignore or save for the unlikely event that more time remained at the end of the school year. See Table 22 for a visual representation of the components of curricular knowledge and their influence on each teacher's unit.

Science Teacher Orientations

Grace's orientation to the teaching and learning of kinetics relies heavily on the assumption that accumulation of factual knowledge and completion of math-driven algorithmic problems is emblematic of knowledge for the topic. She repeatedly made statements in the interview and CoRe document that referred to knowledge in terms of information that students would acquire from her as the 'knower' in the classroom. Students' expected struggles around the rate law math she felt was essential to the topic was an issue that she cited to partially justify her reasoning for not including this topic in her curriculum. Ellie, despite presenting a unit designed to help students engage with and consider potential solutions to ordinary, everyday problems (e.g., how to cool a warm beverage), did not offer any evidence that the unit described was related to the topic of chemical kinetics. See Table 23 for a representation of Grace and Ellie's dominant orientations to the teaching and learning of science for a unit on kinetics, previously discussed in chapter five, and derived from Figure 6.

Table 23

Comparison of Grace and Ellie's Dominant Orientations to the Teaching and Learning of Science for a Kinetics Unit

Teacher's Dominant Orientation to the Teaching and Learning of Science (Kinetics)		
	Grace	Ellie
The Goals or Purposes of Science Teaching amass information ⟷ develop problem-solving skills	Amass information	Develop problem-solving skills*
The Nature of Science fact-driven ⟷ process-driven	Fact-driven	Process-driven*
Science Teaching and Learning limited student ability ⟷ expanding student ability	Limited student ability	Expanding student ability*
transmission of information ⟷ encouraging independent thought	Transmission of information	Encouraging independent thought*

Note: An asterisk (*) denotes where the evidence provided did not align with the substance of NGSS or the standards related to the topic.

Grace's understanding that student difficulty in solving kinetics problems involving math was one that she highlighted as a reason for avoiding the topic in her introductory chemistry classes. These feelings are not unique to Grace's experience and are mirrored in much of the research around the teaching of kinetics (e.g., Marzabal et al., 2018).

Limitations

The most significant limitation of this study is that it involves the experiences of two teachers that teach in similar settings. The findings of this study should only be interpreted as representative of these teachers and contextualized solely within the locations they teach. In addition, the data collection timeline for this study occurred during a period of profound educational disruption associated with SARS-CoV-2 and the COVID-19 pandemic. While teachers were asked to consider their curriculum absent the unique, temporary modifications they were forced to make considering changes to in-person, remote, or hybrid learning schedules at their schools, these concerns may have inadvertently been considered in participant responses.

The interview and document completion portions of the study rely on self-reported data which cannot be guaranteed to be reliable. While subject-matter knowledge is addressed, in part, it is not the focus of the study and should not be interpreted to represent the full extent of a teacher's subject matter knowledge. Any findings that arise from this study should demonstrate external validity by virtue of using multiple sources of evidence in the case study (Yin, 2018). The initial interviews and collection of artifacts such as the CoRe tool (adapted from Loughran et al., 2004) and classroom assessments support an initial understanding in a small sample and is consistent with a case study approach. Collecting and analyzing the assessment(s) used by participants should not be interpreted as an attempt to collect data on teacher knowledge of assessment, another element of PCK. In this context, assessments are used to gain insight into teachers' curricular goals as well as their orientation to the teaching and learning of science, particularly their understanding of the purpose of teaching and learning each topic in an introductory chemistry course. The inherent limitations of that approach, including participant reflexivity and researcher mis-articulation, are largely mitigated by using member checking to establish validity and allows any findings from cross-case comparisons to be more reliable than they would be otherwise.

