LEGITIMATION CODE THEORY AS AN ANALYTICAL FRAMEWORK FOR EXAMINING DISCOURSE WITHIN INTEGRATED STEM EDUCATION

by

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Dedicated to Kaboda. You were by my side when I started this journey and I wish you were here to see me finish it. I will love and miss you furever.

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ABSTRACT

To prepare students for the complex, multidisciplinary problems they will face outside of the classroom, current reform initiatives advocate for the integration of content and practices from science, technology, engineering, and mathematics (STEM) in the science classroom. One approach, integrated STEM, uses the engineering design process as a vehicle for learning. However, these lessons can be challenging for students, so it is essential that science educators employ various teaching practices to scaffold student learning. One way to achieve this is through the use of written and oral discourse that promotes meaning-making. The studies in this dissertation utilize Legitimation Code Theory as an analytical framework to create semantic profiles of an integrated STEM unit and middle school teachers' implementation of integrated STEM lessons. Specifically, we analyze the semantic gravity, or the extent to which meaning is rooted within the context it is acquired in, to map and identify semantic patterns that may promote or constrain meaning-making. The results of these studies indicate that Legitimation Code Theory can be a useful tool for developing and examining integrated STEM curricular materials, evaluating teacher discourse during the implementation of integrated STEM lessons, ascertaining how teachers are integrating multiple disciplinary discourses, and identifying areas where teachers may benefit from additional support as they learn to implement integrated STEM.

Keywords: integrated STEM, legitimation code theory, discourse

1. OVERVIEW OF DISSERTATION STUDIES

The most important challenges that society faces today—e.g., climate change, food availability, biodiversity loss, access to potable water, poverty—require multidisciplinary solutions that draw from various academic disciplines including science, technology, engineering, and mathematics (STEM) (Rennie et al., 2012). The need to prepare today's students with the knowledge, skills, and practices to address tomorrow's challenges has led to a new vision of science education, one in which engineering content and practices are integrated in the science classroom (Honey et al., 2014; National Research Council [NRC], 2012; NGSS Lead States, 2013).

As education stakeholders, and science educators in particular, increasingly focus on the *integration* of STEM disciplines, interpretations of "STEM" as a conglomerate term emerged to refer to various integrated pedagogical models, approaches, and practices. Bryan and Guzey (2020) noted that "the ubiquitous use of the term STEM, with little definitional consistency, runs the risk of diluting its potential value for enhancing, reforming, and informing K-12 research, policies, programs, and practices" (p. 6). They recommend that researchers, policy makers, and other education stakeholders clarify in their work their use of the term "STEM." To this end, in this dissertation, I use the term "integrated STEM" to refer to an instructional approach that uses engineering design as a vehicle for teaching and learning science (English, 2017; Moore et al., 2014). Specifically, I draw from the work of Bryan et al. (2016) in characterizing the five core features of integrated STEM in my work:

1. One or more *anchor disciplines* make up the learning goals for the lesson.
2. Engineering design is an *integrator* for the anchor disciplines.
3. Learning is couched within a *real-world problem* that needs to be solved.
4. Students *justify their designs* by applying content from the anchor discipline(s).

5. Students use and develop *21st century skills* as they design and test solutions.

Incorporating engineering design into the science curriculum allows for learning to be more meaningful and relevant to students and helps them recognize that solving problems requires the application of knowledge from science and mathematics (Brophy et al., 2008). Studies have shown that integrated STEM has the potential to enhance student learning of key science concepts and skills (Baran et al., 2019; Guzey, et al., 2016; Guzey et al., 2017; Kolodner et al., 2003; Sadler et al., 2000) and increase student engagement, interest, and motivation in science (Cunningham & LaChapelle, 2014; Cunningham et al., 2020; Redmond et al., 2011; Shahali et al., 2016; Struyf et al., 2019). However, implementing integrated STEM in the classroom is not without challenges for many science teachers (Capobianco & Rupp, 2014; Honey et al., 2014; Stohlmann et al., 2012), due to lack of formal training in other STEM disciplines (Banilower et al., 2013), limited time and materials (Stohlmann et al., 2012), and school culture (Czerniak & Johnson, 2014; Nadelson & Seifert, 2017).

As with any new reform initiative, teachers must learn and enact new instructional strategies that impact student outcomes (National Academies of Science, Engineering, and Medicine, 2019; NRC, 2012). An essential teaching practice is using language to create dialogic learning environments that promote productive classroom talk (Duschl, 2008). Teachers use their language to frame and organize lessons (Dawes, 2004), elicit, develop, and refine student ideas (Scott, 1998), and help students acquire disciplinary literacy (Moje, 2015). Teacher discourse is an important scaffolding tool for helping students to learn the language of science (Lemke, 1990) and to understand how and when to talk about discipline specific content (Gee, 2004).

Throughout an integrated STEM unit, students engage in authentic learning experiences that depend on effective teacher discourse to make visible the interconnected nature of the STEM disciplines (Honey et al., 2014). Teachers serve as catalysts in classroom discourse by probing student understanding and prompting decision-making discourse (Hogan et al., 1999). Without proper discursive guidance during an engineering design-based activity, students may struggle to identify the need for disciplinary knowledge, how to acquire and interpret that knowledge, or how to apply their knowledge when designing a multidisciplinary solution (Roth, 1996). To scaffold student learning, teachers need to employ multiple discursive tactics (Puntambekar & Kolodner, 2005), such as using analogies (Dagher, 2005), capitalizing on students' prior knowledge (Hewson & Hewson, 1983), and facilitating reflective discussions (Davis, 2000). Given the important role teacher discourse has in student learning, it is imperative that teachers have a strategy for analyzing what they say during an integrated STEM lesson. The studies in this dissertation use an analytical framework that maps the semantic patterns of written and oral discourse within the context of integrated STEM.

Although several analytical frameworks exist for analyzing teacher discourse, many examine the structure of language rather than the content of what is being said (Fairclough, 1992). Considering that integrated STEM is centered around an authentic, real-world context that requires the use of various disciplinary practices and discursive strategies, an analytical framework that studies teacher discourse from a context perspective will allow teachers, teacher educators, and professional developers to examine and enhance teacher discourse during an integrated STEM lesson. I introduce Legitimation Code Theory in this dissertation as an analytical framework that has such potential. Legitimation Code Theory, or LCT, is a multidimensional framework that includes the semantics dimension, which considers how meaning is rooted in context (Maton, 2009, 2014). Within the context of integrated STEM, this framework can help teachers engage in productive classroom discourse that illustrates the interconnectedness of the STEM disciplines while also facilitating student learning of key principles and practices from each individual discipline. In the next section, I elaborate on the theoretical underpinnings of Legitimation Code Theory.

1.1 Theoretical Background

Legitimation Code Theory (LCT) is a framework that offers methods for exploring the organizing principles of academic disciplines (Maton, 2000). Most empirical studies conducted within the education community focus on students' conceptions, the pedagogical strategies being used in the classroom, and whose knowledge is being taught. While such studies are undoubtedly important, research on knowledge as the object of study can enrich the existing body of scholarship on learning and teaching. According to Maton (2000), knowledge comes in various forms, and each form has its own properties and features, all of which have an impact on student learning. Therefore, studies that examine the nature of knowledge articulated during academic discourse and practices have the potential to promote knowledge building and meaning-making in the classroom (Maton, 2013).

1.1.1 Discourse, Knowledge, and Curriculum Structures

LCT builds on the work of Bernstein (1999), who examined how knowledge is produced within academic disciplines by exploring different forms of discourse. Bernstein identified two categories of discourse: horizontal and vertical. Horizontal discourse represents everyday language and reflects knowledge structures rooted in specific contexts, whereas vertical discourse encompasses professional language and is indicative of more specialized, context-independent knowledge structures that are connected to other scholarly knowledge structures. Within vertical discourse are two opposing forms of knowledge structures, horizontal and hierarchical (Bernstein, 2000). Horizontal structures are composed of numerous specialized languages that are linked, but hierarchical structures are coherent and enable new knowledge to be subsumed within an existing knowledge structure (Bernstein, 1999). Conceptualizing knowledge structures this way is a useful starting point for understanding how knowledge changes over time. Maton (2007) noted that missing from this framework is the ability to determine how classroom interactions and practices promote or constrain cumulative learning.

LCT extends Bernstein's ideas of discourse and knowledge structures to include hierarchical and horizontal curriculum structures (Maton, 2009). Horizontal curriculum structures promote activities that stand in isolation and prevent students from connecting scientific ideas. Hierarchical curriculum structures build on science content and skills that students acquired in previous lessons to form a more comprehensive understanding of a phenomenon. Thus, LCT can be used to "theorise the underlying principles generating discourses, knowledge structures, curriculum structures and forms of learning," making it a suitable candidate for analyzing classroom practices to determine if they promote or constrain cumulative learning (Maton 2009, p.45).

1.1.2 LCT: Semantics Dimension

The semantics dimension of LCT explores meaning-making by examining semantic patterns present within different types of discourse. This dimension consists of two separate but related components, semantic gravity and semantic density. Semantic gravity is a measure of the extent to which meaning is rooted in the context it was acquired in and is measured along a continuum ranging from weak semantic gravity to strong semantic gravity (Maton, 2014). Abstract, generalizable, and non-context dependent discourse exhibits weak semantic gravity whereas context-dependent discourse comprising specific instances exhibit strong semantic gravity. For example, a discussion on predator-prey relationships has weak semantic gravity but a conversation about tiger sharks and squid has strong semantic gravity. Semantic density is a measure of the condensation of meaning related to a word or phrase (Maton, 2014). Semantic density is also measured along a continuum ranging from weak semantic density to strong semantic density. Language associated with weak semantic density has low condensation of meaning whereas language with strong semantic density has high condensation of meaning. For example, young students may only identify “copper” as a shiny metal (weak semantic density) whereas a graduate student may consider other meanings including atomic number and various physical and chemical properties associated with the metal (strong semantic density). As the studies in this dissertation take place in middle school classrooms where many science topics are being introduced for the first time, the studies focus solely on semantic gravity.

Looking at how semantic gravity is strengthened or weakened over time as a lesson, activity, or unit progresses can illustrate how instructional approaches transform knowledge and promote or constrain meaning-making (Maton, 2014). Mapping the semantic patterns present in written or oral discourse results in a semantic profile illustrates how the context of what is said changes over time. Some common features of a semantic profile include flatlines, escalators, and waves, as shown in Figure 1 (Maton, 2009). A flatline occurs when discourse remains at a similar level of semantic gravity over a long period of time. This can be problematic if, for example, a science topic is only discussed at levels of strong semantic gravity because students may not be able to apply the science concept in new situations because meaning is tied to the context it was originally presented in. Discourse that exhibits a one-direction shift is called an escalator. A down escalator occurs when a teacher introduces an abstract concept, breaks the concept down into more general ideas, and then provides students with a concrete example, but then moves abruptly onto another topic without connecting it to the previously discussed idea. An up escalator is the exact opposite - discourse begins with a specific example and gradually develops into a discussion about more complex and abstract ideas. Finally, waves represent the oscillation between strong and weak semantic gravity. This represents the continual unpacking and repacking of ideas that are explicitly connected to one another.

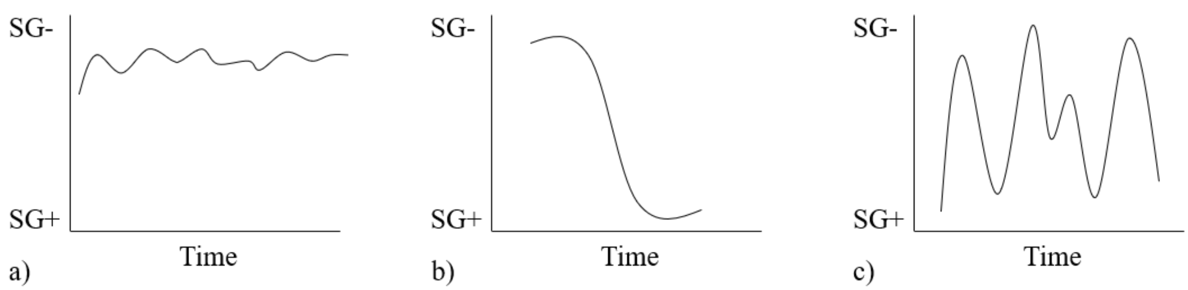

Figure 1. *Three Types of Semantic Patterns: Flatlines (a), Escalators (b), and Semantic Waves (c)*

Studies have shown that the continuous strengthening and weakening of semantic gravity, or making semantic waves, promotes cumulative learning by enhancing meaning-making in the classroom (Clarence, 2017; Kilpert & Shay, 2013). The decontextualization of a concept enables students to relate a complex phenomenon to their everyday life while recontextualizing the content allows students to connect individual ideas back to the original, and additional, phenomenon. This promotes meaning-making by making learning relevant and helping students recognize connections within a discipline. The correlation between semantic waves and meaning-making has the potential to broaden participation in science and help students navigate their way across and within multiple disciplinary boundaries and has allowed LCT to be used in a variety of ways such as identifying students’ knowledge structures, analyzing existing curricular materials and instructional practices, and identifying ways to enhance them.

1.1.3 LCT as an Analytical Framework in Previous Studies

Georgiou et al., (2014) used semantic gravity to assess student responses to an exam question pertaining to thermodynamics to identify student conceptions and where their understanding lies along the semantic gravity continuum. High-achieving students often had greater semantic range and were able to connect specific examples to abstract theory. Similarly, Wolmarans (2015) examined students' understanding as they presented a prototype during a critical design review. The more successful students were those who continuously shifted between areas of strong semantic gravity and weak semantic gravity. Hartley (n.d.) found a positive correlation between student talk that exhibited a wide range of semantic gravity and cumulative GPA. These studies indicate that students with hierarchical knowledge structures have a deeper understanding of content knowledge, suggesting that it is incumbent upon educators to develop curricula that demonstrate semantic waves. Mouton and Archer (2019) analyzed an existing college biology lecture and used its weak semantic profile to redesign the lecture so that it contained more semantic waves. Students who attended the redesigned lecture outperformed students who attended the original lecture, further indicating that the pedagogical strategies that promote semantic waves can facilitate student learning. Likewise, Clarence (2017) observed a greater gap in student understanding of complex law principles in a class during which the teacher's semantic profile consisted mainly of disconnected talk.

Other studies have used semantic gravity as a tool for analyzing syllabi (Monbec, 2018), assessments (Kilpert & Shay 2013; Shalem & Slonimsky, 2010; Shay, 2008), course curricula (Shay & Steyn, 2016), degree programs (Clarence, 2015), teaching practices (Jackson, 2016, 2017), and professional development (Macnaught et al., 2013). These studies were conducted among a vast array of disciplines, but few focused on science education (e.g., Blackie, 2014; Georgiou, 2016; Kelly-Laubscher & Luckett, 2016; Mouton & Archer, 2019). Most studies were situated in a university or postgraduate setting, likely because older students have more experiences and prior knowledge to draw on, giving them greater semantic range than younger students (e.g., Dong et al., 2014; Kilpert & Shay, 2013; Monbec, 2018; Mouton & Archer, 2019; Wolff & Luckett, 2013). The single study set within a K–12 science setting analyzed semantic gravity to compare the textbooks of a high school course and a college biology course (Kelly-Laubscher & Luckett, 2016). These studies indicate that LCT can serve as an analytical lens across disciplines and grade levels, but studies that examine if and how LCT can be used in a middle school science classroom are needed.

1.1.4 How is LCT Different than Existing Frameworks in Science Education?

The study of disciplinary language has a long history in science education literature. Researchers proposed and used a variety of discourse analysis frameworks to study teaching and learning in the context of language use. Discourse analysis comes in many forms, some of which focus on the content of the language whereas others dissect the structural components of language (Gee, 2014). Systemic functional linguistics, for example, is a framework commonly used for discourse analysis as it enables researchers to explore the many facets of language as a tool for meaning-making (Halliday, 1985). Eggins (1994) describes this framework as one that investigates how language is used, and how language is structured to construct specific meanings. The lexical and grammatical components of language used by a teacher are deliberate choices made by the speaker or writer to achieve a goal in a specific social context (Halliday & Martin, 1993; Lemke, 2001). Because students form a community of practice as they learn the ways of doing and learning science, Lemke (1998) advocates for a social semiotic framework, which examines social activities and practices that students learn as they become members of these communities. The context in which learning is situated impacts students' ability to construct meaning, and language facilitates this context (Lemke, 2001). LCT extends on these frameworks by providing insight on the semantic choices teachers make to facilitate student understanding of a science concept and how it relates to other concepts.

Moje (2015) offers a framework of disciplinary literacy that advocates that literacy education must take into account the communities of practice they are a part of. This heuristic approach to disciplinary literacy includes 1) engaging students in disciplinary practices as a means of promoting literacy; 2) eliciting the knowledge students come to class with and engineering it to facilitate further understanding; 3) having students examine how and when they use certain words; and 4) evaluating when specific words are appropriate and useful. Central to this framework is embedding literacy within inquiry so students understand the true meaning of disciplinary texts. This framework is extremely beneficial to the science education community because it connects literacy to the culture of a discipline. This is crucial for helping students navigate between everyday talk and academic talk, which are often in conflict with one another (Gee, 1997; Moje 2015). Teachers must be conscientious about the type of talk they use in the classroom; the continual use of specialized language (e.g., science talk) tends to put non-mainstream students at a disadvantage whereas the frequent use of everyday talk may leave students' true understanding uncovered and disconnected from scientifically accepted understandings. (Gee, 1997). This framework emphasizes the need to be aware of the differences between students' everyday language and academic language, but it does not provide a way of analyzing the complexities of a single unit that infuses multiple disciplinary literacies. LCT provides additional tools to study disciplinary literacies. By dissecting and analyzing the semantic gravity of each activity within an integrated STEM unit using LCT, teachers can better scaffold student understanding to promote cumulative learning. The studies that comprise this dissertation will demonstrate different ways LCT can serve as an analytical framework to examine discourse within integrated STEM education.

1.2 Organization of Dissertation

This dissertation is a multiple article dissertation consisting of three stand-alone articles based on original research. Each article constitutes a chapter, has its own separate list of references, and is formatted to meet the specifications of a target academic journal approved by my co-chairs.

LCT is a theoretical thread that cohere each of the three studies. Specifically, in each of the three studies, I investigated the ways in which LCT may be used to examine the semantic patterns present in integrated STEM curriculum and its enactment, with implications to develop effective curricular materials and improve existing ones, enrich teachers' implementation of integrated STEM lessons, and enhance learning opportunities for science teachers. The following overarching research question frames this dissertation and cohere the three studies:

- In what ways can Legitimation Code Theory serve as an analytical framework to examine integrated STEM curriculum and teachers' implementation of it?

The following research questions guide each of the individual studies:

- Study 1: What semantic patterns that promote or constrain knowledge building are present in a middle school integrated STEM unit and a STEM teacher's discourse during the implementation of the unit?

- Study 2: What semantic patterns are evident in a middle school science teachers' discourse as he scaffolds student understanding during an integrated STEM unit?
- Study 3: What do the semantic patterns present in two science teachers' discourse reveal about the needs of middle school teachers learning to implement integrated STEM?

The final chapter is the concluding chapter in which I summarize the major findings across the three articles, address limitations in the studies, provide overarching recommendations and implications, and suggest areas for further research for the fields of STEM education and STEM teacher education.

1.3 Publication Intent and Contribution Information for Each Study

We intend to combine study 1 with parts of study 2 and submit the paper to the Journal of Research in Science Teaching. For this manuscript, Chelsey Dankenbring contributed 70% of the effort (conception and design of the study, data analysis, data interpretation, and writing the original manuscript), Dr. Lynn Bryan contributed 15% (conception and design of the study and editing the manuscript for intellectual content), and Dr. Selcen Guzey contributed 15% (conception and design of the study and editing the manuscript for intellectual content). For study 3, which we intend to submit to the Journal of Science Teacher Education, Chelsey Dankenbring contributed 80% (conception and design of the study, data analysis, data interpretation, and writing the manuscript), Dr. Lynn Bryan contributed 10% (conception and design of the study and editing the manuscript for intellectual content), and Dr. Selcen Guzey contributed 10% (conception and design of the study and editing the manuscript for intellectual content).

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2. AN ANALYTICAL FRAMEWORK FOR ANALYZING INTEGRATED STEM CURRICULUM AND ITS ENACTMENT

2.1 Abstract

Recent reform initiatives in each of the STEM disciplines inspired the development and implementation of integrated STEM approaches to science learning. Integrated STEM uses engineering principles and practices, such as the engineering design process, to situate learning in an authentic and meaningful learning environment. However, these curricular activities can be cognitively challenging for learners, so it is essential that scaffolding techniques are employed by the teacher to facilitate student understanding. One way to achieve this is through analyzing written and oral discourse within the STEM classroom. This study utilized Legitimation Code Theory as an analytical framework to identify and map the semantic patterns of an integrated STEM unit and middle school teacher's enactment of it. Specifically, this analysis focused on the semantic gravity, or level of context dependency, of the activities and dialogue present throughout the unit. Creating a semantic profile offers a snapshot of how abstract or how specific a concept is presented in relation to other concepts. Curriculum that presents ideas through the formation of semantic waves, or oscillations between areas of high and low semantic gravity, is linked to enhanced learning of complex ideas. The results of this study indicate that Legitimation Code Theory is a useful tool for developing and examining integrated STEM curricular materials and its implementation.

Keywords: integrated STEM, legitimation code theory, engineering design, curriculum, teacher discourse

2.2 Introduction

Teaching and learning recommendations for K–12 science, technology, engineering, and mathematics (STEM) have progressed over the years to adopt a view that learning is situated in specific disciplinary contexts and practices (Honey et al., 2014; International Technology Education Association, 2007; National Academies of Sciences, Engineering, and Medicine, 2019; National Research Council [NRC], 1996, 2007, 2012; NGSS Lead States, 2013). Classroom instruction from this perspective means that students engage in domain-specific reasoning processes and patterns of activity, so that classroom practices better reflect the actual work and knowledge of STEM professionals. For example, scientific inquiry in the K-12 science ntails learning and engaging in the processes of asking questions, planning and conducting investigations, analyzing and interpreting data, and forming explanations and arguments from evidence to understand the natural world (NRC, 2000; 2012). Engineering, on the other hand, employs an iterative engineering design process to develop solutions to ill-structured problems (National Academy of Engineering [NAE] & NRC, 2009; NRC, 2012). During a design challenge, students define a problem, brainstorm potential solutions, build and test a prototype, and optimize their solution to better meet the client's needs (Brophy et al., 2008).

While each STEM discipline has unique attributes, many of the pressing and intractable challenges facing today's global society are multidisciplinary and require knowledge and skills from various academic disciplines, yet each discipline continues to "steadfastly defend their sovereign territories" (Sanders, 2009, p. 21). To prepare students for broader and deeper understandings for solving 21st century challenges, recent science and STEM education reform documents in the United States propose an approach to education that focuses on the interconnected nature of the STEM disciplines (Bybee, 2013; Honey et al., 2014; NGSS Lead States, 2013; NRC, 2012). An integrated curriculum centers learning around core disciplinary ideas and practices that are relevant to students and require using domain-specific knowledge from more than one discipline when applicable (Rennie et al., 2012). This new vision of K-12 science education inspired the implementation of integrated STEM approaches.

Recent research on the implementation of integrated STEM in K-12 classrooms has documented positive impacts on student outcomes (Cunningham et al., 2020; Wendell & Rogers, 2013). In a review of research regarding the impact of integrated STEM instruction on student outcomes, the Committee on Integrated STEM Education found that both student learning and students' STEM interest and identity development were enhanced through integrated STEM instruction (NAE/NRC, 2014). In addition, several recent studies have shown the positive impact on student learning when engineering and technology are meaningfully integrated in mathematics instruction (English & King, 2019) and science instruction (Gardner & Tillotson, 2019; Guzey & Aranda, 2017).