CHAPTER VII: CONCLUSION AND RECOMMENDATIONS

Summary of Study

In this study, the nuclear chemistry and kinetics units of two experienced teachers were explored to gain a deeper understanding of what student learning is intended to look like for these topics in an introductory chemistry class. Prior research (e.g., Burt & Boesdorfer, 2021) indicated that there are multiple topics aligned to state standards that receive comparatively less attention than other topics. Nuclear chemistry and kinetics are topics representative of those that are more likely to be marginalized in introductory chemistry classrooms.

Both participants that were chosen, Grace and Ellie, stated that they currently teach nuclear chemistry and kinetics and that, along with their level of experience as veteran teachers and their willingness to participate, matched the established criteria for their inclusion in the study. Semi-structured interviews were conducted prior to asking teachers to complete a content representation (CoRe) document to further elaborate on the "big ideas" they had generated from the interview. Following completion of the CoRe document, participants were asked to submit their summative assessment(s) for each topic. After initial coding and analysis was complete, a member check interview was conducted to ensure that findings and characterizations of their curricula and practice were accurately captured (See Table 2 for a summary of data collection steps). This process was then repeated for the next topic. The results of this study provide answers to the initial research questions seeking to better understand why certain topics in chemistry are given more (or less) attention and how teachers' subject-matter knowledge and elements of pedagogical content knowledge might shape their curricular decisions.

For the first research question, it appears that the reason that certain topics receive differing levels of attention in teachers' chemistry curricula can be understood in terms of teacher subject-matter knowledge, their knowledge and understanding of NGSS, and their understanding of the purpose ("why") for teaching science (real-world). For nuclear chemistry and kinetics, both participants reported a limited understanding (subject-matter knowledge) of the topics that required independent work on their own (e.g., workshop attendance, Google searches) as a prerequisite for deepening their knowledge base and teach nuclear chemistry in their introductory chemistry classes. Neither teacher reported undertaking that same level of effort to enhance their subject-matter knowledge for the topic of chemical kinetics. Grace reported no longer covering this topic in her classes while Ellie identified a unit that does not align with the topic of kinetics as outlined in NGSS.

Both teachers reported a familiarity with the presence of nuclear chemistry in NGSS, but neither were able to successfully do the same for kinetics. Across nuclear chemistry and kinetics, Grace believed that both topics largely serve as opportunities for teachers to share interesting examples of the topic in the natural or industrial world. In doing so, she asks that students develop knowledge around these examples in the form of isolated facts or understanding and proficiency in the use of simple algorithms. Ellie described student learning in nuclear chemistry that is intended to serve the purpose of not just supporting students' efforts to make sense of nuclear processes, but also to contextualize those processes within the world that students are living in. Neither teacher appeared aware of what real-world connections to kinetics might look like (e.g., rust prevention or water treatment), which might explain why, with their limited subject-matter knowledge, they did not interpret NGSS or kinetics in their chemistry curricula.

For the second research question, teachers' curricular knowledge and orientations to the teaching and learning of science were explored to understand how those components of PCK shape teachers' approach to constructing their units. Grace and Ellie's orientations were similar across both topics (shown on Tables 21 and 23). The only meaningful difference was between Grace's nuclear chemistry and kinetics units. In her nuclear chemistry unit, Grace's view of science teaching and learning reflected a view of expanding student ability. That is contrasted with a view of limited student ability in context of a kinetics unit she described as having math that she perceived to be incredibly challenging for students. These views of science teaching and learning likely influenced each teacher's unit design as both teachers constructed units that reflect their science teacher orientations, including the desire to omit ideas or topics they felt were beyond their students' capacities. For that reason, teachers that more significantly emphasized knowledge as product (Grace) expected students' learning to take place in terms of discrete facts they learned (and captured on a multiple-choice exam). Ellie's view, emphasizing knowledge as process, did not rely on multiple choice questions to capture student learning. Instead, students were asked to respond to open-ended prompt that elicited more nuance about students' individual learning. Overall, teachers' orientations largely persisted across topics, but levels of curricular knowledge differed tremendously for both teachers across topics.

Curricular knowledge for nuclear chemistry was similar for both teachers, with both aware of NGSS and its expectations for students but reported differing levels of desire to ensure those goals were realized in their classes (shown on Tables 20 and 22). Grace and Ellie each reported using a different set of programs (e.g., The NEED Project, 2020; POGIL activities, derived from Trout, 2012) designed to support teachers and students in a nuclear chemistry unit.

For the topic of kinetics, both teachers reported a very low awareness of what the standards called for as well as what potential resources could be utilized.

Implications

The findings of this study have implications for the ongoing research surrounding the implementation of reform-based standards and the practice of secondary science educators in the classroom. The model of knowledge used throughout this study, derived from Kelly (2004) and Greene (2017), served as an initial framework for interpreting the curriculum of practicing chemistry teachers. This model was particularly useful in decoding and interpreting the language used by teachers as they described their goals and intended assessment practices for units on nuclear chemistry and kinetics. Using this, teachers' understanding of what knowledge looks like for a given topic could be more precisely elucidated.

The model of curriculum design, adapted from Gehrke (1992), Kelly (2004), and Slattery (2006) provided additional opportunities to understand more about the construction of teachers' curriculum and the way that they might operationalize their goals for students in the form of curriculum. Understanding curriculum in terms of "the what", "the how", and "the why" served as a helpful framework for interpreting teachers' discussions around their goals for students and the actions they might expect of their students in fulfillment of those goals.

The consensus model (CM) of pedagogical content knowledge (PCK) , described in Gess-Newsome (2015), served as a valuable framework, particularly to understand teachers' orientations to the teaching and learning of science for each topic as well as their curricular knowledge and subject-matter knowledge. The orientations to the teaching and learning of science were particularly useful to decouple teachers' overall views about teaching and learning in science compared to the field of chemistry or specific topics.

Future studies focusing on how teachers enact their curricula would provide greater context around the nature of knowledge that teachers expect their students to acquire, develop, or construct in their learning. This would supplement the work already done to gain a more well-rounded understanding of the nature of teachers' units on nuclear chemistry or kinetics. In that respect, it may also be valuable to learn about changes in chemistry teachers' individual units over time, perhaps as new or inexperienced teachers become veteran teachers. Similar work for other, historically marginalized or reified topics (described in Burt & Boesdorfer, 2021) would add to the existing scholarship on secondary chemistry teaching and learning at the topic-specific level.

Along with providing ideas for future research methods, this study provides suggestions for the focus of professional development to help teachers implement the standards (including all topics in the standards) in their classes. The role of professional development and its ability to shape teachers' conceptions of knowledge relating to a topic as well as their ability to translate their own subject-matter knowledge for curriculum development and instruction would add a needed layer of context for how these views are shaped. Arzi and White (2008) found that, over time, curricular knowledge becomes a leading driver of teacher content knowledge throughout their career. This suggests the outsized role that knowledge of curriculum may play in limiting the potential flexibility and development of teacher-created curricula as they become more experienced.

Grace and Ellie each possessed distinct knowledge relating to each topic, but each also had clear gaps in their understanding that professional development could be targeted to remedy. In terms of nuclear chemistry, both teachers understood that nuclear processes occur naturally as well as through human-induced means, that radiation was a natural consequence of radioactive decay, and others. Both, however, struggled to conceive of the nature of what makes a nucleus unstable and how that radiation might be used (for positive or negative) in our world. In order to challenge existing alternative conceptions (as described in Cakmakci, 2010; Colomuc & Tekin, 2011; Sozbilier, 2004; Tekin & Nakiboglu, 2006) as well as to deepen their subject matter knowledge, specific professional development could be used to remedy those areas of need. While both teachers possessed much more extensive subject matter knowledge in nuclear chemistry than they did for the topic of kinetics, Grace and Ellie might both benefit from a more comprehensive understanding of how nuclear chemistry can be used in everyday life, beyond their own respective experiences. Tying these types of knowledge bases in both nuclear chemistry and kinetics to the introductory chemistry curriculum in a structured professional development workshop might be useful to Grace and Ellie as well as teachers like them who may wish to find support in understanding how a single topic in chemistry might relate to everyday experiences as well as the overlap that exist between topics. Professional development focusing on the content of the standards, alone, may not best serve the needs of teachers if they are aware the standards exist. Rather, for teachers like Ellie, who understand the standards exist and are interested in using them to drive curriculum development, it may be helpful to engage in professional development sessions that emphasize specific PEs rather than focusing on the nature of the standards, themselves. In doing so, teachers like Ellie might be better served by attending focused sessions that pertain to areas they wish to improve, limiting time spent re-learning what they already know and have already embedded into their chemistry curricula. Despite that potential benefit, teachers like Ellie may not realize such gaps exist in their subject-matter knowledge and the very teachers that could benefit most from targeted professional development may not believe it pertains to their own needs.