However, integrated STEM approaches have also proved challenging for teachers. For example, science teachers who seek to integrate science and engineering in their instruction struggle to determine how and when to use discipline-specific practices (Capobianco and Rupp, 2014). Similarly, some students find completing an engineering design challenge difficult because they struggle to propose multiple design solutions, apply science concepts to their solutions, and are not used to dealing with failure (Azevedo et al., 2015). Because of the nuanced nature of knowing, producing knowledge, and communicating between STEM disciplines, teachers need to employ different literacy practices within an integrated STEM curriculum (Moje, 2015; Wilson-Lopez & Minichiello, 2017). The nature of instruction and teacher's interactions with students is crucial to student outcomes (Dawes, 2004; McNeil & Krajcik, 2008), thus it is essential to understand how teachers engage their students in interdisciplinary practices and how they support students in building deep disciplinary knowledge. Studying discursive practices, such as teacher discourse, within STEM classrooms is one way of examining elements of STEM instruction associated with higher levels of student achievement (Schoen et al., 2003; Tofel-Grehl & Callahan, 2016).

Several studies have explored discursive practices of science teachers in integrated science and engineering units (Aranda et al., 2019; Johnston et al., 2019; Roth, 1996; Valtorta & Berland, 2015). Kelly (2008) defined discursive practices as “not only language use, but also a related set of values, beliefs, attitudes, and ways of being in the world” (p. 329). This paper focuses specifically on how teacher discourse is used to make the connections between science content and engineering practices explicit. This interconnected nature of disciplinary knowledge and practices and their relationship to meaning-making in relevant socially constructed contexts is the focus of semantics (Lemke, 1988). However, semantics, which is an important element of, but not limited to, teacher discourse, has not been fully explored in previous studies of integrated STEM. Applying a framework that focuses on semantics can foster a deeper understanding of effective pedagogical strategies for integrated science and engineering teaching and learning. To guide our study of semantics and integrated STEM education, we adopted Legitimation Code Theory (Maton, 2000), which stresses that the context-specific nature of what is said in a text, such as curricular resources, and in the classroom is important for student learning.

2.3 Theoretical Framework and Background Literature

In the following sections, we describe the framework that guided our design of integrated STEM instruction, introduce Legitimation Code Theory as an analytical framework, and demonstrate ways to use Legitimation Code Theory to analyze curriculum materials and classroom discourse.

2.3.1 Integrated STEM Education

There exist a growing number of conceptualizations of integrated STEM education, particularly for the K–12 context (Bybee, 2010; Moore et al., 2014; NAE/NRC, 2014, Rennie et al., 2012). Bybee (2013) described integrated STEM as the opportunity for students to learn about and experience the interconnectedness of each STEM discipline as a means of solving complex problems while promoting STEM literacy. Honey et al. (2014) referred to integrated STEM as the explicit teaching and learning of more than one STEM discipline as students develop 21st-century skills. For the purpose of this study, we adopted a framework for designing K–12 integrated STEM instruction (Bryan & Guzey, 2020; Bryan et al., 2016) that consists of five distinguishing elements of K–12 integrated STEM education:

1) Content and practices of one or more anchor STEM disciplines define the primary learning goals.

2) The integrator is typically the practices of engineering and engineering design as the context and/or an intentional component of the content to be learned.

3) The context of instruction requires solving a real-world problem or task through teamwork and communication.

4) Engineering design or engineering practices related to relevant technologies require utilization of the scientific and mathematical concepts through design justification, and

5) The development of 21st-century skills is emphasized.

The *anchor disciplines* are the primary STEM disciplines addressed in an integrated STEM curriculum. The curriculum contains learning objectives for each anchor discipline, which drives the instructional activities students engage in (Krajcik et al., 2008). Assessment items should also align with the learning objectives and instructional activities. An *integrator* links the anchor disciplines in an integrated STEM curriculum to provide a cohesive learning experience.

Engineering practices, such as the engineering design process, provide a context that requires knowledge of the content and practices from each anchor discipline in order to make sense of a larger topic (Moore et al., 2014). Engineering design begins by introducing a *real-world problem or task* for students to solve (Dym et al., 2005). These real-world problems couch learning in an authentic, engaging, and socially relevant context that piques students' natural curiosity (Kolodner et al., 2003; Krajcik & Blumenfeld, 2006). As students proceed through the iterative and recursive steps of the engineering design process, a community of practice forms in which students are immersed into the culture of each anchor discipline, enabling them to further apply science and engineering languages and practices (Lave & Wenger, 1991). In addition, engineering design requires that students *justify their solution* to the client by addressing how it best solves the problem. Developing solutions requires collaboration as students engage in problem scoping to identify the client, problem to be solved, and the criteria and constraints that a solution must meet. This information helps students identify which science and mathematical principles they need to learn to solve the problem (Sadler et al., 2000; Wendell et al., 2017; Wilson-Lopez et al., 2020). Students apply their disciplinary understandings to construct a prototype. Finally, to solve real-world problems or tasks, students need to master various *21st century skills* including collaboration, communication, and innovation. In an integrated STEM curriculum, the problem or task presented during a design challenge does not have a single right answer, thus students have the freedom to be creative, make decisions, and think critically as they apply what they learn throughout the curriculum (Blumenfeld et al., 1991; Crismond & Adams, 2012; Cunningham & Lachapelle, 2014).

Integrated STEM has been shown to enhance student learning of complex science concepts and increase student interest in science (Cunningham et al., 2020; Guzey et al., 2016;

Honey et al., 2014; Redmond et al., 2011). Nonetheless, participating in integrated STEM curricular activities can be cognitively challenging for students because each discipline has unique ways of knowing, thinking, and doing (Honey et al., 2014). Compared with professional engineers, students spend less time understanding the problem and gathering information while also considering fewer alternative solutions and their feasibility (Atman et al., 2007; Mentzer et al., 2015). Students also struggle to incorporate science content into their design justifications (Azevedo et al., 2015; Purzer et al., 2015; Valtorta & Berland, 2015). Teachers' scaffolding of student learning through productive, disciplinary dialogue in the classroom helps students see connections between individual disciplines and determine when discipline specific practices are applicable during a design challenge (Lemke, 1990; Moje, 1995; Scott, 1998; Wilson-Lopez & Minichiello, 2017). Understanding how meaning is constructed through language is critical in supporting student learning in integrated STEM.

2.3.2 Disciplinary Literacy

Language is an essential tool that students use to construct meaning of their lived experiences. Semantics is the study of meaning in language. More precisely, Lemke (1990) described semantics as the "particular way of creating similarities and differences in meaning" (p. ix). By studying semantics and, more specifically, semantic patterns—or the "pattern of relationships of meanings" (Lemke, 1990, p. x)—educators can identify effective ways of integrating everyday language and academic language in order to facilitate learning. This is important because integrated STEM instruction requires students to understand the meaning of and utilize academic language associated with multiple STEM disciplines (Honey et al., 2014).

Moje (2008) advocated for teaching disciplinary literacy so students can learn "how to access, interpret, challenge, and reconstruct the texts of the discipline" as a way of helping students navigate their way through various subjects and the identities associated with them (p. 100). Disciplinary literacy extends beyond reading and writing texts to help students understand the meaning and use of language within a discipline, because all disciplines communicate differently. Lemke (1998) reiterated this idea by explaining that members of the scientific community "use specialized languages and use common language in specialized ways" (n.d.). Therefore, effective use of language in the science classroom is critical to promote learning, because "dialogue becomes the vehicle by which ideas are considered, shared and developed" (Pritchard, 2005, p. 30). Unfortunately, academic language, or "scientific English," within the classroom often constrains knowledge building (Halliday & Martin, 1993, p. 59). Academic language poses several challenges to students, one being that "the meanings of words are not fixed and settled once and for all in terms of definitions. They vary across contexts" (Gee, 1997, p. 10). Brown and Spang (2008) found that a teacher's specific use of double talk, the coupling of everyday and academic language, helped students learn and discuss science concepts.

Creating discourse-rich classrooms that include the use of double talk to help students develop scientific and academic language while acquiring new knowledge of scientific phenomena can be challenging for science teachers. Such successful teaching strategies require instructional congruence, where teachers effectively blend academic language with everyday language and experiences of students for learning to be meaningful (Lee & Fradd, 1998; Moje et al., 2001). It is even more challenging for teachers when it comes to STEM instruction because questioning, evaluating, and negotiating and communicating ideas in science differ from those same activities in other STEM disciplines. Therefore, teachers need strategies to promote sense making as students encounter new scientific and engineering information in their classroom.

2.3.3 Legitimation Code Theory

Legitimation Code Theory (LCT) is a framework that offers methods for exploring the organizing principles of academic disciplines (Maton, 2000). LCT builds on the work of Bernstein (1999), who examined how knowledge is produced within academic disciplines by exploring different forms of discourse—horizontal and vertical. Horizontal discourse represents everyday language whereas vertical discourse encompasses professional language. Within vertical discourse are two opposing forms of knowledge structures—horizontal and hierarchical (Bernstein, 2000). Horizontal knowledge structures are composed of numerous, linked specialized languages, whereas hierarchical knowledge structures enable new knowledge to be subsumed within an existing knowledge structure.

LCT extends Bernstein's ideas of discourse and knowledge structures to include hierarchical and horizontal curriculum structures to determine if the type of classroom interactions and practices within a curriculum promote or constrain cumulative learning (Maton, 2007, 2009). Horizontal curriculum structures promote segmented learning as activities stand in isolation and may inhibit students from connecting scientific ideas. Hierarchical curriculum structures promote cumulative learning by building on science content and skills that students acquired in previous lessons to form a more comprehensive understanding of a phenomenon. Thus, LCT can be used to "theorise the underlying principles generating discourses, knowledge structures, curriculum structures and forms of learning," (Maton 2009, p. 45) making it a suitable candidate for analyzing classroom practices to determine how they promote or constrain cumulative learning.

LCT has five dimensions, namely specialization, semantics, autonomy, temporality, and density (Maton, 2014a). As this study focuses on the use of semantic patterns present in an integrated STEM curriculum and its enactment, we focused on the semantics dimension. This dimension "conceives social fields of practice as *semantic structures* whose organizing principles are conceptualized as *semantic codes* comprising *semantic gravity* and *semantic density*" (Maton, 2014b, p. A-36). Semantic gravity is a measure of the extent to which meaning is rooted in context, whereas semantic density is a measure of the condensation of meaning within a word or idea. This study takes place in a middle school classroom where many science topics are being introduced for the first time, so we focus solely on semantic gravity.

2.3.3.1 Semantic Gravity

Within the semantics dimension of LCT is semantic gravity, or the degree to which meaning is dependent on the context in which it is acquired. Semantic gravity is measured along a continuum ranging from strong semantic gravity to weak semantic gravity. Strong semantic gravity indicates that meaning is context-dependent and difficult to apply to other contexts. Weak semantic gravity indicates that meaning is not context-dependent and likely represents a more general understanding that can be applied to new situations (Maton, 2014b). For example, a discussion specifically about *Galeocerdo cuvier* (tiger shark) exhibits stronger semantic gravity than a discussion on predator-prey relationships in an aquatic environment, which is more abstract and thus represents weaker semantic gravity. Investigating how semantic gravity is strengthened or weakened over time as an activity, lesson, or unit progresses can illustrate how instructional approaches transform knowledge (Maton, 2014b).

Essential to knowledge building are classroom interactions that oscillate between areas of strong and weak semantic gravity, in contrast to interactions that exhibit a one-directional shift, often referred to as an escalator, or a flatline (Maton, 2014b). Examples of these semantic patterns are present in Figure 1. A down escalator occurs when a teacher introduces an abstract concept, unpacks the abstract concept, provides a concrete example, and then moves onto another topic. An up escalator also has a progression, except in this situation, the teacher begins with a concrete example and gradually uses more complex language to arrive at an abstract concept. These methods of instruction present concepts as disconnected ideas, and students may struggle to understand how they are related to one another. Alternatively, a flatline occurs when a concept is discussed at the same level of semantic gravity for a prolonged period of time. Lastly, semantic waves represent the continuous strengthening and weakening of semantic gravity, which are linked to enhanced learning (Maton, 2009, 2014b).

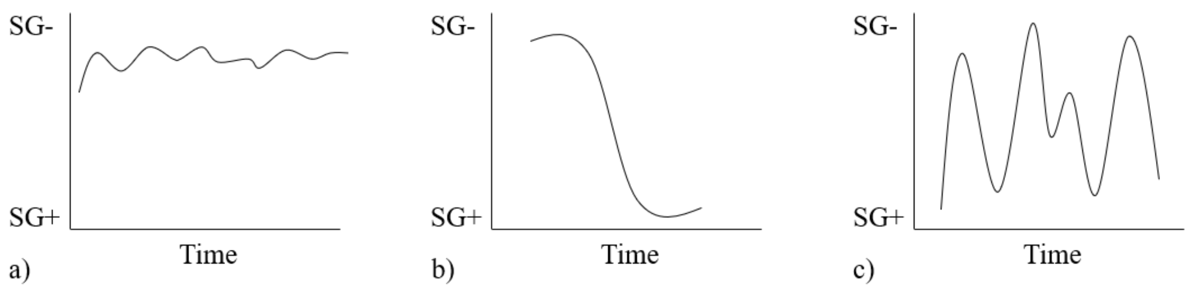

Figure 2. *Three Types of Semantic Patterns: Flatlines (a), Escalators (b), and Semantic Waves (c)*

Context is essential in an integrated STEM curriculum and its enactment. The specific context of the engineering design challenge determines what students need to learn to develop a relevant technology that solves the problem. Each activity within an integrated STEM unit introduces or reinforces scientific and/or mathematical principles that students must consider during the design and redesign stages of the engineering design process. The context of these activities is also crucial. If the context is too specific, students may not be able to apply their knowledge to the engineering design task, but if the context is too general, students may not see how the content is relevant to the task at hand. Semantic gravity is a measure of context dependency, making LCT an applicable tool for identifying and assessing the delicate balance of context within an integrated STEM unit.

2.3.4 LCT, Discursive Practices, and Integrated STEM

In the previous section we described key elements of LCT and how it has been used to investigate knowledge building in various disciplines. A review of the integrated STEM education literature shows that teachers need a strategy to promote knowledge building as students encounter new science and engineering information in their classroom (Stohlmann et al., 2012). As teachers use the discursive support present within a curriculum as a starting point for how they frame their teaching and guide their whole-class discussions, it is imperative that we identify the semantic patterns present within the curriculum. In this section, we report on a single case study in which we used LCT as an analytical framework to identify, map, and compare the semantic patterns of an integrated STEM curriculum unit and the teacher's discourse during its implementation in a middle school classroom as a means of analyzing how the curriculum and the teacher's discourse promote knowledge building among students. Specifically, the purpose of this paper is twofold: (1) introduce Legitimation Code Theory as a tool for examining discourse present in the text of an integrated STEM curriculum and its enactment, and to this end, (2) present a study in which we use LCT as an analytical framework to examine how discourse is used to facilitate knowledge building in an integrated STEM unit and a middle school science teacher's implementation of it. Our study aimed to address the following research question: *What semantic patterns that promote or constrain knowledge building are present in a middle school integrated STEM unit and a STEM teacher's discourse during the implementation of the unit?*

2.4 Methods

This study was part of part of a longitudinal NSF-funded project that aimed to facilitate middle school science teachers' development of knowledge, skills and practices for implementing reform-based science instruction—in particular, engineering integration in life science instruction. This study utilized a multiple case study approach (Yin, 1994), with the written curriculum unit entitled, *Designing a Two-Stage Water Filter,* and a teacher's implementation of the unit comprising the two cases.

2.4.1 Participants

The teacher with whom we collaborated was Mr. Walsh (pseudonym), a sixth-grade science teacher at a rural middle school in the Midwest. Mr. Walsh is a Caucasian male teacher, who at the time of the study, had been teaching for 10 years. However, teaching is Mr. Walsh's second career; he previously worked in an environmental engineering firm, completing engineering tasks related to waste and pollution management. We selected Mr. Walsh because of his K-12 teaching experience, his familiarity with teaching engineering design, and his comfort level with integrating engineering into the science curriculum. Prior to participating in this study, Mr. Walsh completed three years of professional development through our NSF-project on implementing integrated STEM in the life science classroom.

Mr. Walsh taught in a combined middle/high school with an enrollment of approximately 500 students. He is one of four science teachers at the school. During the time of the data collection, the sixth-grade class in which he taught the *Designing a Two-Stage Water Filter* curriculum consisted of 26 students, of which 15 were Caucasian females (55.6%) and 12 were Caucasian males (44.4%). Of these 26 students, 20% received free or reduced lunch.

2.4.2 Curriculum Unit

The integrated STEM unit, *Designing a Two-Stage Water Filter*, was developed by Author 2 and other project personnel. The unit consists of five lessons and culminates in students designing a water-filter system that contains a human-made component and a biological component, with the goal of reducing pollution that enters a local river. To successfully complete the design task, students must demonstrate an understanding of the water cycle, what plants need to live, the process of transpiration, the engineering design process, and the role that criteria and constraints play in the design process. This unit explicitly integrates science and engineering concepts; each lesson has grade-level-appropriate life science and engineering objectives mapped to NGSS and state science education standards. Furthermore, the curriculum unit addresses the five critical elements of integrated STEM education presented earlier.

Table 1 presents an overview of the unit, with each lesson, the primary and secondary disciplinary focus of each lesson, the disciplinary practices focus of each lesson, and timeline for the unit. Lesson 1 introduces students to the design challenge, which set the context for the entire unit. The next three lessons build students' understanding of key science concepts so they can create informed design solutions. Lesson 2 focuses on the water cycle and students complete an inquiry investigation to determine how water percolates through different materials, including sand, soil, and rocks. During Lesson 3, students engage in a virtual simulation about what plants need to live and study transpiration by measuring the distance water traveled up a stalk of celery at various time points. Since the students' water filter must contain a biological component, students must consider how anything in water, like pollutants, are taken up into the plant and affect its well-being. Lesson 4 explores ecosystem interactions as students complete activity stations related to decomposition, which recycles nutrients into the soil. Finally, during Lesson 5 students apply what they learned as they design, build, and test their two-stage water filter.

Table 1 . *Overview of Designing a Two-Stage Water Filter Curriculum*

Lesson Overview	Disciplinary focus	Disciplinary practices	Timeline
Lesson 1: Introduction to Design Challenge	Major, Engineering Minor, Science	Design – problem scoping	Days 1-2
Lesson 2: Water Cycle and Soil Percolation	Major, Science Minor, Engineering	Inquiry	Days 3-5
Lesson 3: What Plants Need to Live	Major, Science Minor, Engineering Minor, Mathematics	Inquiry	Days 6-8
Lesson 4: Interactions in Ecosystems	Major, Science Minor, Engineering Minor, Mathematics	Inquiry	Days 9-10
Lesson 5: Design water filters	Major, Engineering Minor, Science	Design – plan, build, test, and evaluate	Days 11-16

2.4.3 Data Collection and Analysis

The data for this study included the written curriculum and video recordings of Mr. Walsh's implementation of it. Mr. Walsh's implementation of the unit took sixteen 50-minute class periods (approximately 12 hours). Each class period was video recorded and later transcribed. This study focused on the context-dependent nature of Mr. Walsh's talk during class interactions. Multiple discourses were at work in the classroom, including disciplinary discourses, everyday discourses, and pedagogical discourses. However, this study focused on Mr. Walsh's discourse when talking to the entire class, so the transcripts did not include classroom announcements, directions for activities, or small-group conversations of which Mr. Walsh was not a part. Mr. Walsh frequently asked questions to elicit student ideas and repeated student responses aloud for the class to hear. Therefore, the transcripts do provide a snapshot of student dialogue as well.

Using LCT as a framework, Author 1 first divided the video transcripts into units of meaning, or passages that convey a single meaning (Maton, 2009). Units of meaning may be individual lessons, activities, discussions, or even parts of a discussion or activity, depending on the scope and purpose of the analysis. To glean as much information as possible, and to ensure the analysis accurately reflected the details of the curriculum and implementation, the first author and a researcher who was not involved in the project together examined each individual activity in the *Designing a Two-Stage Water Filter* curriculum unit to identify where, within an activity and then across activities, shifts in meaning or purpose occurred. For example, within an inquiry investigation, we analyzed the introductory explanation, relevant activities, class discussion, and the lesson wrap-up individually to determine if each component served a unique purpose. If so, each component was considered a separate unit of meaning.

To develop a coding scheme, we reviewed every unit of meaning with special attention given to those activities that were not very abstract or context dependent. This was done to determine how best to represent the non-extreme regions of the semantic gravity continuum. From this review, we adapted the four-point semantic gravity scale used by Wolmarans (2015) to evaluate mechanical engineering student's design review to better align with discourse appropriate for middle school students. Descriptions and representative examples from the curriculum unit are provided in Table 2. The first author coded 10% of the Lesson 1 data with a researcher who was not involved with this study. They met regularly to discuss discrepancies, clarify codes, and recode the data based on refined understandings. Once both researchers reached 85% agreement, the first author coded the remaining data.

Table 2. *Descriptions and Representative Examples of Codes*

Semantic Gravity	Code	Description of Code	Example from the Curriculum	Example from Mr. Walsh's Enactment
Weaker	SG--	References abstract concept	**Ask:** What do you all think we mean when we say the world "ecosystem"?	Ecosystem interactions, what does that mean?
↕	SG-	References specific science ideas within the abstract concept	**Transition:** …look closer at the important jobs of an ecosystem	How living things interact.
Stronger	SG+	References general everyday examples	**Directions:** Students work with a partner to research and describe the various ecological relationships…	So we have animals, we have plants, we have humans, how does everything interact? Plant needs, figuring out what they need.
	SG++	References a specific example	**Project Wild Oh Deer! Activity** Chart the population of deer from one generation to the next on the board.	Anyone drink coffee? So, when you make coffee…water comes down and it moves through the pot…it percolates.

The code "SG--" represents discourse in the curriculum unit and implementation that presented abstract words or ideas (weak semantic gravity), such as when the teacher introduced new science vocabulary or when the conversation focused on big-picture concepts, such as ecosystems. Discussions about more familiar science ideas are represented by the code "SG-." For example, roles within an ecosystem, such as predator-prey relationships, are not as broad a concept as ecosystems, but may still be abstract to young students. An SG+ code was assigned to discourse in the curriculum unit and implementation in which a more general, everyday example was provided to students. In Lesson 4, for example, the students participated in a think-pair-share activity during which they identified generic examples of an ecosystem. Using a beach or a swamp as an example made an unfamiliar term (*ecosystem*) more relatable to students. The final code, "SG++", was given when a specific organism, location, or context was discussed. To better understand how the availability of abiotic and biotic resources, such as shelter, food, and water, affect organisms in an ecosystem, students played the game Oh Deer! (Council for Environmental Education, 2003). During this game, student understanding was highly context-dependent because the game information was limited strictly to a population of deer.

Semantic profiles illustrate the semantic patterns present within the unit or its implementation. To create the semantic profile, the codes for each unit of meaning were plotted in chronological order as a function of time. Weak semantic gravity is higher on the y-axis to represent an increase in the level of abstraction.

2.5 Findings

In this section we present both the analysis of the *Designing a Two-Stage Water Filter* written curriculum unit and the analysis of Mr. Walsh's discourse during his implementation to investigate how each unit of analysis used context to facilitate students meaning-making in the science classroom. The curriculum analysis illustrated strengths of the curriculum as well as areas where revisions are needed to enhance meaning-making, so individual semantic patterns are described separately. The implementation analysis is divided into ways Mr. Walsh's discourse scaffolds student learning and ways his discourse can be improved to promote meaning- making within an engineering-based lesson.

2.5.1 Semantic Patterns in the Curriculum Unit

The *Designing a Two-Stage Water Filter* curriculum unit consists of five lessons. As shown in Table 3, the degree and frequency of semantic gravity present within the lesson depended on the disciplinary focus (i.e., science or engineering) of that lesson.

Table 3*. Frequency of each Code per Lesson in the Curriculum*

Code	Lesson 1	Lesson 2	Lesson 3	Lesson 4	Lesson 5	Total
SG--	1	3	2	2	0	8
SG-	2	3	2	7	3	17
SG+	0	2	1	5	0	8
SG++	4	2	2	3	3	15
Total	7	10	7	17	6	47

The units of meaning that make up the engineering lessons (Lessons 1 and 5) contain less variation in semantic gravity than most of the science lessons and predominantly represented context specific discourse, SG++, or specific science discourse, SG-. The goal of these lessons is to understand the details of the design task (SG++) design task or identify and apply general science concepts (SG-) to the design task. The science lessons (Lessons 2, 3, and 4) contain more units of meaning, and each level of semantic gravity is present. In fact, with few exceptions, each level of semantic gravity is present with a similar frequency. This is because the curriculum unit was designed to intentionally introduce an abstract idea (SG--), describe the phenomenon in everyday language (SG-), and then provide relatable experiences or examples (SG+ or SG++) to support student understanding. In other words, the curriculum unit explicitly connects each concept to students' prior knowledge/experience or to the design challenge.

For example, Lesson 5 primarily focuses on reviewing the engineering design challenge and reminding them of the criteria and constraints their solution must meet. The following is an excerpt of a sample/suggested script from Lesson 5 that has a strong sematic gravity (SG++):

> **Say:** Today we are going to combine all the knowledge we have gained throughout the
>
> unit by starting our engineering project.
>
> **Ask:** How many of you remember the video we watched at the beginning to the unit? Can anyone remind us of what was said in the video about the treatment of wastewater? (Lesson 5, p 64)

This segment of discourse is strongly rooted in the context of the video students watched at the beginning of the unit and sets the stage for upcoming conversations. Immediately following this excerpt from Lesson 5, the curriculum guide prompts teachers to engage in a dialogue with students in which they review in a large group discussion the science content that students learned throughout the unit.

> **Ask:** What information from the last few weeks will be helpful in developing these filters? If the students don't bring up the soil percolation lab,
>
> **Ask:** Did you learn anything in the soil percolation lab that could be useful in this project? (Lesson 5, p. 65)

In this excerpt, the discourse focuses on having students apply science content from each lesson to their design solutions. The curriculum specifically mentions soil percolation, which is a smaller idea within the larger concept of the water cycle, making this an example of specific science discourse.

The three middle lessons (Lessons 2-4) of the unit focused on teaching new science content, so there was an increase in science specific discourse (SG-) and discourse that provided general examples of the science content (SG+). An increase in these codes indicates that the curriculum provided real-world examples to helps students understand new science content. This type of discourse is often present in the form of a semantic wave, where the degree of semantic gravity gradually increases or decreases while explicitly connecting individual ideas or examples. Lesson 4, for example, addresses ecosystems as well as the roles and interactions present within an ecosystem. One way semantic waves are present in the curriculum is when new vocabulary is introduced (SG--), definitions or other scientific explanations are discussed (SG-), big-picture examples provided to support student understanding (SG+), and specific examples are given to further clarify ideas (SG++). An example of a semantic wave is below.

> **Ask:** What do you think we mean when we say the word *ecosystem*? (SG--)

Definition of *Ecosystem*: An ecosystem includes all of the living things (plants, animals, and organisms) in a given area, interacting with each other and also with their nonliving environments (weather, earth, sun, soil, climate, atmosphere). (SG-)

Think Pair-Share: Can you think of where you have seen an ecosystem? What was happening? How did you know it was an ecosystem? Turn to your neighbor and describe where you saw an ecosystem. (SG+)

Transition: Today and tomorrow we are going to look more closely at the important jobs of an ecosystem. (SG-)

Introduce stations around the room, Station 1—Tomato Observations: Students will observe tomatoes at various stages of decomposition to compare and contrast. (SG++)

(Lesson 5, pp. 40-41)

The increased diversity of degrees of semantic gravity in the science lessons is not surprising since this integrated STEM unit takes place in a science classroom where the primary learning goals focus on facilitating the mastery of science concepts. Incorporating units of meaning with varying degrees of semantic gravity scaffolds student learning by using familiar terms and examples to make sense of unfamiliar, novel science concepts. Connecting units of meaning with weaker semantic gravity to units of meaning with stronger semantic gravity helps students make sense of the "big picture" by dissecting it into smaller, specific ideas, and relating these ideas to their everyday life. On the other hand, connecting units of meaning with stronger semantic gravity to units of meaning with weaker semantic gravity helps students make connections between real life experiences and the science content, which can facilitate transfer of knowledge in new situations. For example, in the excerpt above, after the new term "ecosystem" is introduced, a definition using familiar terms (e.g., "living things" and "nonliving environment") is provided. Then, common examples of living things and the nonliving environment are discussed to ensure students understand each part of the definition. Later, after a discussion about the specific role of decomposers within an ecosystem, students explored tomatoes at different stages of decomposition to make the abstract idea of decomposition relatable to students.

Essential to meaning-making and knowledge building is the presence of hierarchical curriculum structures in the science classroom (Maton, 2014a). To do this, science ideas need to be broken down into smaller, easier to understand pieces, and then connected back to a larger topic. Also important is the explicit connection of one topic to another. Figure 2 shows the semantic profile of the *Designing a Two-Stage Water Filter* curriculum unit.

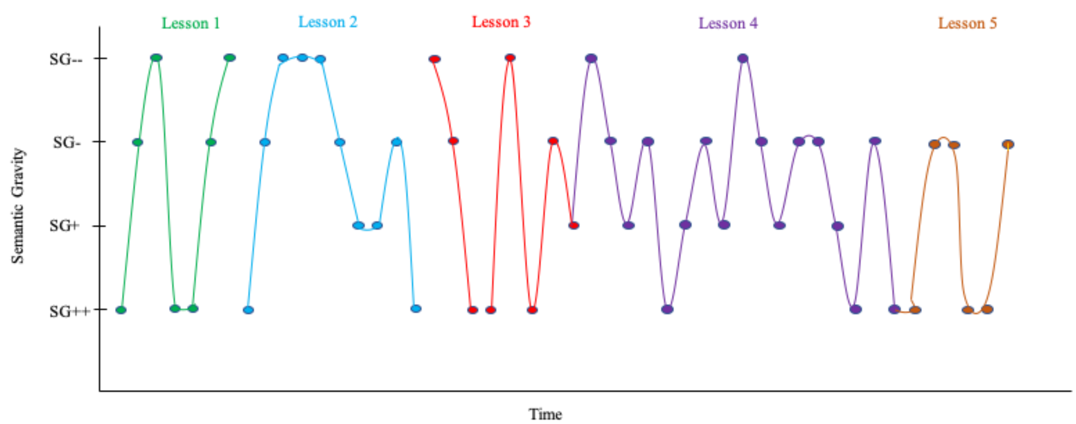

Figure 3. *Semantic Profile of the Curriculum*

2.5.1.1 Flatlines

A flatline is present during Lesson 2 when multiple units of meaning were coded SG--. A flatline indicates times when the curriculum is too abstract or too specific for a prolonged period of time. Discourse that is too abstract (high semantic flatline), as in in Lesson 2, may make it difficult for students to understand the content, see how the content relates to or affects their everyday lives, or may prevent students from understanding a concept altogether. On the other hand, discourse that primarily contains specific examples (low semantic flatline) may make it difficult for students to see how one idea connects to another and may prevent students from transferring their understandings to a new context because meaning is locked into that specific example or activity. The units of meaning that make up the flatline in Lesson 2 are shown below. Please note that the presence of a code at the end indicates a unit of meaning.

> **Say:** Together we are going to talk about water.
>
> **Ask:** Where do we see water in nature? Where does water come from? How does it get into lakes, rivers, and streams?
>
> **Say:** Let's organize these ideas in a more detailed picture . . . Let's draw a picture of the water cycle . . . (SG--)
>
> **Ask:** Where does water go from here? How does water get from clouds to the ground?
>
> **Instruct:** Lead students in a discussion of unit vocabulary and add definitions associated with the water cycle to a running list on the board.
>
> - condensation
> - precipitation
> - runoff
> - percolation
> - transpiration
> - evaporation
> - groundwater (SG--)
>
> **Natural Break:** *If necessary, this is a natural break in this lesson. Prior to students leaving, have them fill out the exit ticket [picture of water cycle with blanks for students to fill in vocabulary terms] (*SG--) (Lesson 5, pp. 16-17)

Each unit of meaning focuses on big-picture or abstract ideas. Students learn about the water cycle, become familiar with several new terms, and complete an exit ticket where they use the new terms to label an image of the water cycle. The water cycle, its associated terms, and how the terms connect with one another all exhibit weak semantic gravity. Adding real-world examples of the water cycle or referring to students' experiences and observations of components of the water cycle such as precipitation or runoff, are means for strengthening student understanding.

2.5.1.2 Escalators

A "down escalator" is present in Lesson 3. The down escalator represents an area in the curriculum unit where a new idea is disconnected from the content presented immediately before and after it. At this point in the unit, half of the class completes an online simulation about the basic needs of plants while the other half of the class observes transpiration in a stalk of celery. As written, the curriculum unit does not explicitly prompt students to discuss how these two activities are related; therefore, the main ideas of the activities appear independent of each other to the students. Escalators typically indicate areas in a curriculum unit where segmented learning—which is when new knowledge is amassed alongside, rather than integrated within, existing knowledge structures—is likely to occur (Maton, 2014a).

2.5.1.3 Semantic Waves

The semantic profile of the unit contains multiple semantic waves, which represent the continual unpacking and repacking of scientific ideas. The presence of semantic waves is linked to deeper conceptual understanding and cumulative learning, where new ideas build on existing ones (Georgiou et al., 2014; Hartley, n.d.; Maton 2014b; Mouton & Archer, 2019). There are discursive disconnects between Lessons 1 and 2, and again between Lessons 2 and 3. This suggests that the curriculum may need to explicitly connect the topics discussed in each of these lessons so students can understand the purpose of each lesson and how they are related to one another. However, there are no disconnects between lessons 3 through 5 which indicates that the curriculum seamlessly connects the ideas present within and across these lessons, which may enhance student meaning-making.

Occasionally in the curriculum unit, there is a jump from an area of strong semantic gravity to one of weak semantic gravity and vice versa. A quick shift from an abstract idea to a concrete example may make it challenging for students to fully understand the meaning behind the example, although this may not always be the case. In the engineering lessons, this type of shift is not surprising because there are many opportunities in the lesson in which students discuss their filter and use a science concept, they learned in an earlier lesson to make design decisions. There are fewer of these shifts in the science lessons because the teacher's role includes more scaffolding of student learning.

To offer more insight into a semantic wave present within the *Designing a Two-Stage Water Filter* curriculum, the semantic profile for Lesson1 is shown in Figure 3.

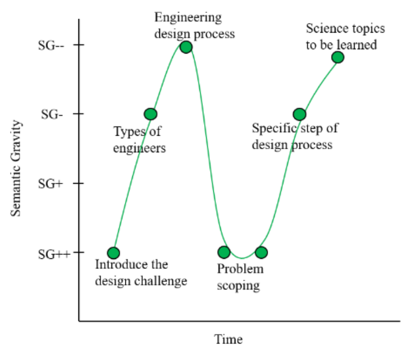

Figure 4. Semantic Profile of Lesson 1

This lesson begins with students watching a video that introduces the design challenge, which is situated within the specific context of helping a local water treatment facility design a two-stage water filter to reduce pollution in a nearby river. Next, students discuss "What types of engineers were involved [in the video]? What do engineers do? What kinds of engineers are there?" As many students are likely unaware of what engineers do (Capobianco et al., 2011), types of engineers and engineering career roles may be abstract ideas for the students. The lesson proceeds with discourse about the engineering design process, the details of which are likely initially unfamiliar or abstract to most students. Students then begin problem scoping by identifying the problem, client, and criteria and constraints their solutions must address. Then, students consider the question, “So far, where are we in the design process?” to remind them of the element of the design process and the respective purpose of each part of the process. Finally, students are asked, “What did the client say we will need to learn?” to prompt a discussion about the various science concepts students must learn and apply to complete the design challenge. These concepts include the water cycle, transpiration, and ecosystem interactions—concepts that will involve novel ideas and terminology for the students.

In this section we illustrated how LCT was used to create a semantic profile of an integrated STEM, life science unit. The profile consists of many semantic waves with one down escalator in Lesson 3. The majority of the waves are continuous, meaning that the waves from one lesson connect to the waves in the next lesson. Areas where this is not the case indicate episodes in the curriculum where lesson content is not explicitly connected to students’ prior knowledge nor is it used to introduce new concepts about to be discussed.

2.5.2 Semantic Patterns of Teacher Discourse

We used the same analysis approach to develop a semantic profile of Mr. Walsh’s discourse during his implementation of the *Designing a Two-Stage Water Filter* curriculum unit. We analyzed the varying degrees of semantic gravity present within each lesson along with the semantic patterns present in the implementation profile of each lesson. Lesson 1 is used as an exemplar for the following sections.

2.5.2.1 Varying Degrees of Semantic Gravity

As is the case for the curriculum unit, the nature of each lesson determined the nature of Mr. Walsh’s discourse. For example, Mr. Walsh formally introduced the engineering design process to students during Lesson 1. To make this unfamiliar process more accessible to students, Mr. Walsh often referred to a previous, less structured, design activity students completed earlier in the year, which accounts for the high number of SG++ codes. Each science lesson included new terminology (SG--) and their definitions (SG-). Mr. Walsh wove many general (SG+) and specific (SG++) examples throughout the lessons to ensure that students were making sense of the science content. Table 4 shows the frequency of each code per lesson during implementation.

Table 4. *Frequency of each Code per Lesson During Implementation*

Code	Lesson 1	Lesson 2	Lesson 3	Lesson 4	Lesson 5	Total
SG--	10	14	13	12	1	50
SG-	31	29	27	21	5	113
SG+	20	16	12	14	0	62
SG++	18	6	9	16	4	53
Total	79	65	61	63	10	278

Figure 4, which shows the semantic profile of Lesson 1, illustrates how the semantic gravity of Mr. Walsh's discourse changed over the course of this engineering-based lesson.

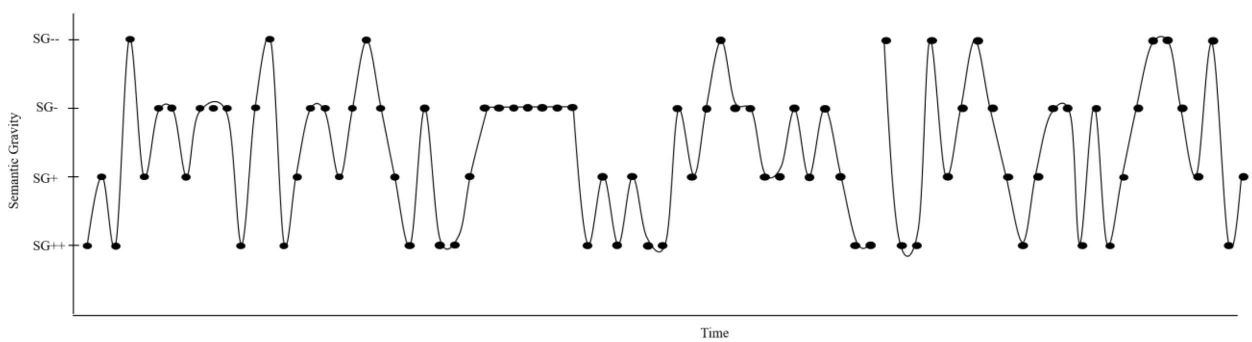

Figure 5. *Semantic Profile of Lesson 1 Implementation*

This semantic profile is made up of many semantic waves, with several instances of Mr. Walsh gradually oscillating between SG+ and SG--. This demonstrates Mr. Walsh's tendency to connect science content to real-world examples to help students make sense of the content. The excerpt below is an example Mr. Walsh's discourse as he explained the water treatment process at a wastewater facility. Each instance of "Mr. Walsh" represents a new unit of meaning.

> **Mr. Walsh:** Now there is … some of that stuff is not going to settle out too easily, that's what they call biological type of matter. (SG--)
>
> **Mr. Walsh:** Matter that [inaudible]. Stuff that doesn't come out. (SG-)
>
> **Mr. Walsh:** So, they have a tank where they are going to aerate it…So they're actually allowing these bacteria, getting things more active by churning things up. Okay, allowing them to do their job of breaking down things. (SG-)
>
> **Mr. Walsh:** So, this is an example [image on slide] where the water goes through this filter and a lot of times the filters have extra bacteria in it to kind of enhance this process. They're using normal things that occur in nature. (SG+)
>
> **Mr. Walsh:** I used to be in the environmental field and one of things we did… we would use what's called bioremediation to just let the bacteria in the soil naturally break down the gasoline. It would use it as nutrients to speed it up. (SG+)
>
> **Mr. Walsh:** Wastewater treatments can kind of do that too. They can add things to speed things up…And then if you remember in the video, they talked about chlorinating the water…to kill any of that nasty bacteria. (SG-)
>
> **Mr. Walsh:** What do you do with your pool? You add chlorine to it right…Chlorine is to make the water clean. (SG+)
>
> **Mr. Walsh:** So, before they're going to discharge it, they take it through, they treat it with chlorine, get that extra chlorine out and then they go through their outflow area. So that's our basic wastewater treatment. (SG-)

2.5.2.2 Semantic Patterns

The semantic waves present within the implementation profile illustrate Mr. Walsh's ability to unpack and repack engineering-related concepts and connect individual ideas to one another. Aside from the single flatline in the middle of the lesson, there are several instances of dramatic jumps from one end of the semantic gravity continuum to the other in the semantic profile. These indicate times when Mr. Walsh introduced a new science term (e.g., soil percolation) and then immediately skipped to a very specific example of the term before really unpacking it. The dialogue below occurred at the end of Lesson 1 after the class listed concepts that they would need to learn to design an efficient water filter:

> **Mr. Walsh:** Soil percolation. What does that mean? Anyone know the word percolation? (SG--)
>
> **Students:** No response.
> **Mr. Walsh:** Does anyone drink coffee?…so coffee is a simple process (draws diagram). Put your filter in there, put your coffee grounds and then the pot underneath and the water come down and it moves through the grounds. If you ever open this up before it's done, what do you see? Blackish water. When the water goes in, does it flow right through? Water moves slowly through, so you have some coming through to your cup. It percolates. (SG++)

Instances such as this represent times during Mr. Walsh's implementation where students may benefit from more scaffolding. Although some students may be familiar with the process of making coffee, they may struggle to make meaning from this example before knowing the definition of percolation (SG-).

2.5.2.3 Making Waves in Lesson 1

To facilitate student understanding, it is important to gradually strengthen or weaken the semantic gravity when explaining a novel concept like percolation. This is illustrated in a more detailed analysis from Lesson 1, which is shown below in Figure 5, when Mr. Walsh introduced the engineering design process to his students.

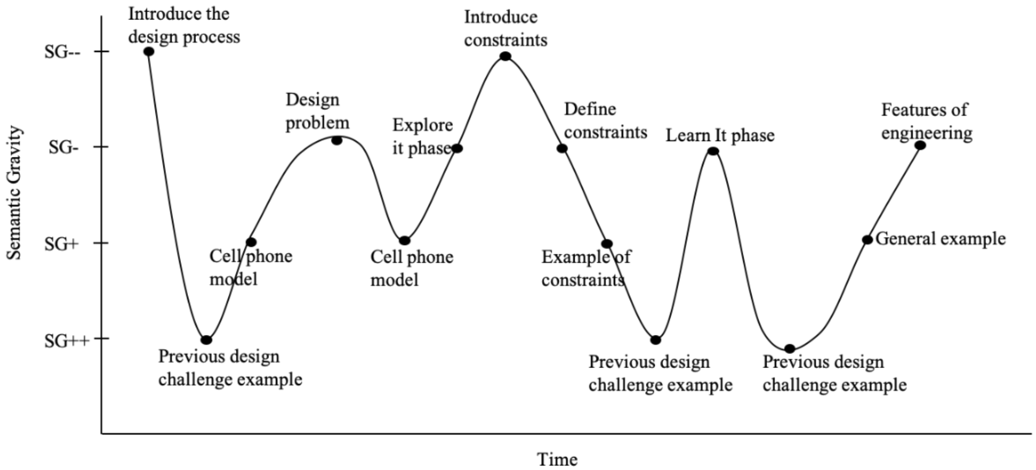

Figure 6. *Example of a Semantic Wave in Lesson 1*

In this part of Lesson 1, Mr. Walsh introduced the engineering design process to his students as a way to solve problems. He then reminded his students of a previous experience with a design activity, one where they designed a Hot Wheels track. However, the current design activity involved a more detailed approach. Mr. Walsh then shared with his students an engineering design process model to use for reference as they engaged in the water filter design task. As shown in Figure 6, the model is in the shape of a cell phone, something most students are familiar with, and each component of the design process portrayed as a cell phone app: EXPLOREit, LEARNit, SKETCHit, PICKit, BUILDit, TRYit, REFINEit, and SHAREit.

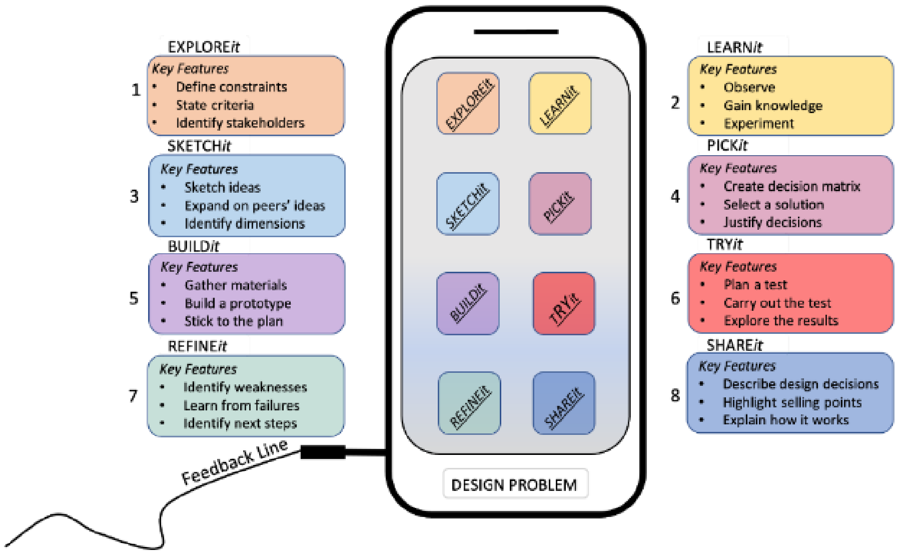

Figure 7. *Model of the Engineering Design Process*

He explained to his students that the first app on the cell phone is understanding the design problem because without a problem, there is nothing to solve. To address the iterative nature of the design process, Mr. Walsh explained that students can always leave one app and move to another one. He then focused on the first app, or phase of the design process, EXPLOREit. During this phase students identified the problem, client, along with the criteria and constraints of the solution. Mr. Walsh began this phase by asking his students what they think constraints means and then defines the term. To better help students understand the term, he said “I feel constrained” while moving his body as though he were in a strait jacket. Claustrophobia is used as an example of feeling constrained. He then had students think about the previous design activity and identify constraints to those solutions. Once he felt confident his students understood what constraints are, he moved through the next phases of the engineering design process including LEARNit, which is where students learn the science that will drive their engineering solutions. Again, he used students’ previous experiences and prior knowledge from the previous design activity to make sense of this phase of the design process.