Given the findings of this study, particularly with respect to research question 1, teacher subject-matter knowledge as well as knowledge of NGSS appear to drive the extent that a given topic is covered in a teacher's chemistry class. Efforts to further implementation of NGSS may benefit from targeted professional development that may play a unique role in supporting teachers' deepening of their subject-matter knowledge and, over time, their pedagogical content knowledge (explored in this study in terms of the knowledge of curriculum and orientations to the teaching and learning of science). As discovered in context of answering research question 2, teachers may not always have a strong understanding of the limitations of their own subject-matter knowledge, which leaves them potentially unable to take advantage of valuable opportunities to deepen their existing knowledge. Without an existing framework or professional development designed to diagnose and identify areas of need for individual teachers (such as in the form of an "audit" of subject-matter knowledge), it continues to be unlikely that those teachers will be positioned to benefit from the findings of this study. Targeted professional development that serves to couple content knowledge development with opportunities to create and design new curriculum centered around well-defined goals for what student knowledge might look like for specific topics could be a powerful tool in supporting more teachers as they continue the work of making the vision of science teaching and learning laid out in NGSS a reality. As described by NRC (2012), "learning science depends not only on the accumulation of facts and concepts but also on the development of an identity as a competent learner of science with motivation and interest to learn more". Reaching these lofty goals requires a better understanding of the current state of the field of chemistry teaching to better identify specific needs to support teachers in fully implementing reform-based standards like NGSS.

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APPENDIX A: SEMI-STRUCTURED INTERVIEW QUESTIONS

Protocol for Nuclear Chemistry Teaching

1. What do you believe is the purpose of a unit (or learning segment) relating to nuclear chemistry?
2. While teaching this unit, how would you respond to a student asking: 'when will we ever use this?'?
3. How does this unit (or learning segment) fit into your chemistry curriculum?
4. Tell me about your unit on nuclear chemistry.
    1. How long does it last?
    2. Has it changed over your career? If so, how?
5. What are the most important science ideas/concepts included in this unit?
6. What do students already know that they will need to use or apply while in this unit?
7. How do you know when learning is occurring?
8. How do you decide what to teach in this unit and what not to?
9. What do the standards say (if anything) about what should be taught in this unit?
10. Are you aware of any other content relating to nuclear chemistry that can be included when teaching this topic?
    a. *If yes*, Tell me about it/them.
    b. *If no*, can you envision anything else that would be a natural fit?
11. Is there anything else you would like to say about your unit on nuclear chemistry?

Protocol for Kinetics Teaching

1. What do you believe is the purpose of a unit (or learning segment) relating to kinetics?
2. While teaching this unit, how would you respond to a student asking: 'when will we ever use this in life?'?
3. How does this unit (or learning segment) fit into your chemistry curriculum?
4. Tell me about your unit on kinetics.
    a. How long does it last?
    b. Has it changed over your career? If so, how?
5. What are the most important science ideas/concepts included in this unit?
6. What do students already know that they will need to use or apply while in this unit?
7. How do you know when learning is occurring?
8. How do you decide what to teach in this unit and what not to?
9. What do the standards say (if anything) about what should be taught in this unit?
10. Are you aware of any other content relating to kinetics that can be included when teaching this topic?
    a. *If yes*, Tell me about it/them.
    b. *If no*, can you envision anything else that would be a natural fit?
11. Is there anything else you would like to say about your unit on kinetics?

APPENDIX B: SAMPLE CoRe TEMPLATE

	Important Science Ideas/Concepts in Nuclear Chemistry				
	Big Idea A	Big Idea B	Big Idea C	Big Idea D	Big Idea E
What do you intend the students to learn about this idea?					
Why is it important for students to know this?					
What else do you know about this idea (that you do not intend students to know yet)?					
What are the difficulties/limitations connected with teaching this idea?					
Are there any other factors that influence your teaching of these ideas?					
What are your teaching procedures (and particular reasons for using these to engage with this idea)?					
Specific ways of ascertaining students' understanding or confusion around this idea (include a likely range of responses).					

Adapted from Loughran et al. (2004).

APPENDIX C: MEMBER CHECK FOLLOW-UP INTERVIEW QUESTIONS

Protocol for Nuclear Chemistry Teaching and Learning

(Begin by describing key data obtained from initial interview, CoRe template, and assessments)

1. Do these ideas accurately represent what you believe to be true and reflect what you do in your practice?
2. Are there any major ideas or pieces of information that you feel could be added or clarified to better represent your approach to the teaching and learning of this topic in your introductory chemistry class?
3. Is there anything else that you'd like to say about nuclear chemistry as a topic or about your chemistry curriculum as a whole?

Protocol for Kinetics Teaching and Learning

(Begin by describing key data obtained from initial interview, CoRe template, and assessments)

1. Do these ideas accurately represent what you believe to be true and reflect what you do in your practice?
2. Are there any major ideas or pieces of information that you feel could be added or clarified to better represent your approach to the teaching and learning of this topic in your introductory chemistry class?
3. Is there anything else that you'd like to say about kinetics as a topic or about your chemistry curriculum as a whole?

APPENDIX D: NUCLEAR CoRe DOCUMENT (GRACE)

	Important Science Ideas/Concepts in Nuclear Chemistry			
	Law of Conservation of Mass	Reactions	The Periodic Table	The Role of Energy in Nuclear Chemistry
What do you intend the students to learn about this idea?	They will learn that the nucleus that is at the beginning of the reaction will break into smaller nuclei that will add together to have the same # of protons and neutrons.	I want them at this point to just understand that we start a reaction with reactants and end with products.	They need to be able to relate the position of the radioactive elements on the periodic table.	E = mc2
Why is it important for students to know this?	They need to understand that all mass is conserved in all reactions including ones that deal with nuclei.	They need to know what comes first and what is last to be able to understand the law of conservation of mass.	They need to realize the larger elements that contain more protons and neutrons are the ones that are more unstable.	It basically proves the law of conservation of mass (energy) and shows how a nuclear reaction can give off so much energy.
What else do you know about this idea (that you do not intend students to know yet)?	They should have a pretty good basic idea of this by now. We have talked about it in two other chapters and draw molecular diagrams to show conservation of mass.	They will not do any types of reactions or use any coefficients to balance. They will only be looking at the nuclei.	We have already covered most of the periodic table and trends at the point.	
What are the difficulties/limitations connected with teaching this idea?	They need to understand that there are times when neutrons break into a proton and electron. It is conceptual like most of chemistry and they have a hard time visualizing what is really going on.	Again this is very conceptual and they have not balanced any equations yet, so this can be difficult for them.	Again since we cannot see any of these individual atoms it is very conceptual.	The math involved in solving this equation can be difficult for them to understand. A lot of it is the small numbers with the exponents get very confusing for them. Also the fact that the numbers are so small yet we get such a large amount of energy is also confusing. They don't always understand there is such a large number of atoms. Again the conceptual.
Are there any other factors that influence your teaching of these ideas?				I tie this into fission and fusion.
What are your teaching procedures (and particular reasons for using these to engage with this idea)?	I use several simulations (pHet) that allow a visual representation of what is happening in a chain reaction and a nuclear reactor. These give the students a better idea of what is happening.	Again we draw out the nuclei so they can see the # of protons and neutrons in the reactants equals the protons and neutrons in the products.	I teach the periodic table prior to the nuclear chapter so that the students will have an understanding of atomic number, protons, neutrons, nuclei etc. This makes it much easier to talk about nuclei now.	I use a work sheet that walks the students through the math involved in using E=mc2. It explains mass defect and nuclear binding energy and how the difference in the mass leads to the release of energy.
Specific ways of ascertaining students' understanding or confusion around this idea (include a likely range of responses).	I have them do molecular drawings of what the nuclei look like. This allows me to see if they are understanding what is in the nucleus to start with and end with. They do struggle sometimes remembering that what they start with they must end with. We use beans to do this.	I use worksheets with examples of nuclear equations and have them balance them. They struggle with the examples that have more than one neutron. Once we draw them out they start to catch on. I also have them do several decay series worksheets and an assessment where they have to look at different "puzzle pieces" of radioactive elements and put them in order.	I don't specifically assess just the periodic table info. I assess this with the decay series assessment where they put the "puzzle pieces" together looking at the atomic numbers and atomic masses.	We just complete the worksheet together and then have a discussion about the amount of energy that is released from one atom and how that relates to the release of energy from billions of atoms.