In this section we demonstrated how LCT was used to create semantic profiles for the implementation of each lesson in an integrated STEM unit. Similar to the curriculum, Mr. Walsh's implementation profile contains many semantic waves. This is because he intentionally relates activities and discussions back to the design task. Explicitly vocalizing these connections made students aware of the role science plays in everyday life and how engineers use science to develop or enhance technology.

2.6 Discussion

Integrated STEM is becoming increasingly recognized as an approach for creating meaningful, relevant learning opportunities for students (Honey et al., 2014; NRC 2012). However, developing and implementing integrated STEM curricular materials is a complex endeavor for curriculum developers and science teachers, requiring not only a robust understanding of the content and practices of individual STEM disciplines, but how to teach in a way that integrates the STEM disciplines (Guzey et al., 2016; Honey et al., 2014; NGSS Lead States, 2013). At the beginning of this paper, we made a case for examining the semantic patterns present in an integrated STEM curriculum unit and a teacher's discourse during implementation of that unit based on decades of research that emphasize the importance of language as a tool for facilitating conceptual understanding in the classroom. Studying semantic patterns in integrated STEM instruction is particularly apropos, as integrated STEM instruction incorporates domain-specific content and practices from multiple disciplines (Bryan et al., 2016; Honey et al., 2014; Wilson-Lopez & Minichiello, 2017). Specifically, we proposed examining semantic patterns by applying a methodological lens of LCT. Finally, we shared results of a single case study in which we employed LCT to map the semantic patterns of in an integrated STEM curriculum unit and a middle school teacher's implementation of it.

LCT provides a framework for identifying semantic patterns present in curriculum and instructional practice (Jackson, 2016, 2017; Maton, 2000, 2007, 2009). Semantic gravity measures the context dependency of discourse or an activity. Creating a semantic profile illuminates patterns of language use present in a curriculum or its enactment as a way of facilitating students' meaning-making in the science classroom. Our analysis of the *Designing a Two-Stage Water Filter* unit illustrates multiple semantic waves in the semantic profile of the curriculum. This indicates that the curriculum oscillates between strong and weak semantic gravity. This approach to teaching helps students make sense of complex concepts by relating it to more familiar ideas. The semantic profile also illustrates continuous semantic waves between Lessons 3–5, which indicates that the curriculum explicitly connects the content presented in each lesson. Within each lesson, individual ideas are connected to previously learned content and new content so students can better understand the "big picture." The presence of semantic waves can also help students transfer their learning to new situations. As shown in previous studies, curriculum with semantic waves provides students the scaffolding needed to develop disciplinary literacy in the classroom (Maton, 2009, 2014b; Mouton & Archer, 2019).

Previous studies elucidated the potential challenges to meaning-making when certain semantic patterns, like escalators and flatlines, are present within a curriculum or its enactment (Maton, 2014a). The semantic profile of the *Designing a Two-Stage Water Filter* includes a single flatline in Lesson 2 and a down escalator in Lesson 3. Escalators within a curriculum promote segmented learning by presenting concepts as isolated facts rather than an interconnected network of ideas. Flatlines indicate areas in the curriculum where significant time is spent at one level of semantic gravity. In Lesson 2, the flatline occurred at areas of weak semantic gravity, so students may have difficulty relating these abstract concepts to their everyday life. Escalators and flatlines are indicative of horizontal curriculum structures and horizontal discourse, both of which constrain the formation of hierarchical knowledge structures. Thus, the results show the need to make some activities in the curriculum less abstract. Although Lessons 1 and 2 both contain semantic waves, the break in the profile between each of these lessons indicates points where students may find it difficult to see how these ideas are related to one another and to the design challenge. Previous studies reported similar trends of semantic patterns (escalators, plateaus and flatlines) in curriculum profiles and address the need for applying the concepts in disciplinary contexts and unpacking the meanings of abstract concepts (Monbec, 2018; Shay & Steyn, 2016).

LCT has the potential to provide the science education community with a resource for examining semantic patterns to enhance instructional practices. Previous studies show that instructional changes made by instructors because of mapping and analyzing their semantic profiles can lead to deeper conceptual learning (Clarence, 2017; Mouton & Archer, 2019). Analysis of teacher discourse through semantic profiles provides insight into both teaching and learning since teacher discourse is an important scaffolding tool to help students learn to talk science (Dawes, 2004). Specifically, a teacher's use of double talk can help students increase their repertoire of science specific language and understand when to use such language in various contexts (Brown & Spang, 2008). Mr. Walsh's continuous use of double talk is indicated by the presence of multiple semantic waves within his semantic profile. The profile of Mr. Walsh's enactment also identified semantic flatlines, which may indicate "sticking points" in a lesson where he struggled to find examples that could bring a specific concept to life or where he could spend a lot of time providing examples and less time connecting them back to the bigger picture. Flatlines represent times when students needed more or less guidance on a particular topic.

Furthermore, the presence of escalators elucidated instances where he ran out of time and was not able to connect two ideas together. These findings highlight the changes that Mr. Walsh should consider to better present concepts or more effectively utilize academic language associated with science and engineering.

In light of these findings, future studies should explore how different semantic patterns present within teacher discourse facilitates student learning and interest in the science classroom. There is not a specific, “correct” way a semantic profile should look, but identifying attributes that foster conceptual change and deeper understanding will elucidate strategies educators can use when teaching complex science topics. An effective semantic profile for life science may look different than one for physical science. Similarly, there may be a need for greater semantic range for high school students than there is for middle school or elementary students. Scaffolding student learning in engineering or mathematics may require the use of different semantic patterns in a curriculum or its enactment. LCT can be a tool to develop and modify integrated STEM curricular materials that promote knowledge building in the science classroom.

2.7 Conclusion

Creating and integrating meaningful learning opportunities that promote discourse and build on students’ prior knowledge is essential for fostering conceptual understanding, and integrated STEM is one approach for doing so (Honey et al., 2014; NRC 2012). The results of this study indicate that LCT has the potential to study and shape the semantic patterns used in curriculum and instructional practice as a way to influence learning and promote meaning-making. Creating and analyzing a semantic profile is a useful tool for quickly observing the semantic patterns present in a curriculum, or its enactment, which are a good indicator if cumulative learning will occur.

The study of disciplinary language has a long history in science education literature. Science education researchers have used different strategies, techniques, and types of data to study classroom discourse (e.g., Lemke, 1998; Moje, 2015). In light of previous research, we understand how the many facets of language used in the classroom depends on the context of the learning environment and the cultural systems of those within it (Halliday, 1985; Lemke, 1998). The social interactions that take place within the classroom, including curricular activities, teacher discourse, and whole class discussions, impact students' ability to construct meaning (Lemke, 2001). Building upon these understandings, we aimed to examine curriculum materials and classroom discourse. Our work contributes to the literature that promotes knowledge building in discipline specific contexts. We used LCT as an analytical framework which provides a toolset for analyzing semantic patterns used to teach students complex science content and practices. Creating a semantic profile of the curriculum provided a visual of how different science topics were presented within an integrated STEM unit. Similarly, a semantic profile of the teacher's enactment of the curriculum showed when and how scientific ideas were unpacked and repacked to facilitate student learning. Dissecting and analyzing the semantic gravity of each activity within an integrated STEM unit can help teachers better relate abstract concepts to students' everyday life while making explicit the connections between individual STEM disciplines. This knowledge and understanding are critical for facilitating students in knowledge-building and meaning-making in science classrooms.

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3. TEACHER DISCOURSE FOR SCAFFOLDING STUDENT LEARNING DURING AN INTEGRATED STEM UNIT

3.1 Abstract

In integrated STEM instruction, an engineering/technology design project or challenge often situates learning in an authentic context while requiring students to incorporate principles and practices from multiple STEM disciplines to solve an authentic problem. Research shows that students' participation in academic productive discussions improves student learning and ability to make connections within and between the STEM disciplines. Thus, teachers' effective use of language can significantly enhance student learning and sensemaking throughout an integrated STEM lesson. In this study, we examined teacher-led discussions in a middle school science class and the kinds of teacher support that scaffolded student meaning-making in integrated STEM unit. We used Legitimation Code Theory as an analytical framework to explore the semantic patterns present within a middle school science teacher's implementation of two lessons as a part of a life science focused integrated STEM unit. Specifically, we examined the varying degrees of semantic gravity, or context dependency, of teacher discourse to identify the discursive strategies the teacher used to promote sense making among his students. The results of this study revealed three discursive strategies: alternating between everyday and academic language, accessing students' prior knowledge, and making interdisciplinary connections. These results suggest ways that teachers can leverage their language to scaffold student learning during an integrated STEM lesson.

Keywords: Integrated STEM, Legitimation Code Theory, teacher discourse

3.2 Introduction

A Framework for K-12 Science Education calls for a transformation of pedagogical practices implemented in science classrooms (National Research Council [NRC], 2012). This pivotal document formally introduced the need to integrate engineering practices and principles alongside those of science. The impetus for this new approach to science teaching and learning focused on the need for STEM literacy:

> Science, engineering, and technology permeate nearly every facet of modern life, and they hold the key to meeting many of humanity's most pressing current and future challenges. Yet too few U.S. workers have strong backgrounds in these fields, and many people lack even fundamental knowledge of them. (NRC, 2012, p.1)

Since the release of the *Framework*, additional reform documents advocate for learning experiences that transcend individual disciplinary boundaries and integrate principles and practices from science, technology, engineering, and mathematics (STEM) (Honey et al., 2014; National Academies of Sciences, Engineering, and Medicine, 2019; NGSS Lead States, 2013).

This new vision of learning demands science educators reconceptualize what science instruction looks like. One instructional approach, integrated STEM, uses engineering design as a vehicle for learning (Moore et al., 2014). Students are presented with an authentic engineering problem and, as part of an engineering team, learn and apply content, practices, and discourse from multiple disciplines to design and test solutions (Bryan et al., 2016). Integrated STEM requires teachers use instructional approaches that immerse students in disciplinary practices unique to each discipline (Nadelson & Seifert, 2017). Thus, to effectively break down academic silos and integrate multiple disciplines, it is imperative that teachers leverage their language to provide scaffolding that facilitates students' meaning-making among and across disciplines (Moje, 1995).

Learning opportunities that promote cognitive development are created and shaped by teacher discourse (Dawes, 2004; Kelly, 2014; Studhalter et al., 2021). Throughout an integrated STEM unit, teachers must deploy different discourse strategies as students engage in discipline specific activities like scientific inquiry (Chin, 2006; McNeil & Krajcik, 2008) or problem scoping within engineering (Johnston et al., 2019) to facilitate student learning within that discipline. However, students often have difficulty in applying specific disciplinary knowledge to a multidisciplinary problem (Azevedo et al., 2015; Honey et al., 2014; Valtorta & Berland, 2015). To help students navigate within and across disciplinary boundaries, careful consideration must be given to how teachers scaffold learning through their discourse in the classroom (Lemke, 1990).

The purpose of this study is to explore how a science teacher's discourse facilitated meaning-making during the implementation of a life science integrated STEM unit by examining the semantic patterns of the teacher's utterances during instruction. More specifically, this study addresses the following research question:

- What semantic patterns are evident in a middle school science teacher's discourse as he scaffolds student understanding during an integrated STEM unit?

3.3 Theoretical Framework

This study is guided by a sociocultural perspective on learning and builds on research on teacher discourse and integrated STEM education. Science learning is a social endeavor that transpires from interactions and discourse that occur within the context of the classroom (Cobb & Bower, 1999; Greeno, 1997; Kelly, 2014; O'loughlin, 1992). The goal of science education is to help students develop a shared understanding of scientific knowledge and acquire scientific habits of mind (NRC, 2012). In other words, students are immersed in the culture of science which includes content knowledge, skills, and specialized language used by members of the scientific community (Lemke, 1998). The scientific ways of knowing, being, and thinking are sometimes incompatible with the values, beliefs, knowledge, and ways of communicating that students bring to the science classroom (Driver et al., 1994; Gay, 2010). These social and cultural experiences serve as a lens that students use to make sense of new information (Lee, 1999). To facilitate meaning-making, it is important that teachers create learning environments that engross students in the culture of science while considering the knowledge and experiences of their everyday culture (Fradd & Lee, 1999; Lee & Fradd, 2001). To this end, teacher discourse frames instructional practices that expand students' linguistic toolkit while also facilitating student learning (Dawes, 2004). In the context of integrated STEM education, students learn and apply discipline specific practices and language from more than one discipline (Honey et al., 2014). Teacher discourse is critical in scaffolding student learning so they can identify when and how to use disciplinary knowledge but also how make connections within and between disciplines.

3.3.1 Teacher Discourse

To support student learning, teachers establish a 'language trail' that guides students from the preconceptions they bring to class to the scientific views of a natural phenomenon (Scott, 1997a). Through their discourse, teachers guide classroom interactions that make student thinking visible while providing the opportunity to generate shared understandings of science ideas (Edwards & Mercer, 1987). Teachers control the progression of discourse to make concepts coherent and accessible to students on the social plane (Scott, 1998). Students use these social experiences to reconstruct and reorganize their internal understandings (Vygotsky, 1962).

Within the science classroom, teachers deploy a variety of discursive strategies to scaffold student learning. Using dialogic discourse (Scott et al., 2006), teachers can continually assess the level of student understanding and adapt the type of support provided to better meet the needs of the student (Palinscar & Brown, 1984; Stone, 1998). One body of research examines the role of teacher questioning in developing students' conceptual understanding (Chin, 2006, 2007; Kawalkar & Vijapurkar, 2013; Roth, 1996). Kawalkar and Vijapurkar (2013) examined types of questions teachers used during an inquiry lesson and found that teachers often progressed from questions that generate ideas to those that help students refine their ideas to align with scientifically accepted ideas. Another scaffolding technique is using metaphors and analogies to explain science concepts (Aubusson et al., 2006; Duit, 1991; Glynn, 1995; Niebert et al., 2012). Chiu & Lin (2005) found that comparing science concepts to more familiar processes and ideas helped students overcome misconceptions and understand complex ideas about electricity. Another scaffolding method uses student reflection as a mechanism for recognizing, evaluating, and restructuring their understanding (Davis, 2003; Pei et al., 2020; van Zee & Minstrell, 1997). These scaffolding strategies require teachers to take on the role of facilitator to elicit and develop student understanding over time (Coll et al., 2005).

3.3.2 Integrated STEM

Integrated STEM education incorporates principles and practices from multiple STEM disciplines. Bryan et al. (2016) identified five core features of integrated STEM education. First, content and practices of one or more anchor disciplines are purposefully integrated throughout the unit. An anchor discipline is a primary discipline that drives the learning goals of an integrated STEM unit or lesson. Second, engineering principles and practices, namely the engineering design process, serve as an integrator. An engineering design task couches learning within an authentic, meaningful, and socially relevant context which sets the stage for the investigations and discussions that occur throughout the unit. In other words, engineering design demonstrates the interconnected nature of the anchor disciplines. Third, students learn and apply scientific and mathematical concepts to evaluate competing designs and justify their final design solution. Fourth, students develop and use creativity, critical thinking, and other 21st century skills to brainstorm and evaluate multiple design solutions. Lastly, as students work in engineering teams to design, construct, test, and redesign their solution, they establish a community of practice based on collaboration and communication.

Teacher discourse is an essential component of integrated STEM education. As students progress through the engineering design process, they engage in a range of science and engineering activities that introduce and reinforce content. These activities alone are not enough to promote sense-making on the part of the student; rather it is the discourse that surrounds the activity that fosters meaning-making (Gee, 1996). Teachers must combine univocal and dialogic forms of discourse in the classroom (Lotman, 1988) to create a ‘rhythm of discourse’ that incorporates the presentation of content knowledge from the STEM disciplines involved in the integrated STEM instruction while providing opportunities for students to explore ideas (Scott, 1997b). Further, teacher discourse must scaffold student learning so students can apply their understandings in a range of contexts.

Few studies have examined teacher discourse within the context of integrated STEM. Aranda et al. (2020) examined two teacher’s discourse during a design-based unit and found certain types of discourse can enhance student learning. Specifically, one teacher employed questioning strategies that elicited students’ understanding, but rather than only acknowledging their response, he used them as a platform for further discussion to elaborate upon their ideas. This teacher also used in depth explanations, including analogies, to make an abstract idea, like the structure of DNA, more familiar to students. In a study by Johnston et al. (2019), the researchers found that a teacher used engineering talk to establish core features of engineering such as teamwork, problem scoping, and communication for students and to provide a real-world context that requires the application of science and mathematics principles addressed in the unit. Additional studies that elucidate how teachers can use their language to facilitate meaning-making within and across disciplines are needed to identify ways to better scaffold student learning so they can apply their understandings to their design solution.

3.4 Methods

This study was part of a longitudinal, design-based project (Cobb et al., 2003) that aimed to assist middle school science teachers in integrating engineering principles and practices into their science instruction. Design-based projects "are iterative, situated, and theory-based attempts simultaneously to understand and improve educational processes," (DiSessa & Cobb, 2004, p.80). For this project, researchers developed curriculum that contain the five core features of integrated STEM. During a three-week summer professional development program, teachers learned about engineering design and how to implement this curriculum in their classroom. The following year, project members observed the teachers' implementation of the unit to identify how to revise the curriculum material to enhance student learning. For this study, we used a case study approach to closely examine a teacher's discourse during his implementation of the *Designing a Two-Stage Water Filter* curriculum (Yin, 1994). Specifically, the case consisted of Mr. Walsh's utterances during the implementation of two lessons of the curriculum.

3.4.1 Participants

We collaborated with Mr. Walsh (pseudonym), a sixth-grade science teacher with over ten years of teaching experience in a small, rural Midwestern school with an enrollment of approximately 500 students in Grades 6-12. We purposively selected Mr. Walsh for this study because of his familiarity with integrating engineering into the science curriculum and his prior work experience as an environmental engineer who worked on pollution and waste management projects.

Prior to the study, Mr. Walsh participated in a three-week summer professional development in which he learned about the engineering design process and how to implement the integrated life science and engineering unit, *Designing a Two-Stage Water Filter*. Mr. Walsh implemented the unit during the following school year with a class of 27 sixth-grade students—12 Caucasian male students and 15 Caucasian female students. Five of the students (19%) received reduced or free lunch.

3.4.2 Curriculum Unit

The second author and project staff designed the *Designing a Two-Stage Water Filter* curriculum materials to reflect the five core features of an integrated STEM curriculum described by Bryan et al., (2016). For this curriculum, the engineering design process serves as an *integrator* and sets learning within the *real-world context* of needing to design a two-component (mechanical and biological) water filter to reduce pollution in a local river. Students develop *21st century skills* as they learn content and skills from the *anchor disciplines* of science, engineering, and mathematics. These science and mathematics principles are used to *justify their design solutions*.

Table 1 presents an overview of the unit. During Lesson 1, students were introduced to the design challenge by watching a video from the city's engineering office eliciting their help. Students engaged in problem scoping and identified science concepts they needed to learn to design their water filter. In Lesson 2, students engaged in an inquiry investigation to determine how water passes through soil, sand, and rock. During Lesson 3, students examined the process of transpiration as they measured the distance water traveled up a stalk of celery, and they completed a virtual lab to determine the conditions a plant needs to be healthy. These activities helped students understand how pollutants in water travel through the ground and into a plant. Then students discussed how some plants tolerate and filter out pollutants while others cannot, making some plants a feasible option for the biological component of their water filter. In Lesson 4, students explored decomposition to understand how nutrients are recycled into the soil for plant use. Then, students applied each of these science principles to design, construct, and present their two-stage water filter in Lesson 5.

Table 5. *Overview of Designing a Two-Stage Water Filter Curriculum*

Lesson	Timeline	Disciplinary focus	Purpose
1	Days 1-2	Major, Engineering Minor, Science	Introduce the design challenge; problem scoping
2	Days 3-5	Major, Science Minor, Engineering	Inquiry lab to examine how water percolates through different materials
3	Days 6-8	Major, Science Minor, Engineering Minor, Mathematics	Transpiration lab; complete a virtual lab on what plants need to survive
4	Days 9-10	Major, Science Minor, Engineering Minor, Mathematics	Determine how biotic and abiotic factors affect a population.
5	Days 11-16	Major, Engineering Minor, Science	Design, build, test, and evaluate design solutions

3.4.3 Data Collection and Analysis

Video recordings of Mr. Walsh's implementation of a science-based lesson and an engineering-based lesson from the *Designing a Two-Stage Water Filter* unit served as the primary data source for this study. The video recordings focused on Mr. Walsh's whole-class interactions while he implemented the curriculum over sixteen class periods (12 hours). Each 50-minute class was videotaped and transcribed. The purpose of this unit is to introduce multiple science ideas to students, so Mr. Walsh used whole class discussions to elicit student ideas, create a shared understanding of the content, and to help students make sense of their collective inquiry experiences. So, the data for this study consisted only of Mr. Walsh's discourse when directed at the entire class.

We conducted a qualitative analysis of the data. To identify instances in Mr. Walsh's implementation where he used discursive strategies to scaffold student learning, we needed to compare the written discourse of the curriculum to the Mr. Walsh's discourse during implementation of the curriculum. Previously, we created a semantic profile of the *Designing a Two-Stage Water Filter* curriculum, by dividing it into units of meaning, which represent points in the curriculum where there is a shift in the purpose of what is being done or said and assigned each unit of meaning a semantic gravity code, either SG--, SG-, SG+, or SG++ (Paper 1). A description and example of each code is provided in Table 2. We used the same approach to develop the semantic profile of Mr. Walsh's enactment of the curriculum. After each video was transcribed the first author divided the transcript into individual units of meaning and two project personnel independently read through the transcript of Lesson 1 and coded 10% of it using the same four-point semantic gravity scale, with an inter-rater reliability of 85%. The transcript for Mr. Walsh's entire implementation of the unit contained 278 units of meaning, so to obtain a more accurate picture of Mr. Walsh's discourse throughout the unit, we created semantic profiles for each lesson rather than one large profile. These semantic profiles, along with transcripts from the unit, were used to identify discursive strategies Mr. Walsh used to scaffold student learning.

Table 6. *Descriptions and Representative Examples of Semantic Gravity Codes*

Semantic Gravity	Code	Description of Code	Example of Code
Weaker ↑	SG--	References abstract principles	Ecosystem interactions, what does that mean?
	SG-	References general science ideas	How living things interact.
	SG+	References general everyday examples	So we have animals, we have plants, we have humans, how does everything interact? Plant needs, figuring out what they need.
↓ Stronger	SG++	References a specific example	Anyone drink coffee? So, when you make coffee…water comes down and it moves through the pot…it percolates.