PPENDIX E: NUCLEAR CoRe DOCUMENT (ELLIE)

	Important Science Ideas/Concepts in Nuclear Chemistry			
	Using Science/Research to Evaluate a Controversial Topic	The Role of Energy and its Relationship to Nuclear Reactions	The Phenomena of Nuclear Processes (e.g., Fission/Fusion)	Assessing Information and Determining its Relationship to "You" as an Individual
What do you intend the students to learn about this idea?	How to locate and assess sources of information. There is often not a single correct answer to many of the big choices in life and perspective does matter. Using evidence to support an argument and communicating this argument out to a community of others.	Where does the energy 'come from'? Why is there so much more energy from a nuclear reaction than a standard chemical reaction? How can the energy be controlled?	What makes something radioactive? How is radioactivity measured? Fission in nuclear power plants and bombs, also radioactive decay. Fusion takes place on the sun. Why is fusion so difficult to cause/control? What is the importance of the chain reaction that drives nuclear fission?	What are the different types of radioactive particles and how are they different? Where do we come in contact with radioactive particles? What is a reasonable level of radiation to be exposed to in a given time? What claims are made about risks and safety of nuclear chemistry that have us
Why is it important for students to know this?	This is a life skill that will not stop at the school doors/graduation.	Nuclear power is a common proposed solution to our energy needs and is a primary source of power in Illinois. Nuclear powered submarines and space transportation are also in use and could be something that students are interested in.	Understanding the differences and similarities in the mechanisms are between radioactivity and nuclear fusion or fission is useful in assessing risk and evaluating credibility to claims they might come across. (cold-fusion cars or the safety issues of a nuclear fission powered car, for example)	Humans are exposed to radioactive materials and radiation all of the time, but commonly students are under the impression that all exposure is harmful and to be avoided. It is important that students can evaluate the inherent risks and potential benefits of radiation exposure or nuclear energy sources.
What else do you know about this idea (that you do not intend students to know yet)?	That this will be a constant and always changing target to aim for.			
What are the difficulties/limitations connected with teaching this idea?	The students often use only a few sources that are summaries and pro/con lists and it can be difficult to get them to reach beyond when peer-reviewed scientific research is so much less accessible.	Conservation of energy and matter are concepts that I want to continue to place value in, just with knowledge of this exception. The idea that energy is released when bonds are broken.	Without being able to SEE radiation and nuclear reactions, it can be difficult to differentiate between the various types.	Students have varying levels of risk awareness and comfort and some can get hyperfocused on perceived danger. Coping mechanisms can lead students to dismissing actual risks because we've brushed off some low risk or even high risk factors that we benefit from enough to take the risk.
Are there any other factors that influence your teaching of these ideas?	That this will be a constant and always changing target to aim for.	$E=mc^2$ is an equation they've seen everywhere and associate with science. The most enduring message the students have received in science courses to this point is that matter and energy are conserved...I find it absolutely nutty that these are both true and mostly incongruent.	Radiation is everywhere and the dose (quantity, duration) and type is the most important in determining risk.	When it doesn't directly affect YOU, risk assessment can be very different. (Nuclear power plants in your general vicinity are debated while our service members are often far more reliant and in closer range without a single thought.)
What are your teaching procedures (and particular reasons for using these to engage with this idea)?	In researching the same topic from various 'perspectives' or roles, students begin to shape their research to fit what they are looking for. After the town hall meeting we	We discuss what life is like on a submarine and then how they stay underwater for so long. Recent classes have been able to "meet" a former student who works in the nuclear plant aboard a	Using marshmallows, BBs and marbles in modeling the radiation types helps students understand without being explicitly told about the differences and then students begin to solve/balance equations and predict products	Constant examples from a wide variety of activities, student discussion and sharing of their ideas and experiences is valuable her. Also, their analysis of what THEY think after they have had to adopt a role for the town hall meeting