3.4.3.1 Legitimation Code Theory as an Analytical Framework

Legitimation code theory (LCT) utilizes multiple dimensions for exploring aspects of academic disciplines (Maton, 2007). The semantics dimension of LCT includes semantic gravity, which measures the degree to which meaning is rooted in the context it was acquired in (Maton, 2014). The semantic gravity of an activity or segment of dialogue runs along a continuum from weak semantic gravity to strong semantic gravity. The stronger the semantic gravity, the more an activity or dialogue is rooted in a specific context. Conversely, the weaker the semantic gravity, the more abstract the activity or dialogue. Various semantic patterns may be present within a curriculum or its enactment. Such patterns include escalators, flatlines, and waves (Maton, 2014), as illustrated in Figure 1. Escalators represent the disjointed packing or unpacking of disciplinary knowledge. Flatlines indicate instances when material is continuously presented in a specific context, which may make it challenging for students to transfer their knowledge to a new situation, or in an abstract context, which may make sense making difficult for students. Semantic waves characterize areas where a disciplinary idea is unpacked, repacked, and connected to the next idea presented (Maton, 2014).

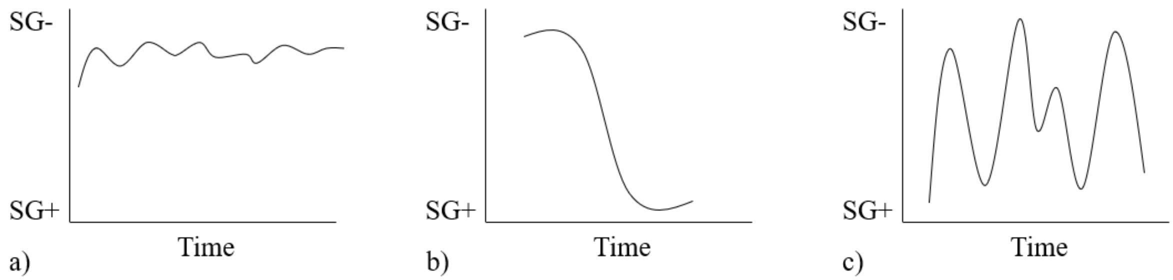

Figure 8. *Three Types of Semantic Patterns: Flatlines (a), Escalators (b), and Semantic Waves*

Previous studies indicate that discourse with weak semantic gravity (SG--) or a strong semantic gravity (SG++) may pose challenges for students (Maton, 2014). Specifically, SG-- discourse may be too unfamiliar so students cannot comprehend what is being said, whereas SG++ discourse may root the meaning of content in a specific context, making it difficult for students to apply their understanding in new situations (Maton, 2014). Brown and Spang (2008) found that double talk, alternating between everyday talk (SG+) and science talk (SG-) increased student learning. Thus, to identify instances where Mr. Walsh's discourse varied from that of the written curriculum, we created an alignment profile. To do this, we needed the semantic profiles of the written and enacted curriculum to have the same number of units of meaning. So, we employed a procedure based on Hartley (n.d.) in which each code is assigned a numerical value: SG—a four, SG- a three, SG+ a two, and SG++ a one. Next, all units of meaning from Mr. Walsh's discourse that corresponded to the first unit of meaning from the curriculum were extracted and averaged. We completed this process for every unit of meaning in the curriculum. We then plotted the semantic gravity of each aligned unit of meaning as a function of time. Lastly, we overlaid the aligned enactment profile and the curriculum semantic profile, as shown in Figure 2. The alignment profile highlights areas where the semantic gravity Mr. Walsh's discourse varied considerably from the curriculum (indicated by red rectangles in Figure 2). Each of these instances includes curriculum units of meaning with discourse that is either very abstract

(SG--) or very specific (SG++), but the units of meaning related to Mr. Walsh's enactment are not. These areas likely represent instances where Mr. Walsh leveraged his language to enhance the curriculum and facilitate sense making throughout the unit.

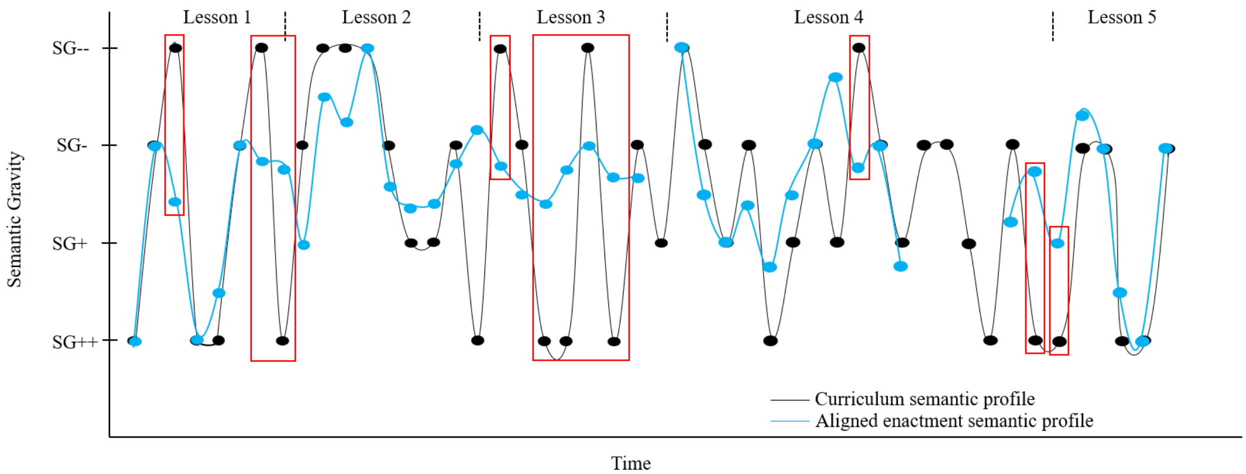

Figure 9. *Alignment Profile Comparing the Semantic Gravity of the Curriculum and its Enactment*

Although differences between the semantic gravity occur in multiple lessons, this study focuses on one engineering-based lesson (Lesson 1) and one science-based lesson (Lesson 3), where the most variation occurs. In the following sections, we describe three ways Mr. Walsh used his discourse to promote students' sense making within each of these lessons.

3.5 Findings

Our examination of Mr. Walsh's discourse during Lessons 1 and 3 identified three discursive strategies he deployed to scaffold student learning: 1) Alternate between academic and everyday language; 2) Access prior knowledge; and 3) Make interdisciplinary connections. Although each strategy is presented separately, Mr. Walsh intertwined these strategies throughout his discourse, so examples of one strategy may appear during the discussion of another strategy. Each discursive strategy is described below, with examples provided from each discipline, along with a semantic profile from either Lesson 1 or Lesson 3.

3.5.1 Discursive Strategy 1: Alternate between academic and everyday language

Mr. Walsh consistently alternated between familiar, everyday language and unfamiliar discipline specific language. This was especially true when he introduced new vocabulary terms. After using a new discipline specific word, Mr. Walsh immediately broke it down using words students are familiar with. On Mr. Walsh's semantic profiles, this strategy is indicated by a unit of meaning coded SG-- (new term) followed by either SG- (science definition comprised of familiar terms) or a SG+ (a common example related to the term), as illustrated in Figure 3.

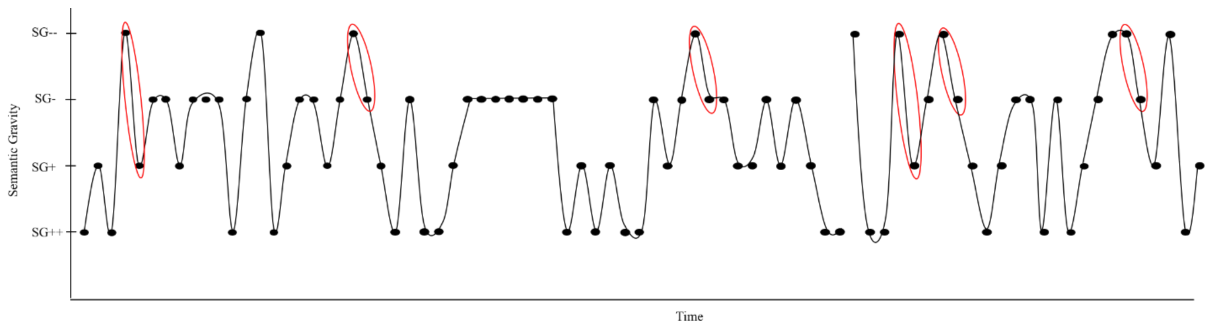

Figure 10. *Instances of Alternating between Academic and Everyday Language during Lesson 1*

3.5.1.1 Lesson 1: Engineering

At the beginning of Lesson 1, Mr. Walsh showed an illustration of the engineering design process and explained each stage of it. During the first step, students engage in the engineering practice of problem scoping, where students identify the client, end user, criteria, and constraints, most of which are novel terms for students. At this point in the lesson, Mr. Walsh said:

> Define your constraints. What do we think constraint means? (SG--)
> Limit. It keeps you from doing something. (SG-)

Later in the lesson, Mr. Walsh revisited the term constraints, but rather than defining the term again, he elicits students' conceptions by saying:

> What are constraints? (SG--)
> Materials is one, what else? Time. Money. (SG+)

Students continued to identify constraints that will limit the design of their water filter. One student identified the width of the pipes their filter will be placed against as a constraint, which led Mr. Walsh to reference the two stages of their water filter. As many students are not familiar with a two-stage water filter, Mr. Walsh used this strategy to ensure students understood what they would be designing by saying:

> Mechanical and biological filter. What do we mean by mechanical? What do you think of when you hear the word mechanical? (SG--)
> Machines, right? Think of a mechanic…mechanical could be machines, right? (SG+)
> …All the debris comes in [to wastewater treatment plant], do you think somebody stands and picks up the sticks? No, they probably use some kind of machine … (SG-)
> What do we mean by biological filter? (SG--)
> What do you think of when you hear biology? Study of biology? Life, right? (SG-)
> So how can we use life as far as one of the stages? [students list examples] (SG+)

In this example, Mr. Walsh consciously unpacks two new ideas, a mechanical stage and a biological stage that together comprises a single water filter. By gradually increasing and decreasing the semantic gravity of his discourse, Mr. Walsh, scaffolded student learning to ensure they understood the task at hand. After mentioning the idea of a "mechanical stage" he unpacked it by relating it to familiar words (e.g., machines and mechanic). Because his students knew what machines and mechanics do, Mr. Walsh then talked about ways machines can be used to filter water. He used the idea of machines as components of a water filter to segue into discourse related to the other component of their water filter, the biological stage. At this point in the year, students had learned about biology, so Mr. Walsh used their familiarity with biology as a subject to direct the conversation towards living things that naturally filter water.

3.5.1.2 Lesson 3: Science

In Lesson 3 students completed two activities to inform the design of the biological component of their water filter. Students measured and graphed how far colored water traveled up a stalk of celery as a way to visualize transpiration. They also completed a virtual lab where they manipulated different variables (e.g., color of light, gas, and type of liquid) to determine how each affected the health of a plant. Throughout this lesson, Mr. Walsh used this strategy to introduce and reinforce new science terminology. He also blended everyday and academic language when explaining new science concepts.

After students completed the transpiration lab and shared their data with the class, Mr. Walsh asked the class why their graphs showed that over time, the amount of water that traveled up the celery gradually increased but eventually tapered off. To help students understand the science behind their data, Mr. Walsh explained:

> Xylem, look at your diagram, what do you think xylem does? It’s in the stem there. What do you think those tubes do? They carry water up to the top, to the leaves and different parts of the stem. So, when you look at the celery, and look at the ends and see those holes, you’re looking at the xylem. You’re looking at those tubes that are going to pull the water up so that water travels up there. So that’s what the goal was, to cut the outside off and be able to see those tubes and see how far that water went up. (SG-)

To help students conceptualize the structure and function of xylem, Mr. Walsh referred to it as a tube that water travels through to keep the plant healthy. Thinking about xylem as tubes enabled students to understand how water travels further up the xylem as time progresses. Mr. Walsh consistently used this type of double talk in his discourse.

3.5.2 Discursive Strategy 2: Access prior knowledge

Through his discourse, Mr. Walsh often accessed students’ prior knowledge to help them make sense of the content. However, the specific approach to accessing prior knowledge differed between the two lessons. In Lesson 1, Mr. Walsh capitalized on prior knowledge related to a previous design task the students completed as well as their personal experiences outside of the classroom to make unfamiliar ideas more relatable. In Lesson 3, Mr. Walsh used well-known examples and personal experiences to help them make sense of new science content.

3.5.2.1 Lesson 1: Engineering

Earlier in the year students completed an informal design challenge where they designed a new racetrack for a toy car. According to Mr. Walsh, although they went through the motions of the engineering design process, they did not learn the details of each stage of the process, nor did they use engineering specific language as they built and tested their tracks. Mr. Walsh used the knowledge students gained from this experience as a springboard for learning new engineering language.

After a discussion about what engineers are and what they do, Mr. Walsh introduced the engineering design process as a way to solve problems by saying:

> So, the [design process] we used for the racetrack, we researched our problem, designed a solution, and built our prototype. We test, we evaluate, we troubleshoot, communicate our results, and redesign. This one [points to the model of the engineering design process] is very similar, okay? (SG++)

Then, Mr. Walsh explained each step of the engineering design process. For the first step, ExploreIt, students learned about the problem by identifying criteria and constraints. To help students make sense of the term “criteria,” he said:

> So, typically, when we looked at racetrack, what was our constraints? … the cost and length were the two that you primarily focused on. You had to have a big length, what were you going to have to sacrifice? Some of that cost, right? Okay, so it was very hard to do both. Sometimes there is a limitation. In the Explore [stage] you find out what those constraints are and who is involved. (SG++)

Mr. Walsh then talked about the next stage of the engineering design process, the LearnIt stage, when he said:

> Okay. After you go to the ExploreIt, you are going to LearnIt. In other words, you are going to gain knowledge … then sketch the ideas, okay? (SG-)
> This is similar to what we did with our racetrack, okay? What did you guys do before you were actually able to test your [previous] design? Each one of you had to come up with some ideas, right? You had to sketch it out … (SG++)

In these examples, Mr. Walsh capitalized on the knowledge students gained from the previous design challenge to familiarize them with a formal model of the engineering design process, the details of each step of this process, and engineering specific language.

Another discursive strategy Mr. Walsh employed during this lesson was to relate new ideas to personal experiences the students had outside of the classroom. For example, to help students understand the problem of the local river being polluted, Mr. Walsh said the following:

> Think about a parking lot or road, what might be in a parking lot or road that you might not want in the water? Possibly food … cars … oil, antifreeze, al the liquids in the cars are pollutant. We need to capture those, so it doesn't contaminate the ground (SG+)
> Here at [school], we have little filters on our drains. Where do those drains go? Straight into the creek back there. (SG++)

Later, Mr. Walsh reviewed the process wastewater treatment facilities use to clean water:

> And then, if you remember in the video, they talked about chlorinating the water. Why would they chlorinate the water? To kill any of that nasty bacteria. (SG-)
> What do you do with your pool? Add chlorine to it, right? (SG++)

In both excerpts, Mr. Walsh used students' real-world experiences, and the knowledge they acquired from those experiences, to help them understand the problem of a polluted river and the process used to solve this problem. Throughout this lesson, Mr. Walsh continuously used specific examples to make unfamiliar process more understandable. Due to the specific context all of these pieces of discourse are situated in, they are all coded SG++. As shown in Figure 4, Mr. Walsh typically alternated between these two approaches to access students' prior knowledge and relate it back to the current engineering design task.

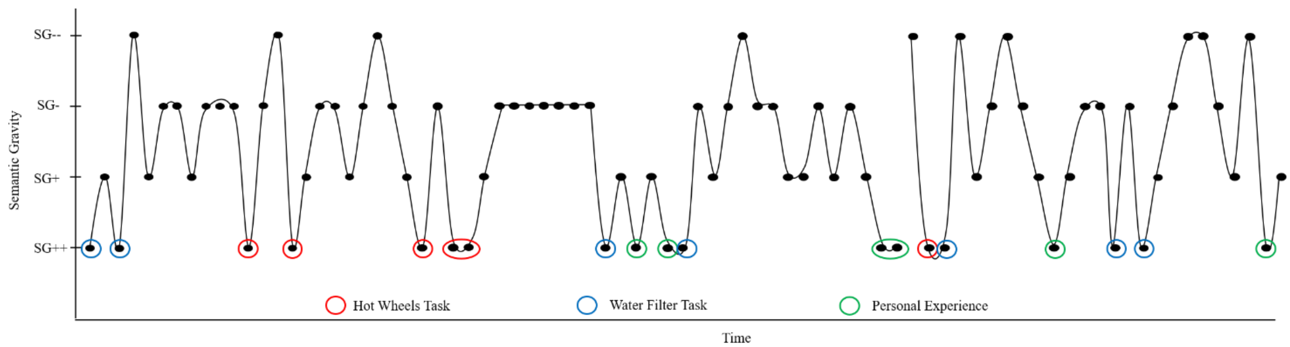

Figure 11. *Instances of Accessing Students' Prior Knowledge in Lesson 1*

3.5.2.2 Lesson 3: Science

During Lesson 3, Mr. Walsh primarily used real world examples to help students make sense of the science content they were learning. Mr. Walsh consistently provided common real-world examples after introducing or reviewing discipline specific language. For example, after explaining that some students are completing a virtual lab to determine what abiotic and biotic factors a plant needs to live, Mr. Walsh said:

> You will be determining the best abiotic conditions for this plant. What is abiotic and biotic? What does abiotic mean? (SG--)
> Nonliving. Something that is nonliving. (SG-)
> What's an example of something nonliving? Rock, table, all those things. (SG+)

Later in the lesson, after students completed the virtual lab, Mr. Walsh alternated between science talk (SG-) and real-world examples (SG+) to help students understand how the color of light affects the health of a plant. During the virtual lab, students selected different colors of light to determine how each color affected the plant. To help students make sense of the affect white light has on the plants, Mr. Walsh said:

> Why would you change the color? … Why would there be different colors of light? (SG-)
> We look right here [motions towards the classroom lights] and we don't see different colors. Are they tinting the light or allowing some light to come through? How do we know they are allowing some to come through? (SG+)

> What do we know about white light? Is it white? What's it made up of? All the different colors, combined, right? (SG-)
> What happens if it rains and its sunny? What do we see? A rainbow. (SG+)
> You get that because it refracts out and we're able to see the different types of light that make up our white light. (SG-).

During this science-based lesson, Mr. Walsh accessed students' prior knowledge to help them understand why certain factors affect plant health and how water moves through a plant, a concept that is new to many middle school students. Using examples that students are familiar with provided a starting point for students to build from and makes learning meaningful. In each of these examples, the semantic gravity of Mr. Walsh's discourse changed by one degree in either direction. This indicates that he used real-world examples to unpack science content (e.g., abiotic factors) or to unpack and then repack complex science ideas (e.g., properties of light).

3.5.3 Discursive Strategy 3: Make interdisciplinary connections

Throughout both lessons Mr. Walsh explicitly connected features of science to features of engineering. The types of interdisciplinary connections made during Lesson 1 differ from Lesson 3. During Lesson 1, Mr. Walsh compared the scientific method, a familiar concept, to the engineering design process, an unfamiliar concept to help students understand how each discipline is unique yet related to each other. During Lesson 3, Mr. Walsh used interdisciplinary connections to organize and frame the lesson and help students identify how engineering solutions require the application of scientific principles.

3.5.3.1 Lesson 1: Engineering

Lesson 1 began with students watching a video that introduces the problem the students need to solve. This segued into a discussion about what engineers are, what they do, and how they do it. Mr. Walsh then introduced the engineering design process as a way to solve problems and said:

> Is that design process exactly the same as our scientific method? What did we say our scientific method was? … With our design process, what did we usually start with? A problem too. With the scientific method we start with a problem… (SG--)
> So, there's different ways we can look at [solving a problem] …Just like the scientific method…we said IHDC for information, hypothesis, analyzing data, conclusion. We can do it different ways. The design process is the same way. Okay. It all comes down to, though, problem solving, right? (SG--)

By comparing the overall goal of the engineering design process to that of the scientific method, Mr. Walsh provided his students with a starting point for their learning. As Mr. Walsh discussed each stage of the design process, he connected it back to the scientific method. For example, after explaining that the goal of the first stage is to learn about the problem, he said:

> We can't solve a problem if we don't know anything, just like we can't do science without any background information (SG-)

Mr. Walsh deployed this strategy for the remaining steps of the engineering design process. As he wrapped up this portion of the lesson, Mr. Walsh ended with this segment of discourse:

> Okay, this is where engineering kind of changes from the whole scientific method a bit. I think the scientific method is a bit more stringent … Okay, I gotta control my variables, I gotta make sure things out so that my data, I can figure out what my conclusions are. Engineering is more fluid, alright. (SG--)

These examples illustrate how Mr. Walsh compared the method of doing science to the method of doing engineering. This enabled students to identify commonalities between the two disciplines, while also highlighting what makes each discipline unique.

3.5.3.2 Lesson 3: Science

In Lesson 3, Mr. Walsh used interdisciplinary connections to make learning relevant and meaningful to students. He did this by relating the purpose and results of the two activities to the engineering design task at the beginning and end of the lesson, respectively, as indicated by pink dots in Figure 5. Mr. Walsh's interdisciplinary connection discourse was always part of a semantic wave and typically occurred at varying degrees of semantic gravity, which likely helped students identify how and when to apply science content to their water filter.

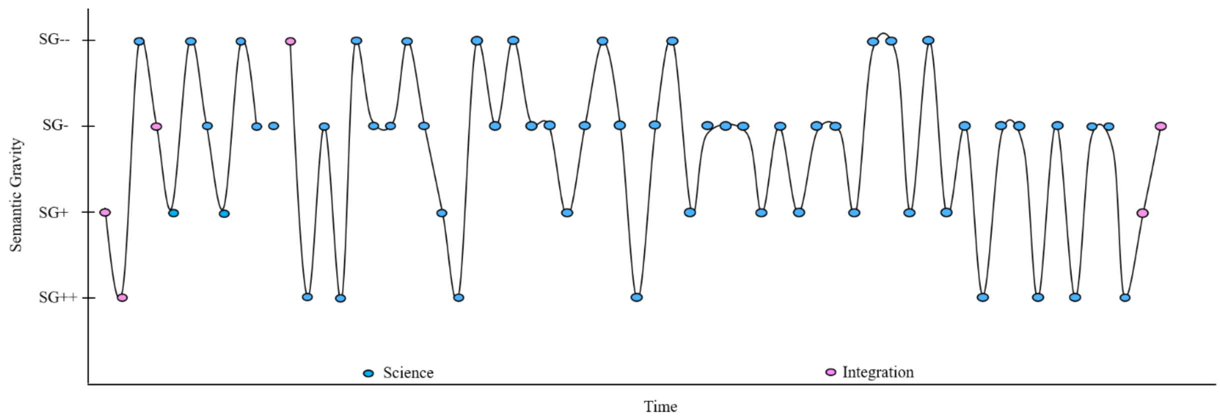

Figure 12. *Interdisciplinary Connections Present in Lesson 3*

On the first day of Lesson 3, before moving on to new content, Mr. Walsh related what students learned about soil percolation in Lesson 2 to the design filter when he stated:

> What we first looked at yesterday, think about our filters, one thing we needed to learn about [was] water flow, especially about what happens as it moves across the ground…it's going to pick stuff up… (SG+)
> So, when we are designing our filter, you have to keep that in mind, that the water is not clean. One from the sewer and two, that storm water may not be clean also. (SG++)

After a brief overview of what the students will be doing that day, Mr. Walsh said:

> So, this all comes back to thinking about a biological component of our filtration, we need to understand how that's going to work. How is, if I have plants cleaning my water… how it is 1) going to do that, and 2) how is it going to affect the plant? (SG++)

By beginning the lesson this way, Mr. Walsh aligned student thinking with the end-goal in mind. Helping students recognize the relevance of the activities can intrinsically motivate them to think about the results and how the data can inform their water filter design.

Mr. Walsh made interdisciplinary connections at the end of the lesson by relating the outcome of the day's activities to the design task. Specifically, the following excerpt is Mr.

Walsh's side of a whole-class conversation about how the virtual lab and transpiration data inform their water filters:

> So, if I have, let's say my plant is in the water, trying to clean it up, and there is a lot of salt in in the solution, what's going to happen to my plant? They're going to die… (SG-) You have to think about, when you're designing your filter, is that plants are going to take in what they need…and the goal of [the filter] is to filter out the [pollutants]. (SG++) Some of the plants can do this very well… so that's something to keep in mind (SG+) Either way, because of capillary action, transpiration, it's going to have an impact. So, you want to know what is in your water, so you know if it's going to destroy the plant or if the plant is going to be able to do its job. (SG-)

During this conversation, Mr. Walsh not only explained how the two science concepts are related, but how science principles are used when designing solutions to a problem. After posing a scientific scenario (SG-) and relating it to the design task (SG++), Mr. Walsh's discourse weakened in semantic gravity by one degree as he repacked the idea of other plants being able to use transpiration and naturally filter out pollutants in certain ecosystems, which is the topic of the next lesson. Gradually changing the degree of semantic gravity can provide students with the steppingstones they need to understand how information they apply to a specific situation, like a design task, can be used in other contexts.

3.6 Discussion

Since the release of the Framework (NRC, 2012), a lot of attention is given to developing and implementing curriculum that contains the essential features of integrated STEM (Anderson & Tully, 2020; Brown & Bogiages, 2019; Estapa & Tank, 2017; Shernoff et al., 2017; Du et al., 2019). Our work, including the *Designing a Two-Stage Water Filter* curriculum is one example of this effort. Using a design-based research approach, the curriculum was developed and implemented in several middle school classrooms to identify areas in the curriculum that can be revised to better support student learning and sense making. We acknowledge that although sample script and prompts for teachers are provided in the curriculum, teachers alter the discursive moves and strategies based on their students' prior knowledge, experiences, and learning needs. Now that teachers and teacher educators are more familiar with the purpose, design, and implementation of integrated STEM curriculum, it is time to focus on additional practices teachers need to facilitate meaning-making within and among the disciplines represented in an integrated STEM unit. Teacher discourse is an essential teaching practice that guides students' cognitive development in the science classroom (Gee, 2004; Kelly, 2014). Studies that examine effective ways teachers can use their talk to enhance student learning and make interdisciplinary connections during integrated STEM lessons will greatly benefit the science education community.

This study adds to the body of literature on integrated STEM by examining how a middle school science teacher used his discourse to scaffold student sense making during integrated STEM lessons. As teachers learn about integrated STEM and gain experience teaching it, they develop knowledge and skills including what language to use to best represent the ideas being taught, and when certain language is most appropriate (Geddis, 1993). LCT as an analytical framework provided a systematically developed alignment profile that allowed us to visualize the similarities and differences between the discourse used in a curriculum and a teacher's implementation of it. This enabled us to identify two lessons where Mr. Walsh made productive adaptations to the curriculum to scaffold student learning. A closer examination of Mr. Walsh's implementation profiles revealed semantic patterns in his discourse that correspond to three discursive strategies he used to facilitate meaning-making among his students: Alternating between everyday and academic language, accessing student's prior knowledge, and making interdisciplinary connections.

Roth et al. (1987) indicate that “[t]eachers should be the key link between the curriculum materials and the students” (p. 546), so even though certain points in the curriculum did not prompt him to do so, Mr. Walsh created semantic waves by unpacking abstract concepts by alternating between academic language and everyday language to help students learn and use discipline specific language. The importance of blending academic language and everyday language in disciplinary instruction is also supported by other scholars (Lemke, 1998; Moje 2008; Moje et al., 2001). Mr. Walsh used these interdisciplinary connections to help make unfamiliar engineering content easier to understand and to make the science content more meaningful. Mr. Walsh also accessed students’ prior knowledge to provide them with a starting point for learning new content. This also helped students realize that science is an essential part of their everyday lives. To elicit students’ prior knowledge, Mr. Walsh asked his students a lot of open-ended questions and follow-up questions to create a stronger ‘language path’ (Scott, 1997b) for students to help them progress from a simple to more sophisticated understanding of science topics.

We propose that the semantic profiles of the curriculum and implementation provide information that is bi-directional—i.e., those using the semantic profiles may be able to see, for example, parts of a lesson for which teachers would benefit from more discursive support or sections of a lesson where scaffolding can enhance student understanding of complex concepts. In general, the semantic profiles provide the impetus for reflection, analysis, refinement of the teaching-learning process, from conceptualization of a curriculum unit through its enactment and impact on student learning. Future studies should examine how teachers adapt curricular materials, so their discourse meets the needs of their own students, and the impacts this has on students in an integrated STEM learning environment. Additional studies using LCT to examine and compare the semantic patterns within multiple teachers' implementation can elucidate how teacher discourse influences student learning in the context of integrated STEM education. These studies would also help us learn more about the strategies teachers use as they adopt new curricular materials.

3.7 Conclusion

Integrated STEM offers teachers a way to break down the silos of individual STEM disciplines to create learning environments that better meet the needs of 21st century students. (Honey et al., 2014; NRC 2012). Although teachers may recognize the importance of integration (Wang et al., 2011), many find it challenging to implement because their expertise falls within a single academic discipline. There exists a need to create curricular resources that leverage teacher discourse to facilitate student meaning-making within an integrated STEM context to make explicit the interconnected nature of the disciplines. Through using a variety of discursive strategies, teachers can make the curriculum units and learning more meaningful for their students as they address the specific needs of the students. Discursive strategies such as blending academic and everyday talk, accessing students' prior knowledge, and making interdisciplinary connections as ways of scaffolding student learning are critical for integrated STEM education. As this study only examines a single middle school teacher's discourse during integrated STEM lessons, future research should focus on identifying and understanding other discursive strategies that teachers can use to support and enhance student learning.

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4. A COMPARISON OF TWO MIDDLE SCHOOL SCIENCE TEACHERS' APPROACH TO INTEGRATED STEM

4.1 Abstract

Reform initiatives advocate for the integration of science and engineering principles and practices within the K-12 science classroom. Integrated STEM uses the engineering design process as a vehicle for teaching and learning science, which can be challenging for science teachers as many lack formal education and experience with engineering. Professional development opportunities aim to help teachers enhance their understanding of the core features of engineering, including the engineering design process and practices. However, an essential component of integrated STEM education is teachers' effective use of disciplinary discourses in instruction. This study used Legitimation Code Theory, specifically semantic gravity, to take an in-depth look at discourse in two middle school science teachers' instructional practices. We analysed and compared the semantic patterns in teachers' discourse and identify areas for professional development to enrich integrated STEM teaching to better scaffold student learning. Our results indicated that each teacher has his own approach to integrating multiple disciplinary discourses throughout the lessons to better address the needs of their students. However, both teachers tended to chunk disciplinary content and practices, have difficulty making interdisciplinary connections, and more discursive disconnects occur when there are more academic disciplines present within a lesson. These results suggest that teachers may benefit from targeted professional development that focuses on discursive practices in integrated STEM education as a way of making meaning within and among disciplines.

Keywords: Integrated STEM, Legitimation Code Theory, semantic gravity, teacher learning, professional development

4.2 Introduction

For the past ten years, reform initiatives have reshaped the K-12 science educational landscape by calling for the integration of engineering content in the science curriculum (National Research Council [NRC], 2012; NGSS Lead States, 2013). An integrated approach to STEM learning necessitates the development of learning opportunities that transcend the traditional disciplinary boundaries of science, technology, engineering, and mathematics (STEM) (English, 2016). To implement integrated approaches, teachers deploy a range of instructional strategies framed by effective discourse to help students make interdisciplinary connections. Effective integrated STEM approaches also require a classroom culture that cultivates the habits of mind associated with each discipline (Fasse et al., 2001). Integrated STEM education incorporates the content and practices from multiple STEM disciplines as students work to design a solution to an authentic, real-world problem (National Academies of Science, Engineering, and Medicine, 2019; NRC, 2014).

For successful integration to occur, teachers need professional development opportunities that immerse them in authentic learning experiences (Honey et al., 2014). To incorporate engineering into the classroom, science teachers need to understand what engineers do and how they use the engineering design process as a mechanism to solve problems (Aydin-Gunbataret et al., 2018). Professional development that places teacher as learner allows educators to work as part of an engineering team to practice discipline specific principles and practices (e.g., making tradeoffs, designing, and redesigning) and expand their discursive repertoire (e.g., criteria, constraints, and prototype) all while enhancing their understanding of integrated STEM education (Ring et al., 2017). These experiences help teachers identify how they can incorporate engineering design into their pedagogical toolkit and leverage their discourse to promote knowledge building by making explicit interdisciplinary connections within the curriculum (Guzey et al., 2019).

Despite a growing emphasis in integrated STEM education over the past ten years, many teachers need support, guidance, and resources as they learn ways to successfully implement integrated approaches (Honey et al., 2014; Nadelson & Seifert, 2017; Stohlmann et al., 2012). Learning new practices take time and effort (Borko, 2004; Fishman et al., 2003; Schneider & Plasman, 2011) and research provides insights on what helps teachers learn and develop new practices (Desimone, 2011; Garet et al., 2001; Wilson & Berne, 1999). However, studies that examine how professional development can influence the language science teachers use in the context of integrated STEM are needed. English (2016) emphasized the “need to investigate ways to make connections among the STEM disciplines more transparent for both students and teachers,” (p. 7). To this end, the purpose of this paper is twofold: (1) to compare the semantic patterns in two middle school science teachers’ discourse as they implemented lessons that they co-created during a professional development program and (2) to identify themes across both teachers that elucidate additional discursive support teachers need as they continue to learn about and implement integrated STEM approaches. Our study aimed to address the following research questions:

- What do the semantic patterns present in two science teacher’s discourse reveal about the needs of middle school teachers learning to implement integrated STEM?

4.3 Theoretical Framework

Three bodies of literature guided this study, namely teacher learning, the role of professional development in teacher education, and integrated STEM education. The desire to enhance student outcomes drives the development of new reform initiatives, which advocate for instructional approaches that usually do not align with those currently used in the classroom (Wilson, 2013). Therefore, implementing new reform-based pedagogies is often difficult for teachers (Berlin & White, 2010; Crawford, 2007; Windschitl, 2003). Although teachers see the value of an integrated curriculum, they have difficulty identifying and communicating connections between disciplines (Frykholm & Glasson, 2005; Kloser et al., 2017). To facilitate educational change, teacher learning must occur. One tool for teacher learning is participation in high-quality professional development. These opportunities help educators understand the purpose and goals of new reform initiatives, acquire and enhance discipline specific content knowledge, and learn how to execute new instructional approaches through experiences (Schneider et al., 2005; Putnam & Borko, 2000).

4.3.1 Teacher Learning

Teachers add new knowledge and skills to their repertoire as they learn and incorporate new teaching strategies. Multiple interacting factors play a role in what and how teachers learn including beliefs, knowledge, resources, and school culture (McDonald, 2016). This makes teacher learning a multifaceted and complex process (Ball & Cohen, 1999; Cohen & Ball, 1999). Additionally, some aspects of teacher knowledge and practice are more resistant to change than others, so the adoption of new pedagogical practices may be a slow and undefined process (Borko, 2004). One approach to teacher learning involves making explicit the tacit knowledge guiding their instructional practices (Loughran, 2014). To do this, teachers can take on the role of learner, participate in authentic activities that allow them to grapple with content, and then use the experiences to reflect on their own teaching (Loughran, 2013). The opportunity to consider and critique their own practices can further develop their ideas of what it means to teach science (Schneider & Plasman, 2011). Additionally, engaging in curriculum development or modification contributes to teacher learning (Ball & Cohen, 1996). As Voogt et al. (2011) states, “the process of (re-)design provides opportunities for teachers to reflect on the curriculum starting from their personal knowledge and beliefs, their practice, and their goals for student learning,” (p. 1236). Professional development opportunities can provide science teachers with these kinds of opportunities and support.

4.3.2 Professional Development

Professional development can impact the way teachers think about teaching and the strategies they use to facilitate learning in the classroom (Loucks-Horsley et al., 2010). Unfortunately, many professional development experiences are disjointed and disconnected from teacher’s everyday experiences in the classroom (Darling-Hammond, 2010). High quality professional development shown to alter instructional practice and effect student learning includes the following features: active learning, extends over a long period of time, focuses on content, is coherent, and promotes collective participation (Desimone, 2009; 2011; Hawley & Valli, 1999; Jeanpierre et al., 2005; Penuel et al., 2007). These opportunities model effective pedagogical and discursive practices that equip teachers with the tools they need to learn new reform-based teaching practices while allowing them to examine and reflect on their day-to-day teaching methods. This is extremely important when teachers are learning new reform-based pedagogies such as integrated STEM.

4.3.3 Integrated STEM

Integrated STEM education uses the engineering design process, a core engineering practice (Dym, 1999), to situate learning in authentic and meaningful contexts while providing students the opportunity to apply scientific and mathematical concepts to solve a multidisciplinary problem (Bryan et al., 2016; Moore et al., 2014; Silverling et al., 2019). The iterative nature of the engineering design process allows students to test their conceptual understandings and learn from failure (Brophy et al., 2008; Dym et al., 2005). While enriching the teaching and learning of science and mathematics, engineering design-based lessons also supply an additional range of practices such as the effective use of scientific and academic language and discourse (Guzey & Aranda, 2017; Honey et al., 2014; Roth, 1996; Valtorta & Berland, 2015). However, teachers' lack of familiarity with engineering principles, practices, and discourse cause teachers to have low self-efficacy related to teaching engineering, (Hammack & Ivy, 2017), harbor misconceptions about engineering (Antink-Meyer & Meyer, 2016) and struggle to incorporate and apply scientific ideas during the engineering design process (Capobianco & Rupp, 2014; Shernoff et al., 2017). To overcome these challenges, teachers need professional development opportunities that immerses them in quality integrated STEM curriculum that models effective instructional and discourse strategies (Brown & Bogiages, 2019; Du et al., 2019; Estapa & Tank; 2017).

Professional development for STEM integration is critical in helping teachers learn integrated approaches to science teaching (Anderson & Tully, 2020; Shernoff et al., 2017). Although limited professional development opportunities are available (Honey et al., 2014), recent research initiatives that utilize well-designed professional development have been successful in helping teachers learn about, develop, and implement engineering design-based curriculum (Estapa & Tank, 2017; Guzey et al., 2016; Guzey et al., 2019; Johnston et al., 2019; Ring et al., 2017). Now that teachers are more familiar with integrated STEM education, they need to learn about similarities between disciplines, what makes each discipline unique, and how to leverage their language to explicitly communicate the interconnected nature of the disciplines.

As language is an essential tool for meaning-making (Dawes, 2004; Lemke, 1990) and teacher discourse is critical for shaping and guiding student learning in the classroom (Scott, 1998), research investigating how teachers incorporate discipline specific language from the individual STEM disciplines to facilitate knowledge building in the science classroom will enable professional developers and teacher educators to design effective integrated STEM learning opportunities, or enhance existing ones, for science teachers.

4.4 Methodology

This comparative case study (Yin, 1994) examined the discourse of two middle school teachers, Mr. Brighton and Mr. Riley (pseudonyms) during their implementation of two co-created integrated STEM lessons. Their utterances during Lessons 1 and 4, which are the lessons that contain discourse from at least two STEM disciplines, were the units of analysis for this study. These teachers were selected based on purposeful sampling because they participated in a three-week professional development (PD) program aimed to provide learning opportunities for teachers to enhance their knowledge and practices of integrated STEM education and develop STEM units. As a culminating activity for the year-long PD, these teachers co-developed the curriculum *Loons Nesting Platforms* used in this study. During the next school year, both teachers implemented the curriculum units they developed and engaged in mentoring and coaching sessions. Studying both teachers provided an in-depth analysis of the different discursive patterns used by each teacher to explain the same concepts while also allowing us to identify challenges common to both teachers.

4.4.1 Context

Mr. Brighton and Mr. Riley taught general science at a suburban middle school in a Midwestern state in the U.S. Of the 1,100 students at this school, approximately 73% are Caucasian, 12% are Asian, 9% are Black, 6% are Hispanic, and approximately 9% of students receive free or reduced lunch. There were 27 students in Mr. Brighton's class and 25 students in Mr. Riley's class. Earlier in the year, both teachers taught a brief engineering lesson in their classes to introduce engineering and engineering design to their students.

4.4.2 Curriculum

Mr. Brighton and Mr. Riley implemented *Loons Nesting Platforms* over 19 consecutive class periods (approximately 47 minutes each class period for a total of 15 hours of instructional time). This unit was designed to include key features of integrated STEM education (Moore, Glancy, et al., 2014; Moore, Stohlmann, et al., 2014), including the use of the engineering design process to solve a meaningful real-world problem. The teachers created a client letter to introduce the challenge, define the criteria and constraints the solution must meet, and couch the problem in a relevant context. This curriculum was piloted at a university summer camp and self-scored by the teachers using the STEM-ICA (Guzey et al., 2016). These experiences provided feedback the teachers used to revise the curriculum before they enacted it in their own classrooms the following year. The purpose of this unit was to provide students an opportunity to reinforce and apply previously learned scientific and mathematical concepts. Specifically, students use multiple data sources to design a loon nesting platform and select the lake it goes in. This authentic context for the curriculum was chosen since the state Department of Natural Resources has a loon monitoring platform and applies artificial nesting platforms to save loons. The purpose of each lesson is provided in Table 1.

Table 7. *Overview of Loon Curriculum*

Lesson	Days	Disciplinary Focus	Purpose
1	1-3	Primary: Engineering Secondary: Science	Introduce the engineering design task Identify ways humans affect the environment
2	4-5	Primary: Science & Engineering	Learn about the needs of loons
3	6-8	Science	Review food chains and food webs
4	9-11	Primary: Science Secondary: Engineering; Mathematics	Analyze data about biotic and abiotic factors Select a lake for their platform Discuss features of a graph and graph data
5	13-14	Mathematics	Use area and proportions to scale down a prototype
6	14-15	Engineering	Design, build, and test prototypes
7	15-16	Engineering	Redesign and retest prototypes

Lesson 1 began with a whole-class discussion about the effects of human activity on the environment including land, water, and wildlife. After identifying specific activities that destroy animal habitats, students played a game, We Build This City, to illustrate how loon populations are displaced by urban development. Students then reviewed what engineers do and how they use the engineering design process to solve problems. Next, students are introduced to the design challenge, building loon nesting platforms, and engaged in problem scoping to define the problem. In Lesson 2, students completed a scavenger hunt to learn about loons and what they need to survive. Students played an online game to review food chains and food webs in Lesson 3. This knowledge helped students in Lesson 4 as they graphed and analyzed data related to biotic and abiotic factors that affect loons in six metropolitan lakes. Students used this information to select the best lake for their loon nesting platforms. In Lesson 5, students calculated the area of an average loon nest to determine the shape of their platform and use proportions to scale down their prototype by 25%. During Lesson 6, students designed, built, and tested, their loon nesting platforms. Students used the results of their testing to redesign and retest their loon nesting platforms during Lesson 7.

4.4.3 Data Collection and Analysis

We videotaped each class period and transcribed instances where the teacher spoke to the entire class. For the purposes of this study, we transcribed and analyzed lessons 1 and 4 because these lessons include the most integration. For the analysis of data, we employed Legitimation Code Theory (LCT) as an analytical framework. LCT can be used to examine multiple facets of an academic discipline (Maton, 2007). The semantics dimension of LCT has been used to identify how different forms of discourse (e.g., teacher discourse and textual discourse) promotes or constrains knowledge building in other disciplines (Jackson, 2016, 2017; Kilpert & Shay, 2013). For this study, we used the semantics dimension to identify semantic patterns present in disciplinary discourse from multiple disciplines. Specifically, we examined the semantic gravity, or the measure of the degree to which meaning is bound to the context it was acquired in (Maton, 2014) of teacher discourse throughout Lessons 1 and 4. Strong semantic gravity indicates meaning is heavily rooted in a specific context, which may inhibit transfer of learning, whereas weak semantic gravity represents instances where meaning is less rooted in context and more likely to be understood and applied to new situations (Maton, 2014).

The transcripts for Lessons 1 and 4 were divided into units of meaning, which is a segment of teacher discourse with its own instructional purpose. Examples of a unit of meaning from each anchor discipline and where two disciplines are integrated are provided in Table 2.

Table 8. *Example of a Unit of Meaning for each Represented STEM Discipline*

Unit of Meaning	Discipline
We're going to be discussing and dealing with the interactions of organisms between each other and between organisms and their environment.	Science
When you were trying to figure out which lake is best, what are the expectations? What does the client want? ... The constraints are whatever is limiting your options.	Engineering
You are going to take the data and make a line graph on the piece of graph paper. Now, who can give me some details about what ... you should include on a good graph?	Mathematics
As you read through this and summarized it, some of the pieces you probably picked out, that the Department of Natural Resources want to prevent this from becoming a serious concern. They're trying to stay ahead of the game, right? There is a concern that potentially in the future, human activity could lead to population issues for the loons.	Integration

Next, we determined which academic discipline the unit of meaning represents and identified any disconnects in the flow of the teacher's discourse. In other words, we looked for instances where the teacher changed topics without explaining how the topics relate to one another. Finally, we assigned each unit of meaning a code based on its level of semantic gravity according to the coding scheme in Table 3. We then generated a semantic profile by plotting the semantic gravity of each unit of meaning as a function of time.

Table 9. *Descriptions and Representative Examples of Codes*

Semantic Gravity	Code	Description of Code	Example of Code
Weaker ↑	SG--	References abstract principles	We're going to be discussing and dealing with the interactions of organisms between each other and between organisms and their environment
	SG-	References concepts or ideas within the abstract principle	So, for the general definition that we'll use a biotic factor is something that is or was alive.
	SG+	References general everyday examples	Give me a biotic factor in a loon ecosystem. A racoon, great. Fish, good… Ducks, sure. Loons…
↓ Stronger	SG++	References a specific example	Loons are the MN state bird… How many of you have been to the lake and seen and heard Loons out there making their Loon calls?

4.4.3.1 Levels of Analysis

We conducted two levels of data analysis on teacher discourse during their implementation of the *Loons Nesting Platforms* curriculum. Our macroanalysis focused on larger, more encompassing units of meaning to identify how teachers used their discourse to discuss and connect big ideas within and between disciplines. A more fine-grained, microanalysis examined shorter units of meaning to better identify semantic patterns specific to the individual teacher during his implementation of each lesson. For example, in Lesson 4, Mr. Brighton devoted the beginning of class to reviewing biotic and abiotic factors, so for the macroanalysis, everything he said pertaining to biotic and abiotic factors made up one unit of meaning. However, during the microanalysis, we divided that same unit of meaning into thirteen units of meaning, some of which are shown in Table 4. These two levels of analysis allowed us to 1) examine how individual disciplines are discussed during an integrated STEM lesson and 2) identify if and how connections are made between disciplines.

Table 10. *Break Down of One Unit of Meaning (Macroanalysis) into Many (Microanalysis)*

Unit of Meaning
Does anybody know of any, or can someone give me some examples of a biotic factors in a loon ecosystem? So, we spent time last week talking about food webs and chains um but let's bring in the nonliving component also. So, what did I ask? Biotic?
Okay, Julie, give me a biotic factor in a loon ecosystem. A racoon. Great. Joe? Fish. Good. Dan? … Ducks, sure.
Great. So, a lot of living things, biotic things. Abiotic, the nonliving.
Yeah, a boat, sure. Sarah? Water, good yeah. Kevin? Air…Rocks … So, we make a distinction between those things that are living and those that are not.
Now, how about a dead squirrel. I know we don't like to think about it, but it happens. Okay, so uh raise your hand if you think a dead squirrel would be classified as biotic. [most ands in the air]. Okay, hands down. Raise your hand if you think a dead squirrel would be classified as abiotic [couple hands]. Okay. Okay, possibly, good.
Um, so for the general definition that we'll use a biotic factor is something that is or was alive.