	are able to discuss how varied the information and recommendations were. This begins to shape their understanding of bias and lens and how to zoom out and attempt to look at the greater picture.	naval submarine and teaches incoming "Nukes". Another entry point for this is to discuss nuclear bombs and students really enjoy the documentary "Uranium: Twisting the Dragon's Tail"	of reactions as they process these two subatomic particles and the idea that SOMETHING is conserved.	
Specific ways of ascertaining students' understanding or confusion around this idea (include a likely range of responses).	This is often the first or second opportunity in my course to practice this skill of evaluating claims using scientific research, so my review of their sources in their town hall presentation is often considered more formative. I provide feedback.	We do a few iterations of formatives on these types of questions and then students take a written summative assessment. A number of students also cover these concepts as they encourage or discourage the use of nuclear power in their town hall presentations.		The summative questions I use to assess students' ability to communicate and defend a claim is written within questions I have specifically written to keep students and their own ideas involved in the processing. I learned these from Erik Francis of "Now That's a Good Question" and I want to do more of this, but I need to solidify the feedback and rubric/expectations.

APPENDIX F: KINETICS CoRe DOCUMENT (GRACE)

	Important Science Ideas/Concepts in Kinetics		
	Factors that Influence a Chemical Reaction (e.g. reaction rate)	Law of Conservation of Mass	The Role of Energy in Breaking Down or Forming Substance(s)
What do you intend the students to learn about this idea?	The students need to understand that there are several factors that will make a reaction either speed up or slow down.	At this point students need to remember that anytime we discuss reactions that all matter is conserved.	The students need to understand that energy plays a role in chemical reactions and how the reactants form the products. And how fast/slow this happens.
Why is it important for students to know this?	They need to know this to help them to understand that reactions don't always run at the same rate and there are times when we need to slow down or speed up a reaction. To do this we need to understand what factors will help us to do this.	They need to understand that a reaction can speed up or slow down and the particles that are present are still present. They do not "disappear" because the reaction goes faster or slower.	They need to remember that bonds broken or made release or gain energy and this all ties into new products being formed.
What else do you know about this idea (that you do not intend students to know yet)?	We will not include anything on rate laws.	At this point we have covered this a lot.	
What are the difficulties/limitations connected with teaching this idea?	This can be a very conceptual idea for the students just like most other chemistry topics. It is very hard for them to visualize what is actually happening.		Again I don't usually have enough time to go in depth with this information.
Are there any other factors that influence your teaching of these ideas?	I do not have enough time to include this as a separate topic.		
What are your teaching procedures (and particular reasons for using these to engage with this idea)?	I show a video that shows the students how all of the factors that speed up a reaction can be used by a high school student to get a date to the prom. This is something they can relate to and it helps them remember the factors better.	At this point it is more of a discussion and reminder that we have talked about this several time throughout the year and don't forget it still applies.	
Specific ways of ascertaining students' understanding or confusion around this idea (include a likely range of responses).	I do not assess the students on this individual topic but we have a discussion after we watch the video that gives me a pretty good idea of whether they understand the factors that speed up a reaction.	Nothing specific here.	Nothing specific here.