4.5 Findings

We examined the semantic patterns present in two teachers' discourse to identify areas where teachers may benefit from discursive support as they learn to implement integrated STEM lessons. From the analysis of Lesson 1, which included discourse from science and engineering, we identified the following two themes: (1) teachers taught individual STEM disciplines separately, and (2) discursive disconnects occurred between disciplines. From the of Lesson 4, which included science, engineering, and mathematics discourse, we identified two additional themes: (3) teacher discourse became more disjointed as they integrated more disciplines, and (4) teachers used different approaches to STEM integration. Each theme is described below.

4.5.1 Theme One: Teachers Taught Individual STEM Disciplines Separately

Traditionally, individual academic disciplines are taught in silos and classroom content focuses primarily on that one subject. This prevents students from making important cross-disciplinary connections that exist in the real-world. Integrated STEM breaks down these silos by incorporating multiple anchor disciplines into one lesson and students use the principles and practices from each discipline as needed during an engineering design task. Our macroanalysis of Lesson 1 showed that when multiple disciplines are represented in a lesson, teachers tend to discuss them one at a time.

Mr. Brighton’s semantic profile for Lesson 1 is shown in Figure 1. The lesson began with scientific discourse about the effects of urban development, deforestation, and other human activities on the environment. Throughout *We Build This City*, everyday discourse was used to illustrate how different types of urban development have larger impacts on populations. Next, Mr. Brighton changed to engineering discourse to remind students of a previous engineering activity they completed and facilitated a brief discussion on what engineers do and how they solve problems. Mr. Brighton then provided students with a memo from the Department of Natural Resources to introduce the design challenge, which provides the opportunity to continuously integrate science and engineering discourse as he relates the need for loon nesting platforms back to urban development and loon displacement. The remainder of the class consisted of engineering specific discourse as Mr. Brighton engaged students in problem scoping and reviewed the engineering design process (EDP). Essentially, Mr. Brighton’s discourse created three chunks of content within Lesson 1: science, integration, and then engineering.

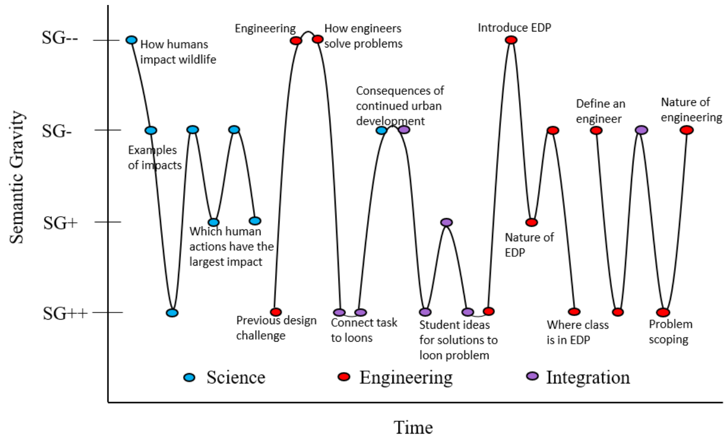

Figure 13. *Macroanalysis of Mr. Brighton's Implementation of Lesson 1*

With few exceptions, Mr. Riley also separated his use of science discourse and engineering discourse, as shown in Figure 2. However, unlike Mr. Brighton, integration discourse did not stand alone. Rather, Mr. Riley added integration discourse to the ends of each engineering-based discussion. The semantic patterns present within Mr. Riley's profile, namely the down escalator when he first introduced engineering content and the up escalator as he reviewed the memo and connected it to the loon problem, illustrates how integration discourse ultimately caused Mr. Riley to create several small chunks of engineering discourse.

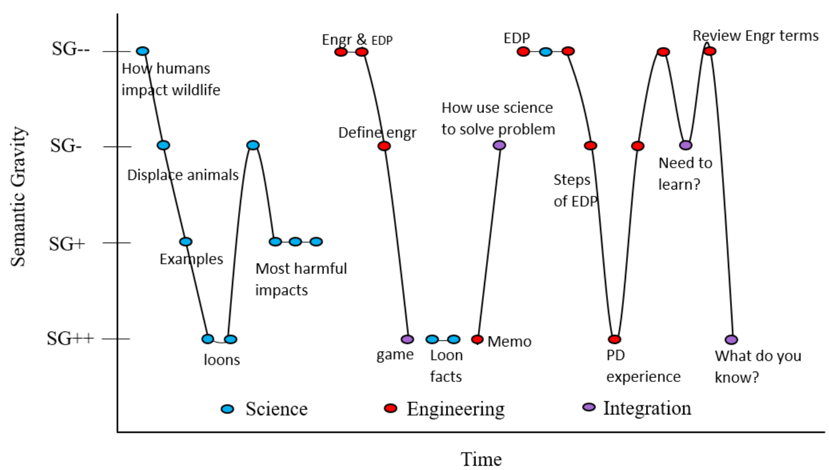

Figure 14. *Macroanalysis of Mr. Riley's Implementation of Lesson 1*

Although both teachers attempted to integrate both anchor disciplines throughout Lesson 1, discipline specific discourse was primarily used in isolation. This approach is not surprising early in the unit as students need the science background to fully understand and appreciate the problem they need to solve. However, these semantic profiles suggest that Mr. Brighton and Mr. Riley would benefit from learning where and how to seamlessly incorporate integration discourse throughout the lesson to create semantic waves that incorporate multiple disciplines.

4.5.2 Theme Two: Discursive Disconnects Occurred Between Disciplines

Teacher discourse is an essential tool for facilitating sense making in the science classroom (Kelly, 2014). To prevent students from viewing content as isolated facts, teachers must consciously and explicitly connect each idea to topics covered previously. This is particularly important during integrated STEM because each discipline has its own unique ways of knowing and communicating. Students need support identifying when to use domain-specific knowledge when multiple disciplines are present within a lesson or unit (Honey et al., 2014). Our microanalysis of Lesson 1 revealed that discursive disconnects often occurred between the two anchor disciplines and at points of integration.

As Figure 3 illustrates, our microanalysis of Mr. Brighton's implementation of Lesson 1 revealed three breaks in his semantic profile. Each disconnect occurred near chunks of discipline specific discourse. Excerpts are provided for the two disconnects indicated with a long arrow. The first represents a disconnect between disciplines and the second illustrates a disconnect within a discipline. To provide adequate context, each excerpt contains two units of meaning before and after the disconnect, which is represented by a dashed line.

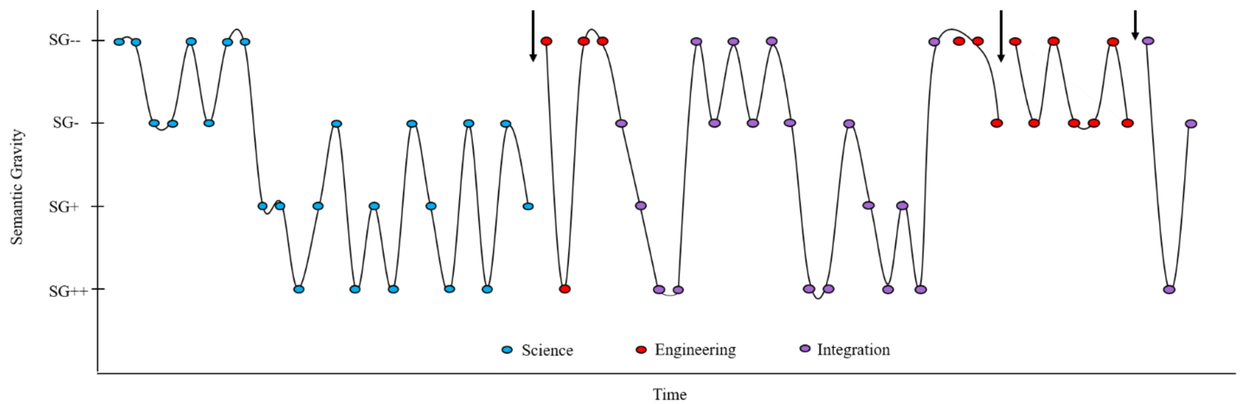

Figure 15. *Microanalysis of Mr. Brighton's Implementation of Lesson 1*

The first semantic break occurred as Mr. Brighton wrapped up an in-depth science-based discussion about the ways humans impact the environment by having students reflect on the results of We Build This City when Mr. Brighton said:

> So, think of [the results of We Build This City] this way. Let's say this is a year's worth of development here…if three loons had to leave, that's 20% of the population (Science). Okay, so we talked about how many loons you lost. What developments had the biggest impacts? (Science).
>
> ---
>
> Okay, so you guys will be working in engineering teams. Your teams will be those people at your tables with you (Engineering).
> We've done a little engineering in this class during the first trimester, if you'll recall we worked on our space plant activity. So, you have a little background on that (Engineering).

The conversation continued as students talked about engineers using mathematics and science to solve problems by. Mr. Brighton then seamlessly integrated these engineering principles with the science issue of loon population displacement by saying:

> So, as we think about our imaginary city…that we constructed to simulate the lost habitat. Do you think in Minnesota we have a legitimate concern as it relates to loons, our lakes, and our populations? Do you think it's something that is relevant and something we should actually think about? (Integration)

However, after a productive conversation about why loon displacement is a valid concern, Mr. Brighton transitioned to engineering discipline-specific talk as he introduced the engineering design process and explained the individual steps of this process. However, a discursive disconnect occurred as Mr. Brighton changed from one engineering topic (client) to the next (engineering design process):

> Then remember, an engineering has a client, okay? (Engineering)
> And an engineer works for that client to meet their needs, okay? (Engineering)
>
> ---
>
> So, what you should also notice here [in the engineering design process) is that there is all these arrows bouncing all over the place. Because, if you get down to the decide step and say, "hey, this isn't quite good enough," you need to go back. You might have to go back and plan again or you might have to go back again and redefine what you're doing… (Engineering)
> Okay, Joe, what do you think? Where are we [in the engineering design process]? (Engineering)

This disconnect may make it challenging for students to understand how the iterative nature of the design process effects the client they are working to help. To overcome this, Mr. Brighton could have explained that engineers often revisit steps of the engineering process to develop a solution that best meets the client's needs.

Mr. Riley's semantic profile also contains semantic waves with disconnects occurring as he transitioned from one type of discourse to another, as shown in Figure 4. Mr. Riley had a discursive disconnect at the same point as Mr. Brighton (indicated by the second long arrow), when he transitioned from an explanation of the engineering design process and eliciting students' ideas about information, they need to learn to design an effective loon nesting platform.

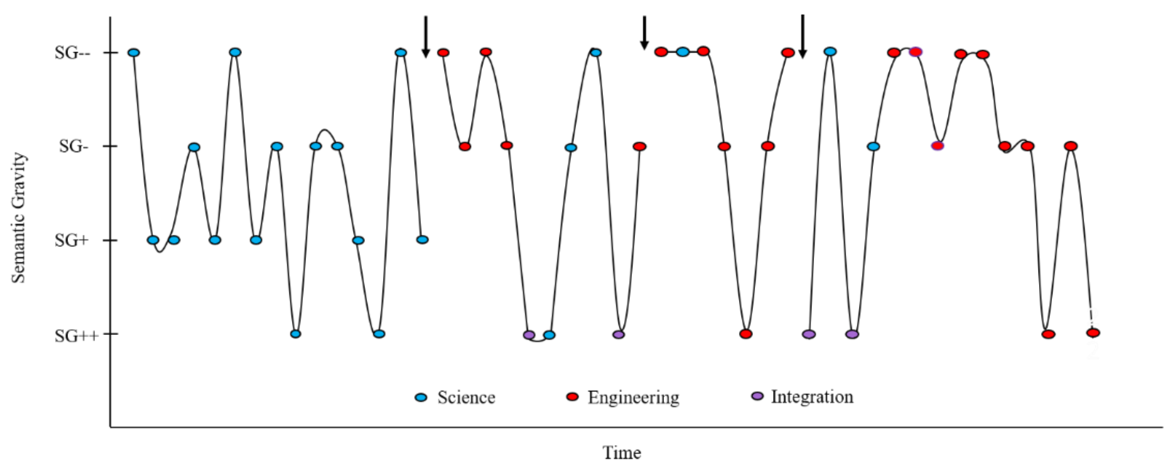

Figure 16. *Microanalysis of Mr. Riley's Implementation of Lesson 1*

Also, like Mr. Brighton, discursive disconnects often occurred shortly before or after integration discourse. For example, after discussing human impacts on wildlife, Mr. Riley moved on to integration discourse by having students brainstorm potential solutions to the loon problem. The example below illustrates a disconnect that occurs as Mr. Riley transitioned from integration talk to engineering talk:

> What about, ah, potential fixes [to the loon displacement problem] here? What is one way we could stop it? So, possible solutions to the problem (Science).
> We could make special habitats…stop building stuff you don't need…limiting land to build … conserve land, so again, go through maybe and see where they are at right now and conserve it … (Science).
>
> ---
>
> Right, ah, anybody want to share what they think engineers do? ... Ah, so it sounds like you're saying they come up with solution to problems, uh, making blueprints (Engineering).
> So again, that may be one way they solve problems (Engineering).

This example shows how Mr. Riley's presented engineering as a standalone discipline, isolated from the fluid science conversation students had right before. Mr. Riley could scaffold student sense making by using his discourse to connect the science (ways to mitigate the loon displacement problem) and engineering (engineers solve problems) ideas in the excerpt. Both teachers would benefit from additional support on how to identify opportunities in the curriculum to make interdisciplinary connection within the curriculum and how to use their discourse to explicitly illustrate those connections to their students.

4.5.3 Theme Three: Teacher Discourse became More Disjointed as they Integrated More Disciplines

Students must apply science, engineering, and mathematic skills and concepts in Lesson 4 as they analyze biotic and abiotic factors that serve as data to select which lake their loon nesting platform will go in. In this lesson, teacher discourse focuses on different sources of data (science), features of graphs and trendlines so students can predict how a factor may change over time (mathematics), and how students will use this information to ensure the lake they select meets the criteria and constraints set forth by the client (engineering). Our macroanalysis of Mr. Brighton's and Mr. Riley's implementation of this lesson, shown in Figure 5, revealed that both teacher's semantic profile lacks continuous semantic waves and contain semantic patterns like escalators, flatlines, and ideas presented as isolated facts, all of which promote segmented knowledge and may negatively affect student learning. This indicated that the more disciplines present within a lesson, the more challenging it was to use language to seamlessly transition between disciplines and between discipline-specific and integration discourse.

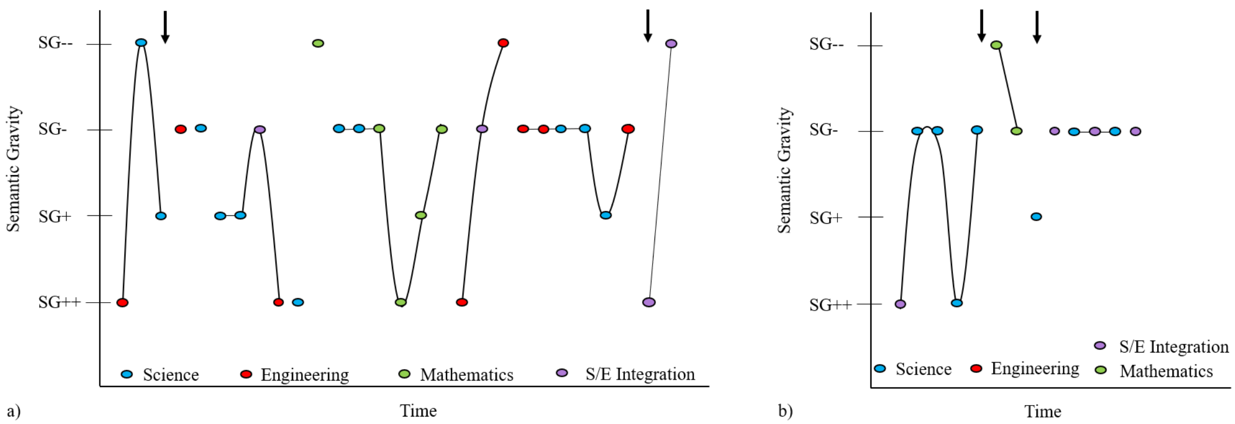

Figure 17. *Macroanalysis of Mr. Brighton's (a) and Mr. Riley's (b) Implementation of Lesson 4*

Mr. Brighton discussed several more topics in Lesson 4 than Mr. Riley, especially at the beginning of the lesson where he used his discourse to promote student understanding of the purpose of the lesson activities and activate prior knowledge needed later in the lesson. Specifically, he began Lesson 4 with a class discussion about the client's needs, which includes selecting a lake for their nesting platform. The excerpt below illustrates a time when Mr. Brighton's discourse became fragmented as he transitioned from science discourse to engineering discourse and then back to science discourse:

> You're going to get a chance to look at some of the biotic and abiotic factors associated with the different lakes in the metro areas so that hopefully you can make a decision that will be a successful decision based on the evidence that we have (Science, SG--).

Does anybody know of any, or can someone give me some examples of a biotic factor in a loon ecosystem?... Abiotic, the nonliving? (Science, SG+).
Okay, [goes to poster of the engineering design process] we're kind of bounding down to this plan step… (Engineering, SG-)
Here is a video…you can see [a loon] is crossing a large area [of the lake] (Science, SG-).

Alright, Robin, tell me about [examples of] abiotic factors. (Science, SG+)

Each unit of meaning in the excerpt above relates to the overall goal of the lesson, but the sequence of his discourse does not make these relationships clear. As teacher discourse is critical in framing a science lesson, transitions that explicitly connect one big idea to the next are important for scaffolding student sense making. A similar situation occurred when Mr. Brighton ended Lesson 4 with an up escalator while attempting to integrate the design task and the science content needed to successfully complete the task. However, this conversation is disconnected from the engineering conversation before it, as shown below:

So, it'd be pretty easy to split us up into groups and have a debate [about which lake is best for the platforms] … this provides us a good opportunity to refine our justifications…So, if at the end of the day, the client comes in and interviews each group independently, you kind of know what that group is going to say… (Engineering, SG-).

Okay, so, do you have additional post-its still on the T-chart, raise your hand. Tracy, tell me what [questions] you got [about the design task]. Like what type of [science and engineering] things? (Integration, SG++)
We will probably wrap up our learning and planning stage early next week so by the end of the week you'll be well into the trying and testing, okay. So, and remember, we talked about how we bounce around [the engineering design process] (Integration, SG--).

Although Mr. Brighton ended this lesson by setting the stage for what's to come in Lesson 5, the abrupt change from selecting a lake to listing science topics they need to learn about may cause students to lose sight of the overarching goal of the lesson. The significant difference in degrees of semantic gravity for the two units of meaning that make up the escalator may also be problematic. Creating a robust list of questions regarding the design task (SG++) and an equally robust list of science topics (SG--) may leave students wondering which science topics will help them answer each specific question. In this instance, students may benefit from a more scaffolded discussion about the knowledge they need to thoroughly address each question.

Mr. Riley's semantic profile contains a down escalator right after he completes a science-related discussion focused on data that students will need to select a lake for their platforms. The conversation below illustrates the difficulty in transitioning between disciplines:

> What do you notice at your lab station? Two things. You have an aerial view of your lake… [and a data table] with clarity. What does water clarity mean? (Science, SG-)
>
> ---
>
> In your group you need to graph that data table, figure out again if you can't remember, what's your independent variable, what's your dependent, where does that go? On the x and y axis. Make sure you have labels for those axes. Make sure you have a title for your overall graph. The other thing that I really need you to focus on, is the increment. (Mathematics, SG--)
>
> The next thing, I want to just say a little about trend lines … [discussion on how intervals affect the spread of the graph] … (Mathematics, SG-)
>
> ---
>
> I want you in your group to look at the map and talk about what you see. Not only with size, but the surrounding area. What are some major structures that you might see that could impact somethings? (Science, SG+)

Mr. Riley did a good job scaffolding student understanding of the importance of accurate scales when creating and interpreting a trendline. However, Mr. Riley's abrupt transition to the types of scientific observations students can make about each lake may cause students to struggle to understand how scientific observations and graphing are related and connect back to the design task. Mr. Riley missed an opportunity to make an interdisciplinary connection about how each discipline generates and uses data, which serve as evidence when making a claim.

Another common semantic pattern present in both Mr. Brighton's and Mr. Riley's semantic profiles are flatlines. A flatline represents areas where the same level of semantic gravity is used for an extended period. An example of a flatline present within Mr. Riley's semantic profile is illustrated below:

> When you're making high and low points [on a graph], you are looking at the actual data. "Approximate" is [making] the prediction of [what water clarity will be in] 2016. Again, if you drew the data … what do you think the approximate value will be for 2016 and then the trend observed (Integration, SG-).
>
> ---
>
> [Here] is the map of all six lakes… I'm also going to give you some more data about the lakes with the acreage…human activity … fish species in the lake … and then I need you as a group to make two additional observations from the map (Science, SG-).

So again, you already went through and predetermined five things that you think the loons need in a lake … tell me about what lake you choose and then to the right down here, give me any data or evidence, facts about that lake…one of the most important things is your explanation and justification to why you chose to choose that lake (Integration, SG-)

First off what lake did you [choose] …why did you choose [that] lake? (Science, SG-)

You presented a solution to one of the problems that the client wanted, which was selecting a lake in the Metropolitan area that you can put this platform. Okay, we're gonna start to see what size that platform could potentially need to be based off of the size of loons nesting patterns so again how big how massive it would be... [discuss additional information students need to build their loon platforms] (Integration, SG-)

In this example, Mr. Riley referred to a lot of discipline-specific content and skills, such as analyzing data, making observations, and using data to justify design related decisions. The middle three units of meaning are explicitly connected to one another, allowing the students to ascertain how this knowledge and skills help them make inform design-related decisions, like selecting the right lake for their loon platforms. However, students unfamiliar with terms like "observations," and "justifications" which are common at this level of semantic gravity, may feel overwhelmed or unable to contribute to future design conversations and decisions.

Incorporating the knowledge and practices of a third academic discipline into the lesson resulted in a more fragmented semantic profile. The profiles of both teachers contain semantic patterns that promote segmented learning, which can hinder sense making within each discipline. Very few, if any, semantic waves are present and there are multiple instances of discipline specific ideas presented in isolation, both of which will likely prevent students from making connections between the disciplines. Identifying semantic patterns within both teachers' semantic profiles illuminate the challenge of using different degrees of context within their disciplinary and integration discourse during an integrated STEM lesson.

4.5.4 Theme Four: Teachers Used Different Approaches to STEM Integration

Lesson 4 contains content and practices from three academic disciplines. Our microanalysis portrayed the detailed nuances of each teacher's discursive approach to integrating these disciplines. As mentioned in theme one, both teachers tend to chunk their disciplinary discourse. However, Mr. Brighton utilized an "add on" approach to integration whereas Mr. Riley tended to sprinkle integration discourse throughout each lesson.

As shown in Figure 6, Mr. Brighton incorporated three different types of integration throughout the lesson: science and engineering (S/E), science and mathematics (S/M), and science, engineering, and mathematics (S/E/M). These instances of integration typically occurred at the end of a long segment of discipline specific discourse to wrap up the conversation and connect the content back to the design task. This approach resulted in multiple semantic waves within his discipline specific discourse. For example, in his science discourse there are several points in the semantic waves where sequential units of meaning differ by a single degree of semantic gravity. This illustrates the scaffolding Mr. Brighton provided to help students make connections between science ideas.

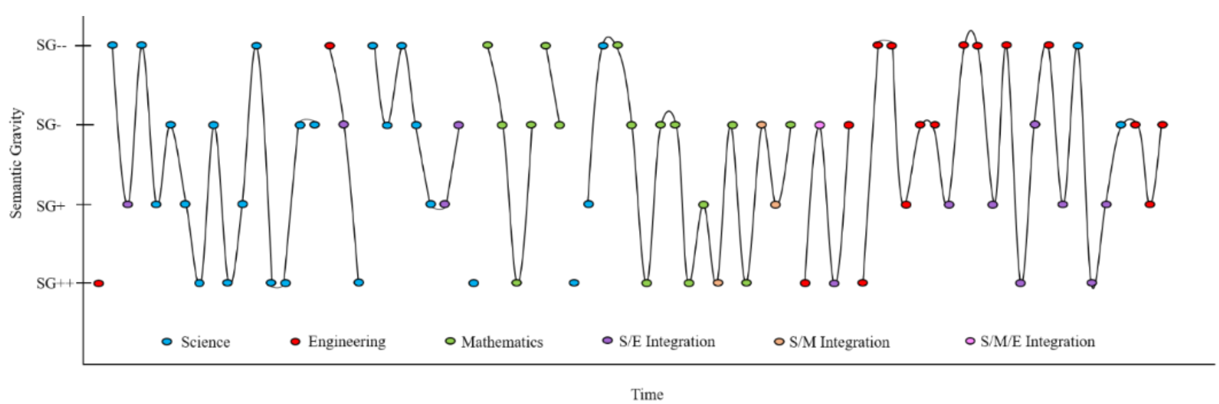

Figure 18. *Microanalysis of Mr. Brighton's Implementation of Lesson 4*

Mr. Brighton's mathematics discourse also included many semantic waves with several instances of integration discourse. Mr. Brighton consistently unpacked and repacked mathematics content and emphasized how this content is important in science. Specifically, Mr. Brighton highlighted how scientific data is used to create graphs, which can then be used to make scientific predictions. Mr. Brighton also integrated all three disciplines when he said:

> The reality of engineers is that they compete with other engineers … there are lots of engineering companies probably that are presenting the same problem to the same client … So, when you are starting to make decisions, this is really the first big decision that your engineering team is making, um, you want to make sure that you have the evidence to back it up. And that's why we spent time collecting the data on the lakes, graphing, and talking about all that.

These interdisciplinary connections are essential for students to understand how the disciplines relate to one another and how problem solving requires skills and content knowledge from multiple disciplines.

Mr. Brighton also integrated science and engineering discourse at the end of the lesson. It is worth noting that Mr. Brighton's mathematics discourse tended to oscillate between SG- (general discipline specific discourse) and SG++ (specific examples of the idea being discussed) whereas his engineering discourse oscillated between SG-- (abstract ideas) and SG+ (general everyday examples of the content). These differences may be related to the purpose of the disciplinary discourse. For mathematics, students needed to understand the features of a graph so they could accurately interpret and use scientific data related to each lake. For engineering, students needed to understand engineering terminology to make sure they used the graphs and data to select the lake that best meet the needs of the client.

Unlike Mr. Brighton, Mr. Riley distributed integration discourse throughout the entire lesson, as shown in Figure 7. Mr. Riley frequently included integration discourse after a few segments of discipline specific discourse. Consistently using integration discourse will enable students to recognize how science and engineering, and science and mathematics relate to one another and will help students apply science and mathematics content when designing their loon nesting platform. Near the end of the lesson, Mr. Riley seamlessly blended engineering, science, and integration discourse to make a series of semantic waves. This semantic pattern suggests that Mr. Riley's discourse helped make explicit connections within and between the disciplines.

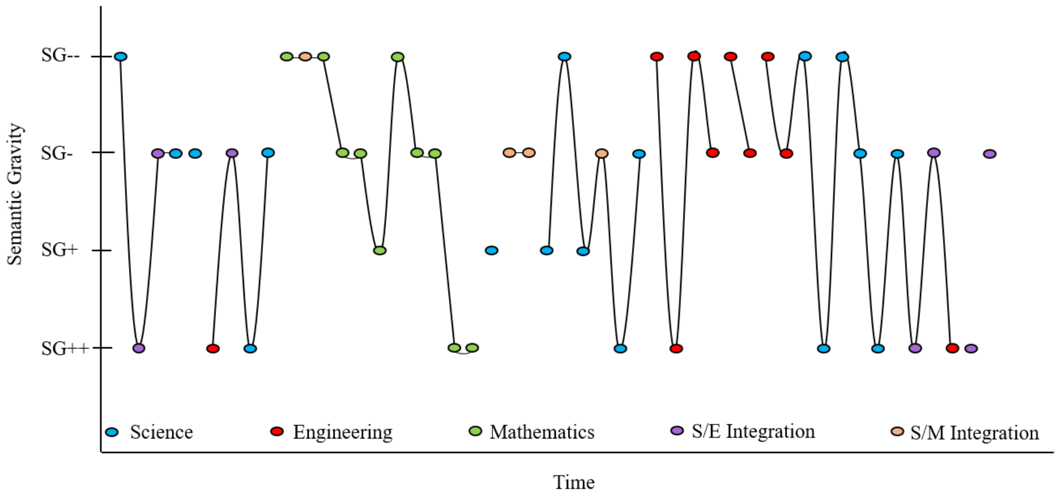

Figure 19. *Mr. Riley's Implementation of Lesson 4*

Both teachers integrated multiple disciplinary discourses throughout Lesson 4. However, they took different approaches to integration, which results in different semantic patterns within their semantic profile. Both profiles include semantic waves and many instances of integration discourse. These semantic profiles do not reflect quality of teaching, nor imply that one method of integration is better than the other. Rather, both approaches represent different types of integration of multiple STEM disciplines.

4.6 Conclusions and Implications

Current reform initiatives emphasize the need for students to cross the boundaries of individual STEM disciplines to learn when and how to apply domain-specific knowledge and practices in an authentic and meaningful context (NRC, 2012; NGSS Lead States, 2013; Honey et al., 2014). This type of science learning requires teachers to create learning environments they are not familiar with nor have any experience participating in (National Academy of Enginering, 2010). One way to facilitate knowledge building in an integrated classroom is through rich classroom discourse (Moje, 2015). In this study we sought to identify semantic patterns in two teachers' classroom talk as they implemented a co-created life science integrated STEM unit to identify areas where they supported students making meaning of discipline specific principles and practices, and areas where they need additional support to enhance student understanding. Our findings indicate that both teachers approached integration differently. Mr. Riley tended to sprinkle integration discourse throughout each lesson whereas Mr. Brighton chunked his integration discourse. Both approaches successfully integrated multiple STEM disciplines and included semantic patterns shown to promote sense making in the classroom (Maton, 2009). While some students may be able to make larger connections with integration at the end of a lesson, some students may benefit from the foreshadowing provided by smaller bits of integration discourse spread throughout the lesson.

Although both teachers integrated the STEM disciplines, the semantic profiles of both teachers also included semantic patterns that promote segmented learning, such as flatlines, escalators, and ideas presented as isolated facts. This elucidates the challenges teachers have in using discourse to transition from one activity to the next to ensure students see how one the knowledge and skills from one discipline enhances those from another discipline. Without explicit instruction, it is unlikely that students will identify these isolated pieces of information as information needed to inform their design solution (Azevedo et al., 2015; Purzer et al., 2015; Valtorta & Berland, 2015), a core feature of integrated STEM education (Honey el al, 2014;

NRC, 2012). Another pattern present in both teachers' profiles are drastic jumps from discourse with weak semantic gravity to discourse with strong semantic gravity, either in the form of an escalator or within a semantic wave. These shifts represent potential challenges for students as learning is rooted in context, and sudden changes in the degree of contextual understanding may inhibit knowledge building as demonstrated by previous studies (Jackson 2016, 2017; Kelly-Laubscher & Luckett, 2016; Kilpert & Shay, 2013; Maton, 2009).

The findings in this study also highlight the fact that teachers need assistance developing discursive practices that facilitate seamless integration of multiple disciplines in an integrated STEM unit. Teachers learn new practices when they are active learners and participants in professional development that enables them to develop and enact integrated STEM curricular materials. Guzey et al. (2014) found that science teachers can effectively incorporate engineering content and practices into their classrooms after participating in a high-quality professional development that gave teachers the opportunity to participate in activities that explicitly integrate science and engineering. Thus, there is a need for professional development that helps teachers identify points of boundary crossing and demonstrates how to use language to illustrate the interconnected nature of the disciplines.

Research also shows the importance of providing teachers with opportunities to reflect on their instructional approaches to promote teacher learning and improve student outcomes (Desmoine, 2011; Schön, 1987; Vermunt & Endedijk, 2010). Because learning is rooted in context (Lemke, 1998; Vygotsky, 1962), it is important that teachers consider the specific language they use when teaching science (Moje, 1995; Scott, 1998). Using LCT as a reflective tool will allow teachers and teacher educators to monitor teacher learning as their semantic profiles change over time. Semantic profiles can also serve as a starting point for teachers to reflect on the classroom conversations they initiate or identify points where additional discourse will benefit their students.

Implications of this study pertain to the need of professional developers, teacher educators, and curriculum developers to offer more support and guidance for teachers to successfully integrate multiple disciplines into their classroom practice (Honey et al., 2014). Curriculum developers can benefit from these results by using macrolevel analysis to elucidate points of tension in a curriculum where revisions can be made to enhance student sensemaking within and between disciplines. Professional developers and teacher educators can benefit from the microlevel analysis by observing how teachers translate the intended curriculum in their classroom and get a better picture of the nature of representation of disciplines teachers enact within a unit.

The study has several limitations. One limitation of LCT as an analytical framework is that it can be easy to make assumptions about a teacher's instructional practice after glancing at the size and shape of their semantic profile. The number of units of meaning is not an indication of the quality of a teacher's implementation, rather it is more reflective of teaching style and the nature of the classroom. Also, the presence of disconnects in a semantic profile is not always bad. In fact, the nature of the lesson or unit will impact the features of a semantic profile. The *Loons Nesting Platforms* unit served as an opportunity for students to apply previously learned content in an authentic context and to gain experience with the engineering design process. For this reason, both teachers frequently transitioned between topics in order to tap into students' prior knowledge on various topics as classroom discourse dictated (i.e., students asked questions or the opportunity for teachable moments arose). Future studies should consider how language can be used to illuminate connections between the disciplines.

Legitimation Code Theory as an analytical framework provides the opportunity for teacher educators and professional developers to map a teacher’s semantic patters over time (Maton, 2014) and explicate when and how integration occurs as teachers navigate between and within STEM disciplines. This study demonstrated that each teacher had a different approach to integrating the disciplines, yet both struggled to use language to help their students boundary cross. The results can inform teachers, teacher educators, and curriculum developers who aim to improve integrated STEM education for all students.

4.7 References

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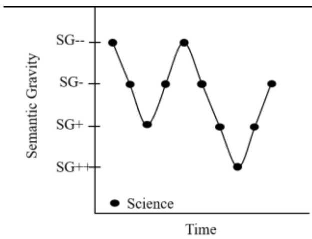
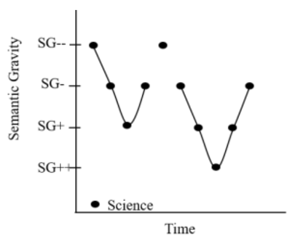
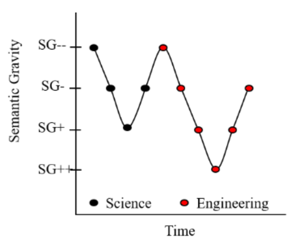
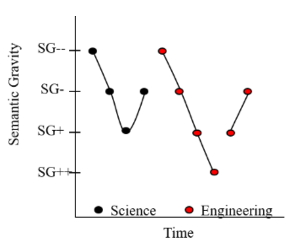
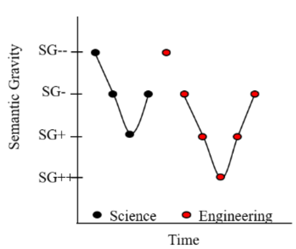
5. OVERARCHING THEMES ACROSS ALL THREE STUDIES

Each study in this dissertation analyzed data to address the research question: *In what ways can Legitimation Code Theory serve as an analytical framework to examine integrated STEM curriculum and teachers' implementation of it?* Even though the purpose for applying Legitimation Code Theory (LCT) varied from study to study, some common themes emerged that help address the research question. The details of each theme are explored in this chapter.

5.1 Theme 1: LCT is a Useful Tool for Examining Discourse Within the Context of Integrated STEM in Middle School Classrooms

Most studies using LCT as an analytical framework, specifically the semantics dimension, occurred in the context of higher education and outside of science education (Dong et al., 2014; Kilpert & Shay, 2013; Monbec, 2018; Mouton & Archer, 2019; Wolff & Luckett, 2013). Each study in this dissertation demonstrated that LCT is a suitable framework for examining integrated STEM curriculum and its implementation in the middle school classroom. Semantic gravity ranges on a continuum from weak abstract) to strong (context specific). The coding scheme used throughout each study elucidated new semantic patterns within an integrated STEM curriculum and in teacher discourse that are indicative of either segmented learning or cumulative learning. Table 1 illustrates these semantic patterns with the first image as point of comparison as other studies have indicated the importance of semantic waves within a single discipline (Maton, 2014). These new semantic patterns offer valuable insight for educators, teacher educators, and professional developers who aim to develop and refine curriculum resources to enhance student learning. Future studies should examine these semantic patterns influence student sense making and discursive strategies for overcoming the semantic patterns that promote segmented learning to promote knowledge building in the science classroom.

Table 11. *Semantic Patterns that Indicate Cumulative and Segmented Learning*

Semantic Pattern	Description	Implication
	Semantic wave within a single discipline	Cumulative learning: Connections made between ideas within the same discipline; appropriate scaffolding provided as an abstract idea is unpacked and then repacked over time.
	Isolated topic within a single discipline	Segmented learning: A topic within a discipline is discussed in isolation from the topics that are discussed before and after it.
	Interdisciplinary semantic wave	Cumulative learning: Connections made between ideas within the same discipline; connections made between two disciplines; appropriate scaffolding provided as an abstract idea is unpacked, repacked, and related a topic from another discipline over time.
	Down escalator and an up escalator	Segmented learning: Some connections are made within a discipline but not between disciplines. Some engineering topics are discussed independently of others.
	Interdisciplinary disconnect and isolation	Segmented learning: Discursive disconnect between disciplines with one engineering taught in isolation from the remaining engineering topics.

5.2 Theme 2: LCT as a Tool for a Design-Based Approach to Curriculum Development

Each study suggested that integrated STEM curricular resources can benefit from a concerted effort to make explicit the connections between the STEM disciplines. The past ten years have focused on developing and enhancing curriculum that contain the five core features of integrated STEM and helping teachers become familiar and comfortable with incorporating engineering in their classroom (Estapa & Tank, 2017; Ring et al., 2017). These resources have improved teachers' implementation of integrated STEM (Guzey et al., 2019; Wang et al., 2011) which can have positive effects on student learning, interest, and motivation in science (Cunningham et al., 2020; Guzey et al., 2016; Honey et al., 2014; Redmond et al., 2011). As teachers become more assured of their ability to implement an integrated STEM curriculum, researchers, teacher educators, and curriculum developers can focus their attention on providing additional discursive support to these curricular resources to help teacher scaffold student learning.

LCT as an analytical framework offers a starting point for these curricular enhancements. Observing semantic patterns that promote segmented learning, like an escalator, suggest points where additional scripts or prompts can be provided to help teachers make connections between individual science topics to help students see how one science idea relates to another (Maton, 2009). Similarly, flatlines and isolated points in a semantic profile allude to points where teachers may need additional scaffolding to help students make sense of a series of discipline specific discourse or understand how segments of everyday discourse tie back to the disciplinary principle being discussed.

Examining and modifying areas where semantic waves are present can also enhance student meaning-making. For example, points in a semantic profile where there are drastic changes in the degree of semantic gravity may represent pain points for students. Adding additional segments of discourse with more gradual shifts in the level of semantic gravity may better scaffold student learning. Also, revising a semantic wave to have greater semantic range can also be beneficial (Maton, 2014). Thoroughly unpacking and repacking ideas so students learn new terminology and can use and apply it in appropriate everyday contexts is ideal.

5.3 Theme 3: LCT as a Tool to Study Discursive Strategies

In each of these studies, the semantic patterns present within a teacher's implementation of an integrated STEM lesson identified discursive strategies that have the potential to develop student meaning-making and help them understand the interrelatedness of the STEM disciplines. For example, teachers in each study used double talk (Brown & Spang, 2008), asked open ended questions to elicit students' ideas, and capitalized on students' personal experiences to make science learning relevant and meaningful. These discursive strategies often correlated with specific semantic patterns within in an implementation profile. For example, all three teachers often capitalized on students' prior knowledge by including a familiar real-world example (SG+) immediately after discussing a specific science concept (SG-). Identifying the semantic patterns associated with additional effective discursive strategies can help curriculum developers and teacher educators enhance existing curricular resources to better scaffold student learning.

5.4 Theme 4: LCT as a Tool to Identify Areas Where Teachers Need Support

Using LCT as an analytical framework illuminated areas where all three teachers can better facilitate meaning-making within and across disciplines. The implementation profiles from all three studies include escalators, flatlines, and segments of discourse that stand in isolation, disconnected from the content presented before or after it. These semantic patterns are indicative of areas where teachers can use additional support making connections in the curriculum. This is an opportunity for teacher educators and curriculum developers to provide examples within a curriculum to draw from if they lack domain specific knowledge or experiences. Additionally, even though the integrated STEM units used in these studies incorporate content and practices from multiple STEM disciplines, teachers tend to chunk disciplinary content rather than integrating them in a smooth, connected manner. Thus, teachers need discursive support on how to pivot between disciplines in a non-disjointed fashion.

5.5 Limitations

As the purpose of this dissertation is to identify ways LCT can be used in K-12 STEM education, each study in this dissertation contains a small sample size. This allows us to determine the feasibility of using LCT to analyze an integrated STEM curriculum and teachers' enactment of it, but it does limit the generalizability of the findings and transferability of the findings to another curriculum and its implementation. Additionally, the studies of this dissertation focus on the semantic patterns present in discourse specific to 6^{th} grade classrooms. It is likely that elementary and high school teachers will have additional discursive needs to facilitate meaning-making as more complex phenomenon are discussed. Finally, the four-point semantic gravity scale may need to be adapted to accommodate the semantic range of younger and older students.

5.6 Implications and Future Work

The studies in this dissertation illustrate different ways LCT can be used as an analytical framework to examine integrated STEM curriculum and its enactment. The presence of semantic waves in curriculum and teacher discourse is linked to enhanced student understanding (Georgiou et al., 2014; Hartley, n.d.; Maton 2014; Mouton & Archer, 2019). Mapping the semantic patterns present within written and oral discourse can provide valuable insight on how teacher educators and professional developers can integrate academic and everyday language to enhance knowledge building. Implications from the studies in this dissertation and future work related to these implications are described below.

5.6.1 Teachers Need Ongoing Support

Implementing integrated STEM in the middle school classroom requires teachers to incorporate principles and practices from multiple disciplines (Moore et al., 2014). This is especially challenging because many middle school science teachers lack experience and expertise in the other STEM disciplines (Banilower et al., 2013). The results of these studies suggest that teachers need professional development opportunities that not only help them learn about the core features of the other STEM disciplines, but also offer strategies for teaching these discipline specific features to their students (Honey et al., 2014). Providing long-term mentors or coaches who could assist them in incorporating discursive strategies into their teaching practice and provide feedback on their language use can help teachers better scaffold student learning (Di Domenico et al., 2017; L'Allier et al., 2010). Throughout an integrated STEM lesson or unit, students need to know when discipline specific knowledge is relevant and how to apply that knowledge to create a design solution. For students to be successful in this type of learning environment, teachers need an extensive discursive repertoire so they can frame and organize lessons that make explicit connections within and among the disciplines to promote student understanding of how the STEM disciplines are unique yet interrelated (Duschl, 2008; Kelly, 2014). To achieve this, professional development programs can facilitate collective participation among teachers implementing the same unit so they can capitalize on their combined expertise to identify interdisciplinary connections within the curriculum and share their experiences in helping students make meaning throughout an integrated STEM lesson or unit (Birman et al., 2000).

It is incumbent upon teacher educators and professional developers to include opportunities for teachers to identify or incorporate interdisciplinary connections within an integrated STEM curriculum. No two educators will implement a curriculum in exactly the same way, as they must make productive changes to better meet the needs of their student (Davis et al., 2016). As teacher discourse is an essential component to science learning (Lemke, 1990), studies that examine how teachers modify the discourse provided in a written curriculum is essential to creating effective integrated STEM curricular resources. As the studies in this dissertation focused on either one or two teachers, future work should investigate how different teachers modify the discourse within an intended curriculum to better align with the needs of their students. Studies that examine how the different features of semantic waves (e.g., semantic range and incremental changes in semantic gravity) affect student learning will help curriculum developers and teacher educators create curriculum and teacher training materials that incorporate language that better promotes meaning-making among students.

5.6.2 Teacher Experience is Crucial for Implementing Integrated STEM Approaches

These studies elucidate the importance of teacher experience when implementing integrated STEM. Not only did Mr. Walsh have more science teaching experience, but he also worked as an environmental engineer prior to starting his teaching career, which gave him valuable insight that most teachers do not have. His familiarity with engineering principles and practices enabled him to make interdisciplinary connections, explicitly demonstrate how engineers rely on science and mathematical principles to solve problems and use the engineering design task to frame his science instruction. This additional expertise likely contributed to the numerous semantic waves, with very few discursive breaks, present within his implementation. Additional studies should examine the discursive strategies deployed by teachers to facilitate sense making between and among disciplines to better create an integrated learning experience for students.

At the time of Study 3, Mr. Brighton and Mr. Riley had about half as many years teaching experience, and no formal engineering experience, which may have contributed to why there were significantly more escalators and flatlines in their semantic profiles. This suggests that exposure to engineering principles and practices, whether through professional development, attending conferences, or guest speakers, can provide teachers additional knowledge and experiences to draw on in the classroom. Additional studies that examine how these types of opportunities affect teachers' pedagogical practices and their effects on student learning, will help teacher educator and curriculum developers design rich learning experiences for educators.

5.6.3 The Purpose of an Integrated STEM Unit Affects Teacher Discourse

The integrated STEM unit used in Studies 1 and 2 was designed to teach students several new science topics, including water percolation, transpiration, relationships within an ecosystem, and decomposition whereas the unit implemented in Study 3 served as an opportunity for students to apply previously learned concepts in a meaningful context. All three classes had some previous engineering design experience, although they did not use engineering specific language as thoroughly in those activities. The semantic profile for Mr. Walsh's implementation of the *Designing a Two-Stage Water Filter* contained significantly more units of meaning and more semantic patterns that promote knowledge building than either teacher implementing the *Loons Nesting Platform* curriculum. This is likely due to Mr. Brighton and Mr. Riley only needing to remind students of science topics as opposed to having in depth discussions of them like Mr. Walsh did. Mr. Walsh's profile also indicates his use of multiple discursive strategies to scaffold student sense making as they learned a plethora of new vocabulary, concepts, and practices. This suggests that teachers need access to high quality professional development to learn how to leverage their language to better scaffold student learning.

5.7 References

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