APPENDIX G: KINETICS CoRe DOCUMENT (ELLIE)

	Important Science Ideas/Concepts in Kinetics		
	Energy Transfer	Conservation of Energy	Harnessing (Controlling) Energy
What do you intend the students to learn about this idea?	Heat is transferred through materials differently based on structure. Energy moves from high to low. Cold doesn't spread, heat does.	Energy isn't created so it must come from somewhere. Energy isn't destroyed, so it must be transferred to something/somewhere else.	Energy can be moved through materials quickly or more slowly depending on the structure and design of the materials used. "losing" energy is really just letting it go when you don't want it to and steps are often taken to help avoid this.
Why is it important for students to know this?	See the Controlling Energy Transfer column	See →·	Students will encounter in their lives a time when energy loss can be avoided with appropriate steps. It can be important in them as a consumer or even a person who must redesign or fix a problem (big or small)
What else do you know about this idea (that you do not intend students to know yet)?	→·	Potential energy in chemical reactions can upset their current understanding of energy moving from one place to another Nuclear reactions do not abide by this	←·
What are the difficulties/limitations connected with teaching this idea?	Students sometimes refer to energy as particles and hold on to the idea that 'cold' can transfer. Students see that metal is a conductor, but continue to recommend a metal container for insulation without explaining the vacuum between two layers OR they struggle to flip design concepts between insulation vs. conduction.	We do this before nuclear energy is covered now, but I have tried them in reverse and it is much more difficult to keep them focused on the conservation of energy as they've begun to take energy 'creation' for granted a bit.	With more time and materials, I might have them more completely design something, rather than experiment with solutions to the tea problem and then describing a tea pot design as they currently do. I like the thawing plate ideas that I have seen, but I have not taken these steps.
Are there any other factors that influence your teaching of these ideas?	I work on modeling a lot here - I think that students who are better at visual thinking pick up this concept much more quickly than students who aren't able or willing to draw out their thoughts as much.		The cooling of tea or the deep dive into the structure of cups is sometimes such a 'small' problem to some students that they don't find it at all important. On one hand, it is totally accessible and demonstrates the scale of energy transfer problems from big to small but for some it is too small.
What are your teaching procedures (and particular reasons for using these to engage with this idea)?	Students measure temperature drop in hot water (coffee) in various cups and mugs. Students learn about the structure of the materials and discuss patterns in the temperature change compared to the materials used. Students models a variety of systems showing heat transfer, movement of particles and structure of various materials to help build understanding.	Students create LOL diagrams, identify components in systems that are endothermic and exothermic, draw models showing heat transfer and explain heat 'loss' without using "loss".	Students design a tea pot on their summative with certain design requests. Students determine a possible solution to cool down a beverage more quickly, without ice or refrigeration, and they design and conduct an experiment to provide evidence that the solution was effective.
Specific ways of ascertaining students' understanding or confusion around this idea (include a likely range of responses).	Many formatives asking for models of various situations and lots of opportunity for students to explain and revised their thinking.	LOL diagrams help a lot here.	Asking students to apply what they've learned to suggest a new design or a fix to a problem helps them see a variety of applications where we might want to 'engineer' something to encourage or inhibit energy transfer.